2013 Optical Metrology

Technical Summaries

- Optical Measurement Systems for Industrial Inspection
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Although low coherence microscopy (LCM) has been known for long time in the context of interference microscopy, coherence radar and white light interferometry, the whole subject has attracted a wide interest in the last two decades particularly accelerated by the entrance of OCT, as a noninvasive powerful technique for biomedical imaging. Today LCM can be classified into two types, both acts as three-dimensional imaging tool. The first is low temporal coherence microscopy; also known as optical coherence tomography (OCT), which is being used for medical diagnostics. The second is full field OCT in various modes and applied to various applications. FF-OCT uses low spatial and temporal coherence similar to the well-known coherence probe microscope (CPM) that have been in use for long time in optical metrology. The CPM has many advantages over conventional microscopes in its ability to discriminate between different transparent layers in a scattering medium thus allowing for precise noninvasive optical probing of dense tissue and other turbid media. In this paper I shall discuss the status of this technology in optical metrology applications on which we have been working (references) to improve its performance as well as its limitations and future prospective.

References:

Optical thickness measurement of transparent plate using wavelength tuning interferometry and excess fraction method
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Mask blank glasses are widely used in the semiconductor and display industries. These glasses have been increasing in size to satisfy the requirements of mass production, to reduce costs, and because of the technical advantages of the larger size. As mask blank glasses continue to increase in size, the demand for precise measurement of their properties such as flatness, thickness, and refractive index is increasing. The white-light interferometers are commonly used for the optical thickness measurement of a transparent plate. In this technique, however, the size of an observing aperture is restricted to less than a centimeter in diameter because an accurate translation of a large reference mirror along the optical axis is difficult. Wavelength-tuning interferometry has also been used for the optical thickness measurement of a transparent plate. However, these techniques are not suitable for measuring the thickness distribution because they assume that the sample has a spatially uniform thickness.

For large-diameter samples, such as mask blank glasses with thicknesses of more than a few millimeters, the shortcomings of a white-light interferometer can result in a lack of accuracy owing to the wavelength dispersion as already mentioned, and lateral scanning is also necessary along the observing aperture. In contrast, a wavelength-tuning interferometer is easily scalable to a large diameter, and is insensitive to the refractive index dispersion. In this study, the absolute optical thickness of a mask blank glass was measured using a three-surface wavelength-tuning Fizeau interferometer and excess fraction method. The air gap distance between the measurement sample and reference surface was adjusted to be 13.7 mm, approximately three times the optical thickness of the plate. The source wavelength was measured by the wavelength meter, which was calibrated by a stabilized HeNe laser. In the raw interferogram, there are three groups of fringes observed, among which the concentric fringes in the lower left part of the figure are generated by the beams reflected from the top and bottom surfaces of the sample.

First, the wavelength was finely scanned from 632.0608 nm to 632.1143 nm, and 37 interference images were recorded at an equal wavelength interval. During the scanning, the signal interference fringes corresponding to the optical thickness changed by two periods of 4 radians. The amount of phase shift for each step equals 2/19 for the optical thickness fringes. Because there was a nonlinearity of approximately 3% in the PZT response (fine scanning mode) of the source laser cavity, a quadratic voltage increment was applied to the PZT so that the resultant wavelength scanning would be linear. As a result, the nonlinearity decreased to 1% of the total phase shift. The initial phase was calculated by the algorithm of Eq. (5). Second, the wavelength was scanned back to 632.0705 nm and then scanned coarsely to 641.4827 nm over a 9.4 nm width at a rate of 0.02 nm/s. During the scanning, 2621 interference images were recorded by the CCD camera. The order displacement N of the interference orders of the image was estimated using Fourier analysis. The dominant peaks for the displacement of the raw Fourier analysis were observed at N = 212 and 211, corresponding to the optical thickness. Finally, the wavelength was finely scanned from 641.4374 nm to 641.5279 nm, and another 37 interference images were recorded at an equal wavelength step. The fractional phase was calculated similarly from these images. The integral displacement was determined from the correlation between the theoretical fringes and the recorded 2621 images. The optical thickness at the central wavelength was calculated by substituting this corrected displacement and the measured fractions.

The optical thickness at the central wavelength was then calculated with the help of the dispersion relation. It can be observed that the optical thickness has noise in a fringe-shaped pattern of approximately 0.8 m PV. These pixels were distributed mainly on the dark interference fringes of the optical thickness. This noise was caused by cross-talk between the different frequency components in the phase-shifting calculations, which is common in multiple-surface interferometry, and was originally involved in the fractions. This cross-talk occurred because there was a residual nonlinearity in the phase shift while recording the 37 images and because the frequencies of the interference components did not distribute at the strict integer ratios.

The optical thickness deviation calculated by unwrapping the fraction was fitted to the measured optical thickness using least-square fitting method. Finally, substituting this uniform thickness and the optical thickness deviation, the interference orders at the initial wavelength were determined.
8788-3, Session 1

Metrometry for adhesive layer of temporary bonding wafers using IR interferometry

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Temporary bonding of the device wafer to a carrier wafer allows thin wafer without the risk of breakage after wafer thinning and backside processing. However, the voids at interface of bonded wafers might cause wafer thinning failure. Besides, adhesive thickness variation will contribute to thin wafer thickness non-uniformity. Scanning acoustic microscope and IR transmission imaging are commonly used approaches for voids inspection. Scanning acoustic microscopy (SAM) has proven useful to detect and characterize bond voids at the interface. It provides a spatial resolution of 50 μm at operating frequency of 230 MHz and takes about 10 minutes for a 12-inch full wafer scanning. A concerned limitation of the SAM technique is that the high frequency sound waves cannot propagate through air. Thus a couplant material, for example, water is the most common couplant is used to carry the high frequency sound waves. IR transmission imaging is a non-contact full-field approach which allows for rapid detect the voids at the interface of bonded wafers, but has limited spatial resolution and ability to detect thin voids. Here, a new measurement technique to detect voids in bonded using whole-field infrared (IR) interferometry is described and used to detect voids in direct-bonded silicon wafer pairs. The void measurements obtained from back side of carrier wafer with the whole-field IR interferometry technique are compared to measurements made on the same wafers using scanning acoustic microscopy.

In this work, we developed a whole-field IR interferometer to characterize voids at interface of temporary bonded wafer and measure the adhesive thickness variation. The interferometer operates at wavelength larger than 1100 nm to prevent the interference fringe formation from the silicon wafers. When a linear polarized IR light passing through the bonded wafer, this light can be scattered as an interference cavity. The interference pattern is formed from a front surface reflection and a double pass reflection of the bonding adhesive. The optical path difference that is measured is a function of the adhesive thicknesses, and the index of refraction of the material, n. When a measurement is performed on a bonded wafer pair with voids at specific locations, multiple interfaces are detected at each location. By examining the optical path difference between the layers, one can determine which measured layers correspond to a void at the interface. Then the interference beam is delivered to a /4 waveplate with 45 with respect to the plane of interferometer and analyzer. The phase shifting can be carried out by varying the orientations of analyzer and then a series of interferograms are captured by IR camera. To examine the capabilities of IR interferometry, a temporary bonded wafer pairs was used. The experiment shows that silicon and adhesive interference fringes appear when IR light source operates at wavelength 700-900 nm while only adhesive fringes are presented when IR light source operates at 1200 nm. Therefore, the adhesive thickness variation can be determined by using phase shifting and phase unwrapping algorithm and the voids at interface can be also detected due to the steep slope occurs on adhesive profile.

8788-4, Session 1

Concept, realization and performance of a two-beam phase-shifting point diffraction interferometer

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Interferometric inspection of optical surfaces and wavefronts requires permanently increasing accuracy. Therefore interferometric equipment is being improved and improved continuously. There is one kind of interferometers already pretending to provide the highest possible accuracy – point-diffraction interferometers (PDI) with an “inbuilt” reference wavefront originating from light diffraction by a pinhole aperture. However this family of devices has its own drama of passions regarding various configurations where benefits are going hand in hand with great disadvantages. The most mentioned configurations and their versions like Linnik-Smart and Sommargren schemes produce low-contrast spare-striped fringe patterns instead of full-contrast distinct interferograms, like e.g. produced by Fizeau interferometers, with clear phase shifting (PS) data flow.

In the paper there is presented a new version of PDI with two independently controlled beams – reference and working ones. This PDI differs from the known Sommargren arrangements and other similar versions by using a pinhole plate with several pinholes as a beam coupler instead of a single-mode fiber or single-pinhole plate. Each beam can be well focused to its own pinhole not disturbing adjustment of another beam. Phase shifting of the beams is made by a PZT unit which provides exact changes of the optical length of the reference beam.

The concept of this PDI is to provide two perpendicularly outgoing wavefronts – working and reference ones – having as great numerical aperture (NA) as possible and provide stable phase shifts of one wavefront relative to the other. Such concept is targeted to provide user-friendly measuring conditions similarly to interferometers which are in common use.

Advantages of such arrangement of the PDI are: high numerical aperture (NA = 0.55), clear fringe patterns of high contrast, high accuracy of surface figure testing with wave-front RMS error 0.125 nm and repeatability wave-front RMS error 0.05 nm. Performance of the PDI is illustrated by tables of repeatability and test surface profile plots for different azimuthal angles.

8788-5, Session 2

Sparsity-based denoising method of wrapped-phase reconstructions in digital holography

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The presence of noise in real experimental wrapped phase reconstructions represents a challenging problem for the phase unwrapping framework. For this reason, recently, many proposed methods are based on a preliminary wrapped phase maps denoising that produces a denoised image as input of a digital phase unwrapping algorithm. Here we propose a sparsity-based denoising algorithm for digital holography retrieved wrapped phase maps mod 2π by using a modified version of the SPADEDH (SPArty DEnoising of Digital Holograms) algorithm, proposed by Memmolo et al. in 2012 (Optics Express). The SPADEDH method, successfully applied for noise removal of off-axis digital holograms, is based on a l1-norm minimization of the numerical reconstruction of digital holograms, that has been chosen as the sparse representation. In the case of wrapped-phase maps, we identify the better sparse domain in which compute the l1 minimization, using the Gini index. We solve the designed l1 minimization problem through the Stage-wise Orthogonal Matching Pursuit algorithm. We test the proposed method on numerical wrapped phase reconstructions, in which we add a zero-mean Gaussian noise considering different value of standard deviation, and experimental wrapped phase maps obtained by digital holograms of living cells. We quantify the performance of the proposed algorithm using two efficiency parameters, i.e. the universal image quality index, and the peak signal to noise ratio, and we compare it with other popular denoising strategies. In particular, the universal image quality index is computed between the simulated noiseless wrapped phase map and the denoised ones, and it takes account of three contributions: the correlation coefficient between the two aforementioned maps, the closeness of the mean luminance between the images and the similarity between the contrast of the two maps. Instead the peak signal to noise ratio is evaluated on the simulated noisy wrapped phase maps and the denoised ones in order to establish which technique makes up it more. In addition we evaluate other kinds of distortion that typically occur with other wrapped-phase denoising methods, like smoothing and bias. Finally, we also show that the proposed algorithm can be used as a helper for the typical local phase unwrapping algorithms. For this purpose, we choose...
two different unwrapping method, the flood fill algorithm and the Goldstein’s branch cut algorithm. The aim of this analysis is to show that, for a fixed unwrapping algorithm, the denoised wrapped phase map obtained by the proposed method is better unwrapped with respect to the original one. The method works properly for cell analysis on 2D substrate and even for quantitative phase maps obtained to study the 3D cells migration.

8788-6, Session 2

Holographic Interferometry based on photorefractive crystal to measure 3D thermo-elastic distortion of composite structures and comparison with finite element models

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Scientific, earth observation and telecommunication spacecrafts are subject to severe thermal environments while their mission performance objectives require always higher stability of the structures to deliver high quality images or to insures accurate pointing. The accuracy verification and prediction of the thermo-elastic distortions of these structures are therefore of primary importance for the success of such missions.

Thermo-elastic distortions have been measured by a holographic camera using a BSO photorefractive crystal as the recording medium. This instrument is based on real time holographic interferometry. First the hologram of the structure in its initial state is recorded into the photorefractive crystal. Then a thermal load is applied to the structure and the hologram is readout, showing the interference between the transmitted and readout images.

The first phase of the test campaign was performed on four CFRP struts with different types of titanium end-fittings glued to the tips of the strut. These samples are representative of the connections/junctions used in stable structures and identified as significant contributors to the instrument stability.

The tests have been performed with the samples in a vacuum chamber and for temperature variations between -10K and +15K from the ambient temperature. The holographic camera was located outside the chamber and configured with two illuminations to measure the relative out-of-plane and 50K from the ambient temperature. The distortions of the strut itself as well as the displacement of the base plate have been measured. The temperature has been monitored thanks to thermocouples and a thermographic camera. Thermo-elastic distortions have been measured with the same holographic camera used in phase 1, but for four illuminations, instead of two, have been used to provide the three components of displacement. This technique was specially developed and validated during the phase 2 in CSL laboratory. Four holograms are simultaneously recorded in the photorefractive crystal and the hologram readout is sequential, with two separate interferogram captures corresponding to each illumination.

The second phase of the test campaign was performed on a flight representative instrument structure composed of a large Silicon Carbide base plate supported by 3 GFRP struts with Titanium glued end-fittings. This assembly is representative of stable structure for space applications. The physical properties of the materials involved are assumed to be well known.

The tests have been performed by applying thermal loads to one, two or the three struts. The temperature variations are typically between 18K and 30K from the ambient temperature. The distortions of the strut itself as well as the displacement of the base plate have been measured. The temperature has been monitored thanks to thermocouples and a thermographic camera. Thermo-elastic distortions have been measured with the same holographic camera used in phase 1, but for four illuminations, instead of two, have been used to provide the three components of displacement. This technique was specially developed and validated during the phase 2 in CSL laboratory. Four holograms are simultaneously recorded in the photorefractive crystal and the hologram readout is sequential. The system has been designed to measure a maximal object size of typically 250x250 mm; the measurement range is such that the sum of the maximal relative displacements in the three measurement directions is about 20 µm. The validation of the four-illuminations technique led to measurement uncertainties of 120 nm for the relative in-plane and out-of-plane displacements, 230 nm for the absolute in-plane displacement and 400 nm for the absolute out-of-plane displacement.

These tests were performed in the frame of an ESA project coordinated by EADS Astrium who was also in charge of the finite element analysis and the correlation between test and prediction results. The objective of the first phase of this project was to improve and develop analytical predictions and verification of thermo-elastic distortions using sample testing for modelling correlation. The test results have been compared to the predictions obtained by Astrium and the correlation of these results was quite good.

The second phase of the project aimed at evaluating and validating the outcomes of phase 1 on a flight representative hardware. Predictions obtained by Astrium using the outcomes of phase 1 have been compared to the test results. From this comparison, the accuracy of the predictions and validity of the modelling guidelines, on a complete instrument, have been assessed. The overall measurement uncertainties have been considered (thermal mapping, modelling and test). The strut axial displacement, which has been identified as the main contributor to overall thermo-elastic stability, was well correlated: the difference between predictions and test results was within the overall measurement uncertainty.

8788-7, Session 2

Lensless single-exposure super-resolved interferometric microscopy

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Lensless holographic microscopy relates with the capability to achieve microscopic imaging working without lensless in the regime of holography. Microscopic imaging implies measuring phase from depth resolutions in three dimensional imaging, the lensless configuration proposes an extremely simplified setup where no lenses are used for imaging, and holography allows sample phase distribution availability. Moreover, lensless holographic microscopy in combination with numerical imaging reconstruction provide numerical refocusing and processing strategies of the three dimensional sample. However, lensless holographic microscopy lacks high numerical aperture (NA) due to both geometrical distortion and the mandatory compromise between the illumination pinhole diameter, the illumination wavelength, and the need to obtain a reasonable light efficiency.

Optical super resolution relates to the capability to overcome the resolution limit of imaging systems imposed by the wave nature of light. Such limitation was firstly established by Ernst Abbe who, aside of explaining the role of NA and illumination wavelength concerning resolving power in microscopy, also pointed out that the resolution of an imaging system is increased by increasing the illumination with respect to the optical axis. Since then, tilted beam illumination (or angular multiplexing) in combination with interferometric recording has been widely applied in digital holography and digital holographic microscopy as a way to achieve super resolution imaging.


The decoding stage is based on image plane holographic recording in a single CCD (color or monochrome) snapshot by adding three RGB coherent reference beams at the output plane and allows the complex amplitude distribution recovery of the three bandpass images after applying Fourier filtering tools in the digital domain. The one dimensional resolution is obtained in a single exposure after a digital post-processing stage yielding in the generation of an expanded synthetic aperture. General mathematical...
analysis of SESRIM as well as experimental results for SESRIM by image-plane wavelength-dispersion multiplexing are reported. In this contribution, we extend the applicability of SESRIM to the field of lensless holographic microscopy in order to improve typical NA values (nowadays in the range of 0.5 when considering optical tools). To allow this, we propose the use of a pinhole mask containing three pinholes instead of a single pinhole as it is commonly used in lensless holographic microscopy. The pinhole mask provides the three RGB illuminations (one on-axis and two off-axis) allowing two-color multiplexing of the input object spatial frequency range. Thus, three Gabor holograms are recorded one for each illumination wavelength and each one containing a different spatial range of the input object. A digital processing stage of the three holograms essentially involving numerical propagation to focus onto the sample plane, scaling due to the different wavelengths used in the experiment, and assembling of the generated synthetic aperture is needed to finally provide a one-dimensional super resolved image as Fourier transform of the information contained in the generated one dimensional synthetic aperture. Experimental results are reported validating this new kind of super resolution imaging method named as lensless SESRIM (L-SESRIM).

8788-8, Session 2
Resolution enhancement and autofocusing in digital holographic microscopy by using structured illumination
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Digital holographic microscopy (DHM) is a full-field and non-invasive phase imaging technique and widely used for biological investigations and industrial inspection. Usually in DHM the sample is illuminated by a plane wave, and as a consequence the spatial resolution is limited (diffraction) by the numerical aperture of the imaging system. On the other side DHM allows to refocus the specimen image by numerical calculation, and many attempts have been reported on focus plane determination to perform autofocusing. However, most of the reported methods can only be used for pure amplitude objects or pure phase objects.

Here we present a resolution enhancement and autofocusing holographic system based on structured illumination. Binary phase gratings with different orientations and phase shifts are written sequentially into a spatial light modulator (SLM). The object wave under such illumination is holographically recorded by a common-path DHM configuration, which has long-term stability and enables us to use a low-coherence laser as light source to reduce the coherent noise. After the waves along different diffraction orders of the structured illuminations are reconstructed, they are combined in the Fourier plane to achieve a synthetic aperture and an enhancement in spatial resolution by the factor of two. Compared with other synthetic aperture methods, the one proposed here allows to produce different illumination directions without mechanical movement, and thus the resolution enhancement of phase imaging with high speed and high repeatability is realized.

The image plane location is determined by considering the minimal deviation between the reconstructed images under different structured illuminations, which carry the specimen replicas through different paths before overlapping in the focus plane. This method does not depend on the type of specimen, and can be used for amplitude and phase objects.

Theoretical investigations and experimental results are presented.

8788-9, Session 2
Hybrid and transflective system based on digital holographic microscope and low coherent interferometer for high gradient shape measurement
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A very important part of the phase photonics microstructures manufacturing chain is an accurate measurement and controlling process. In general, the most suited techniques for quantitative and accurate determination of the phase distribution are based on the interferometry and especially the digital holography (DH) in microscopic configuration.

In DH system the complex object wave is captured and it can be reconstructed at arbitrary plane using numerical diffraction tools. It is worth emphasizing that method of measurement based on digitally holographic microscope are very quick, accurate and allows to characterize wide spectrum of metrological and biological objects, also with high numerical aperture (NA). Among numerous examples, the method is applicable for visualization of movement of biological life samples, controlling dynamic driven micro elements and measurement of parameters like topography.

However there exist well known limitation of coherent full field interferometric techniques: the phase increase between neighboring samples cannot be larger than 2π, or objects shape have to generate light that can be collected by used optical system. On the other hand there exist well established technique that is low-coherence interferometry (LCI) which allows for absolute shape measurements with a nanometer resolution and does not have 2π limitation on coherent interferometric techniques. In practice, the LCI measurement range is limited by the range of a scanning motion along the measurement axis of either the specimen under the test or a reference mirror. Besides its great potential in object’s shape measurement LCI might be used as a tool in distance measurements as it gives unambiguous information about the distance value. However the LCI technique does not allow for measurement of high NA topographies and in this paper we focus on the metrology of such a elements.

In this work dual channel measurement system for characterization of high numerical aperture objects is presented. The system combines functionalities of the LCI system based on Twyman-Green configuration and the DHM system based on Mach-Zehnder configuration. The DHM allows to measure sample in transmission while LCI setup provides reflective measurement data. Combined system configuration for one sample provides measurements in reflection and transmission modes and therefore is a more complete tool for topography characterization. In the paper we focus on the measurement of high gradient objects were both method fails independently; the LCI gives measurement only in the object low NA area while the DHM cannot provide absolute shape characterization. Then the dual channel system extends capabilities of both methods. The functionalities of development system are connected with the fast height measurement mode realized in LCI by scanning movement of low coherent light and high NA measurement by application of High NA microscope objective and the LRA method in DHM system. Such an approach eliminates need for measurement of sample on another equipment minimizing measurement errors. In our paper we present experimental results for topography measurement of high NA microlenses. The low coherent interferometer part of dual channel system provides precise measurement for absolute shape in the microlens area (microlens center area (low NA shape) in reflective mode while the DHM part extends measured shape for off axis microlens area (high NA shape). The DHM methods uses recently developed LRA technique. The LRA technique requires accurate determination of focusing plane, the spatial position of the focusing plane must be known precisely. Otherwise shape of high NA sample cannot be accurately recovered. In our system the LCI part of dual channel transflective system gives such a capability. In the paper the accuracy of development method is discussed and both simulation and experimental data are provided.

8788-10, Session 2
Total compensation of chromatic errors in digital color holography using a single recording
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The set-up is a basic off axis digital holography set-up, using three different wavelengths and a negative lens in front of the sensor. The numerical reconstruction of the three color image necessitates compensating for the inherent image size variations due to the discrete Fresnel transform. The proposed method combines a modified version of the wavelength zero-padding algorithm and the adjustable magnification approach. The object that is used is a reference
The first step is to reconstruct the three images corresponding to the three wavelengths and having the same pixel pitch using the wavelength zero-padding algorithm at the different distances given by the aberration. The reconstructed images have now the same physical reconstruction horizon, but they are slightly shifted in space and have a different size. The lateral shift can be estimated and will be compensated at the next step with the convolution algorithm. The difference in sizes must be evaluated. This is achieved by measuring the pitch of the grid along each wavelength using the Hough transform. Finally, the estimated transverse magnification and lateral shift position are used as inputs in the algorithm with adjustable magnification. This paper presents a robust, simple and effective way to compensate the chromatic aberrations induced in every digital color holographic display, in which an optical system is used to compact the dimensions of the set up. The method combines a modified version of the wavelength zero-padding algorithm and the adjustable magnification approach. The object that has to be used is a reference rectangular grid with a good contrast. Experimental results confirm the suitability and robustness of the proposed approach.

8788-11, Session 2
Quantitative phase contrast microscopy by phase retrieval and quasi-mono-monochromatic source
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Quantitative microscopy provides shape information of the object under investigation. For biological specimen as well as technical objects like micro electromechanical systems, three-dimensional microscopy will provide vital information. Conventional microscopy (bright field microscopy) fails when the reflection and absorption coefficient of the specimen is low. It will provide only low contrast intensity images at a single object plane. One needs to go for phase contrast techniques to image these specimens. But to have the quantitative information (thickness or height information) one needs direct access to phase of the wavefront interacting with the specimen. Digital holographic microscopy (DHM) is one of the most widely used quantitative phase imaging technique. DHM uses interferometric recording and numerical reconstruction to provide amplitude and phase of the wavefront. It has the advantage of numerical focusing without the need of mechanical movement. DHM is a two-beam technique, which requires coherent superposition between the beam interacting with the object and a reference beam. Two-beam technique is prone to vibrations and also requires adjustment of beam ratios for high contrast fringes. A single-beam technique providing quantitative phase information of the object will be ideal in this case. We have already applied single-beam wavefront reconstruction technique using multiple intensity sampling and iterative phase retrieval, using highly coherent sources, for imaging technical and biological objects, by converting low frequency object wavefront into high-frequency intensity pattern using a diffuser. The diffuser converts the object wavefront into a volume speckle field, which appreciable intensity variation in transverse and axial directions. If the diffraction pattern from the object under study produces appreciable intensity variation, then the diffuser can be avoided and a partially coherent light source can be used. Here we describe the development of single beam phase retrieval three dimensional microscope using quasi-monochromatic light.

8788-12, Session 2
Lensless object scanning holography for diffuse objects
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In a recent paper, we have proposed Lensless object scanning holography (LOSH) as a fully lensless method, capable of improving image quality in digital Fourier holography applied to reflective objects, and involving a very simplified experimental setup. LOSH is based on the recording and digital post-processing of a set of digital lensless Fourier transform holograms which finally results, in a synthetic image with improved resolution, field of view (FOV), signal-to-noise ratio (SNR), and depth of field (DOF).

Super-resolution (SR) imaging is achieved through the generation of a synthetic aperture (SA) The method to generate the SA consists in the successive recording of different areas of the input object when it is linearly moved along a given direction while maintaining as statics the rest of the setup elements. Those time-multiplexed band-pass holograms allow the synthesis of an enlarged synthetic hologram containing high order spatial frequency components of the object’s spectrum and, thus, originating a superresolved image of the input object. The same scanning principle that makes possible SR imaging also enlarges the object FOV since different regions of the input object pass in time sequence through the reconstructed and restricted FOV provided by the experimental setup. After appropriate assembling, it is possible to recover a synthetic image with enlarged FOV.

With reflective objects, SNR improvement was achieved by coherent artifacts averaging due to the addition of the multiple band-pass images. Finally, DOF extension is inherent to the LOSH coherent nature since phase information is available. In this paper, LOSH is extended to the case of diffuse-based objects. Now, the speckle can affect the resolution and it will not be a function of only the size of the aperture. The fact of increasing the aperture can produce the decrease of the size of the speckle. Moreover, there is an overlapping of speckles of the successive images. This overlapping affects the successive images provided by the holograms. Different kinds of digital processing can be applied to obtain the final synthetic image. On one hand, the fully incoherent processing implies the addition of the absolute (intensity) value of the recovered images. This processing provides an enlarged field of view, super-resolution with a resolution gain factor of 2 and SNR enhancement due to averaging of the speckles; but it does not allow depth of field extension since phase information is cancelled. On the other hand, fully coherent processing implies the coherent addition of all the recovered band-pass images allowing field of view enlargement, super-resolution effect with a gain factor higher than 2, and depth of field extension due to preservation of phase information; but it does not permit SNR improvement since the speckle has decreased in size but has not been cancelled. Finally and as intermediate possibility, partial coherent processing, arising from the incoherent sum of several sets of images coherently added, provides an enlargement in the field of view, an improvement in the resolution and also in the SNR due to partial averaging of the speckles. Experimental results for a diffuse object are presented for all the previously commented kinds of digital processing.

8788-13, Session 3
A long trace profiler with large dynamical range
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Due to their submicroradian level measuring uncertainty, long trace profilers (LTPs) have been the leading measuring instruments used worldwide to test the surface slope profiles of long grazing incidence X-ray optics at synchrotron radiation laboratories and X-ray telescope mirrors with cylindrically symmetric geometry. However, due to the limited extension of the detector and the small angular acceptance of the optical components collecting the probe beam after reflection from the test surface, existing LTP devices have a limited dynamical range (typically below 10 mrad). For this reason, they can only be used for the characterization of optical surfaces with very large radius of curvature (typically from hundreds of meters to kilometers) and limited sagitta. In the frame of our activity, finalized to the characterization of the slope profiles and the figure errors of grazing incidence aspherical optical components, a vertical LTP prototype has been developed to achieve a 100 mrad-level dynamical range, which is much higher than what currently achievable by existing setups.
The vertical configuration has been adopted because the instrument has to measure the inner surface of cylindrically symmetric mirrors that shall stand vertically during the measurements to minimize profile distortions induced by gravity.

In order to extend the dynamical range of the instrument, the following upgrades have been taken into consideration:

- the optical path delivering the probe beam to the test surface and the light path reflected by the test surface to the detector have been separated;
- the probe beam is delivered to the surface through a pair of mirrors assembled on the carrier of a translation stage. The double mirror assembly is adopted instead of a pentaprism as a flexible configuration to match the probe beam angle with the sample surface orientation while reducing the effect of the translation stage moving errors;
- the laser beam that is reflected from the surface is collected by a flat folding mirror that can be shifted horizontally and tilted correspondingly. This upgrade allows the reflected beam to be collected over a quite large displacement and be redirected into the Fourier transform lens aperture and, finally, into the field of view of the detector.

From a practical point of view, the entire slope profile of a surface with a large slope variation is acquired through a discrete number of scans. While the probe beam progresses continuously through the measured surface, the folding mirror is moved to predefined positions and tilts for each scan. The full slope profile is subsequently reconstructed by a post processing that overlaps the adjacent slope segments through a simple shift of the acquired signals. Height profile of the surface is calculated by integration of the reconstructed slope.

To prove the functionality of this scheme, a prototype has been tested by measuring the figure error of cylindrically symmetric aspherical mirrors having length up to 200 mm and surface slope variation up to 60 mrad. The results are compared with the profiles measured on the same mirrors by a different scanning profiler, the MPR700, which is a height measuring system featuring an optical confocal sensor and laser interferometers. As described elsewhere, the MPR700 has been tested in terms of precision and accuracy up to 7 nm rms and less than 40 nm peak to valley respectively over the length of 200 mm, thus representing our metrology reference for internal manufacturing processes.

Comparison between the two instruments is performed in terms of both power spectral densities (PSD) and figure errors. The PSD shows extremely good agreement, while an height measurement accuracy correspondingly. This upgrade allows the reflected beam to be collected over a quite large displacement and be redirected into the Fourier transform lens aperture and, finally, into the field of view of the detector.

8788-15, Session 3

Optical characterization method for very small microlenses (sub-50 micron) for industrial mass-production applications

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Microlenses and microlens arrays are nowadays widely used sub-components in many optical systems. Fabrication methods for mass-production of high-quality microlens arrays have been well established. For instance, a wafer-based micro-machining technique consisting of photolithography, resist melting, and plasma etching leading to plano-convex-type microlenses. For characterization of such refractive microlenses several mechanical and optical metrology tools, e.g., stylus surface profilers, interferometers and confocal microscopes are commonly used. Unfortunately most of these tools do not allow to fully characterize microlenses with lens diameters smaller than 50 microns. An interference microscope, which provides magnification to investigate small-size specimens, i.e., microlenses, leads to a limited number of pixels on an image sensor even with high magnifications. Often, it gives insufficient data points to analyze geometrical and optical characteristics. Moreover, small-size in general leads to a short focal length, which forces the back focus of the lens staying in the substrate. In this case, an immersion condition is necessary to avoid aberrations in the observation system. To cover those issues, we employ a high-resolution interference microscope (HRIM) with an option for an oil immersion. The HRIM consists of an optical microscope and a Mach-Zehnder interferometer to record the interference fringe within the clear aperture of such small microlenses with a sufficiently large pixel resolution of the image.

In this paper, we present several characterization methods based on the immersion-HRIM, which are suitable for such small-size microlenses. For an individual microlens, we apply full characterization for optical performance, i.e., focal length, aperture diameter, etc. To characterize the optical performance, e.g., a Strehl ratio and Zernike coefficients, by using the HRIM. The Strehl ratio provides a glance of the optical performance, which represents the peak intensity degradation compared to that of an aberration-free focal spot. The Zernike coefficients show the details of the wavefront aberrations, for instance, spherical aberration, coma, astigmatism, and etc. Second, a confocal microscope is applied to investigate the surface parameters. The surface characteristics of the lens are related to the sag, which can be defined by two primary parameters, a radius of curvature (ROC) and a conic constant. A stylus-type surface profiler is not suitable for small-size microlenses since its resolution of the positioning is poor and the tip radius of the stylus is relatively large. Therefore, microscope-based optical profiler like a confocal microscope is more preferable. By using reference spheres, we can retrieve the ROC and a conic constant of such small microlenses. Third, the HRIM allows scanning the microlens array along the optical axis (z-axis) by using a piezo actuator.
Georges Allen, Daniel J. Hobrock, Luleå Univ. of Technology (Sweden); Jean-Pierre Marquet, Luleå Univ. of Technology (Sweden); goalkeeper, Luleå Univ. of Technology (Sweden)

In this paper we present a new method that from numerical propagation of the recorded holograms uses speckle movements induced in different planes to calculate the object shape. Phase ambiguity is an inherent limitation of dual wavelength holography for the measurement of shape that is a reason to use multi-wavelength methods. The basic idea with using multiple wavelengths is to increase the bandwidth over which the phase gradients can be determined uniquely. In an industrial production line, the use of many wavelengths may become a problem as it is necessary to acquire all holograms simultaneously due to environmental disturbances. One is therefore often left with an undetermined system and ambiguities in phase when unwrapping the phase maps. This problem is most common for objects with large steps or steep slopes. For an industrial applicability of holographic shape measurement it is therefore important to investigate alternative approaches. As the speckle movements carry information about the surface position and shape, the slope of the shape can be determined uniquely with dual wavelength. The Intermediate Value Theorem is utilized to determine the distance to the object and the normal vector of the object surface is determined from the gradient of the variation in speckle movement. The speckle movements relationship with different distances and wavelengths and also the features of the proposed method are presented in this paper.

Results and properties of the new method are demonstrated and the potential to use the method for automatic industrial geometry control is discussed.

8788-17, Session 4
Shape reconstruction using dual wavelength digital holography and speckle movements
Davood Khodadad, Luleå Univ. of Technology (Sweden); Emil J. Hällstig, Optronic (Sweden); Mikael Sjödahl, Luleå Univ. of Technology (Sweden)

In this paper we present a new method that from numerical propagation of the recorded holograms uses speckle movements induced in different planes to calculate the object shape. Phase ambiguity is an inherent limitation of dual wavelength holography for the measurement of shape that is a reason to use multi-wavelength methods. The basic idea with using multiple wavelengths is to increase the bandwidth over which the phase gradients can be determined uniquely. In an industrial production line, the use of many wavelengths may become a problem as it is necessary to acquire all holograms simultaneously due to environmental disturbances. One is therefore often left with an undetermined system and ambiguities in phase when unwrapping the phase maps. This problem is most common for objects with large steps or steep slopes. For an industrial applicability of holographic shape measurement it is therefore important to investigate alternative approaches. As the speckle movements carry information about the surface position and shape, the slope of the shape can be determined uniquely with dual wavelength. The Intermediate Value Theorem is utilized to determine the distance to the object and the normal vector of the object surface is determined from the gradient of the variation in speckle movement. The speckle movements relationship with different distances and wavelengths and also the features of the proposed method are presented in this paper.

Results and properties of the new method are demonstrated and the potential to use the method for automatic industrial geometry control is discussed.
from the central axis of the pipe is also restricted less than 0.4 deg. Three stepwise phase-shifting of 2/\(\pi\)-radian are introduced in the reference beam using the PZT mirror. The beam reflected by the cone-shaped mirror inside the pipe illuminates its inner wall. Then, the reflected and/or scattered light from the inner wall is reflected back to a CCD plane as the object beam. In this configuration, the information of the inner surface profile is transferred to the wavefront of the object beam. Therefore, the lateral information of the illuminated inner surface is transferred to a circular image of the mirror.

When the center of the cone-shaped mirror deviates from the pipe’s center, the experimental height profile of the inner wall is deformed due to the asymmetrical optical path length from the wall. To evaluate the deformation, the distribution of an optical path length \(L(x,y)\) for the misaligned mirror position is calculated within the area of object beam. The compensation of the deformation due to the misalignment is conducted by subtracting the optical path length \(L(x,y)\) from the experimental height profile \(h(x,y)\). The amount of the misaligned mirror position \((x,y)\) required for the calculation of \(L(x,y)\) can be directly obtained from the experimental surface profile \(h(x,y)\) using a newly proposed curve fitting method. It has been shown that the deformation occurring in the experimental surface profile is nicely reduced using the proposed compensation process and the time required for calculation can also be reduced in comparison with the former method.

Using the proposed technique, two pieces of metal sheet with different thickness pasted on the inner wall of the pipe and the defects such as a hole, scratch, and rust in the wall are detected. To measure the three- dimensional (3D) profile of the metal plate on the inner wall, we transformed the circular image into a rectangular one corresponding to the developed surface of the pipe by using a simple image processing. By the image processing, we could obtain the 3D profile of metal plates.

In the experiment, a copper pipe of length 150 mm and inner diameter 14.0 mm was used. The proposed holographic method was applied to evaluate the 3D profile of metal sheet having a thickness of 0.2 mm on the inner surface and detect defects such as a hole having a diameter of 2.3 mm in the wall, and rust for which both the reconstructed intensity and phase information are required. By virtue of the proposed method, the profile of metal sheet and a hole can be evaluated. Thus, the technique seems to be promising for conducting inspections of the inner walls of straight pipes.

8788-19, Session 4
Seeing through smoke and flames: a challenge for imaging capabilities, met thanks to digital holography at far infrared
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The possibility to offer a clear vision through smoke and flames represents a great challenge for its applications in the industrial and the safety field. Indeed, in industrial processes the failure of furnace and boiler equipment can cause quality problems or even force the shutting down of an entire process line. On the other hand, many efforts have been spent to try to extend the human eye capabilities in case of fire accidents, where an imaging device able to see clearly beyond the flame can be of fundamental importance both for rescue purposes and the post analysis of the fire scene. So far, the adopted thermographic detectors make use of infrared bolometers which can successfully image moving targets through smoke but they are blinded by flame-emitted radiation. This is due to the lens focusing that conveys the radiation to a few detector elements, which in turn saturate. As a result, imaging and continuous monitoring of alive people in fire scenes is impaired whenever a flame occludes the line of sight between the detector and the target. Here we propose a different method for successful imaging and continuous recording of objects and alive people through smoke and flames with no blind areas.

Indeed, we employ lensless Digital Holography at far infrared (IR-DH) to get rid of the blurring the saturation of the detector elements. We demonstrate that a continuous wave laser at 10.6\(\mu\)m can be adopted to achieve the continuous monitoring of dynamic human size targets independently of the source emitting spectrum. The independence on the emission spectrum of the involved burning materials make this interferometric technique suited for all kind of flames, so that a wide set of industrial processes can be safely monitored. Moreover, the long wavelength employed is the key to record holograms of human size targets, as it will be discussed. Furthermore, numerical processing can be exploited to further enhance the image quality by means of an incoherent combination of multiple holographic acquisitions, obtaining an improved holographic reconstruction where more details can be appreciated. This could be of help in case a post analysis of the fire accident is required.

Three kinds of experiments have been carried out. At first, we placed a bronze statuette in a plexiglass box where smoke has been injected in controlled way to simulate a typical situation in which the naked eye view is hindered. In this case both the thermographic acquisition and the holographic reconstruction performs well, discarding the smoke contribution and returning a clear view of the target. Then we recorded holograms of a plastique 190cm tall mannequin to demonstrate the capability of IR-DH of imaging human size objects. Finally we recorded digital holograms of both small objects and alive people hidden by curtains of flames occluding the target-detector line of sight. In this case both the white-light view and the thermographic one cannot see through the flames, resulting in blind areas. Conversely, the holographic reconstructions provide a clear vision beyond them, with no blind areas and with appreciable details. Thanks to these capabilities we also achieved for the first time the holographic dynamic recording of people moving behind flames generated by a portable mini-stove and a comparison with the results obtainable with an IR bolometer are shown. We think that these results can give a new possibility both to operate safely during industrial processes and to save people involved in fire accidents.

8788-20, Session 4
A computational tool to highlight anomalies on shearographic images in optical flaw detection
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Shearography is an optical and nondestructive technique that has been largely used for damage detection in layered composite materials where delaminations and debondings are the most common flaws. Shearography is a relative measurement in which two images are recorded for different loading conditions of the sample. The applied loading induces some deformations or alters the deformation state of the sample surface. Typical loadings are thermal, acoustical or mechanical being possible to be applied in a static or dynamic way. The absolute difference of two images recorded at two different loading instances produces an interference fringe pattern which is directly correlated to the displacements produced on the material surface.

In some cases, depending on the loading level and mainly the sample geometry, interference patterns will contain fringes resulting from these geometry changes. This will mask those fringes correlated to defects presented into the material, resulting in an image misinterpretation. This phenomena happens mainly when the sample has curved geometries.

This paper presents an algorithm which uses a mathematical processing to improve the visualization of defects in shearographic images. The mathematical processing is based on the calculation of the divergent and used to search for local deformations contained at the image. This algorithm highlights defected regions and eliminates fringes caused by geometry changes, providing an easier interpretation of the resulting images.

This paper also shows the principle and the algorithm used for the processing. The results, advantages and difficulties of the method are presented and discussed by using simulated fringe maps.
8788-21, Session 4

ESPI based on spatial fringe analysis method using only two sheets of speckle patterns

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Speckle interferometry is one of important deformation measurement methods for an object with a rough surface. The method has been developed as ESPI with a high resolution power by using TV-technology and fringe scanning methods. However, least three speckle patterns have been usually required for a high resolution fringe analysis because the method uses the general fringe scanning methods. Recently, the method sometimes is employed to a high speed deformation measurement with a high speed camera. Then, three sheets of speckle patterns also are required. Generally, if higher the speed of deformation of a object is, the higher speed camera should be employed. However, there will be a physical limitation concerning high speed cameras. In order to solve such a problem, the development of fringe analysis that uses as less number of frames as possible for analyzing deformation information is strongly required. Some technologies based on Duffys idea have been proposed for solving the problem. Under these technologies, the fringe orientation analyzing method using only one sheet of speckle pattern that is calculated by Fourier transform, is proposed. In the optical system, the fringe orientation of a speckle pattern is calculated by using a new optical system, which uses a plane wave as the reference beam of the speckle interferometer. The new optical system has been developed as ESPI with a high resolution power by using TV-technology and fringe scanning methods. However, is strongly influenced by the random noise included in speckle patterns. As the results, it is confirmed that it is difficult to analyze the deformation in high resolution by these methods. In this paper, the fringe orientation analyzing method using a new optical system, which uses a plane wave as the reference beam of the speckle interferometer, is proposed. In the optical system, the spatial information as interfering-fringes can be given into each speckle by using the plane-wave. Furthermore, the frequency of this spatial information can be controlled by adjusting the angle of the mirror of the optical system. When the optical system is employed in the fringe analysis, the deformation information and the bias components of the speckle patterns clearly are separated in frequency domain. The new optical system has such useful feature. Therefore, the deformation information can be readily extracted by using Fourier transform. In the process for extracting the deformation information from speckle patterns, there are also some interested phenomena concerning the location and the shape of the deformation information on the frequency domain. The location of the deformation information in frequency domain depends on the spatial information of the specklegram. The shape of the information in frequency domain is formed by the aperture of the observing lens system of the optical system. In the fringe analysis processing, when the deformation information is extracted by Fourier transform, a pair of a real-part and an imaginary-part components concerning the information are given. Then, the fringe information corresponding to a specklegram concerning the deformation is given by multiplication operation between the real parts of extracted information from the speckle patterns grabbed before and after deformation. At the same time, another specklegram by the real part before deformation and the imaginary part after deformation also is given by the same way of multiplication operation. These specklegrams are filtered spatially. When the ratio of them is introduced to arctangent function, the wrapped phase map of the deformation is given.

However, because such fringe images produced by real and imaginary parts of speckle patterns generally include some noise in the low frequency area as the 1/f noise, the analyzed phase map includes some error. Therefore, the fringe analysis in this paper is operated in the high frequency area by using the spatial fringe analysis method in order to avoid such an error. That is, two specklegrams whose phase is different of /2 rad are not employed, but one sheet of specklegram that is multiplied by only real part data extracted from speckle patterns before and after deformation is employed for fringe analysis. Furthermore, when the real part of the information before deformation is calculated in this process, the real information is formed on the frequency domain in order to give carrier fringes. Consequently, the specklegram is calculated between the shifted real part of the speckle-pattern before deformation and the non-shifted real part of the speckle-pattern after deformation. Then, the fringe image, which includes the spatial carrier-information, is given as specklegram. The specklegram is spatially filtered. Sequentially, the phase map is calculated by using spatial fringe analysis method from the filtered specklegram. From experimental results, it is confirmed that the new method can analyze a deformation process with a convex and/or concave phase distribution in a high resolution power. It is also confirmed that the rest information of the specklegram becomes much lower, so that the method is much higher than 1/100 of the light source of the optical system.

8788-22, Session 5

Measurement of low polarization rotations using speckle correlation

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Measurement of rotation of plane of polarization of linearly polarized light can provide important information about the system with which it interacts. This rotation of polarization state may be brought about by properties of the object like optical activity, external forces like magnetic field or electric field applied to the object under study etc. Accurate measurement of rotation of polarization state can therefore provide information on these parameters. But for many many practical applications, measurement of these rotations becomes necessary. So methods with higher sensitivity need to be developed for the measurement of low rotations. Here we describe the development of a polarization rotation sensing technique using speckle correlation. The developed technique measures rotations by determining the changes occurring to a speckle pattern generated by a laser beam passing through the medium under investigation.

Developed technique was used to determine small Faraday rotations occurring in magneto-optic materials. Faraday Effect is the rotation of plane of vibration of linearly polarized light passing through a material medium due to magnetic field applied parallel/anti-parallel to the incident light beam. This effect is used in many applications such as analysis of hydrocarbon mixtures, in optical modulators, plasma diagnostics etc. In the case of Faraday Effect, the amount of rotation depends upon three parameters i) length of the medium, ii) strength magnetic field and iii) Verdet coefficient of the medium. Most of the materials showing Faraday Effect have small Verdet constants leading to small rotations and hence the measurement of these rotations using polarizer-analyzer pair becomes difficult. We applied the developed speckle correlation technique to measure these small rotations in the case of Quartz cylinders. A polarized laser beam was allowed to pass through the Quartz cylinder kept inside a solenoid. The beam after passing through the object was converted into speckle pattern using a ground glass diffuser. This speckle pattern is recorded by a CCD and is used for analysis. Diffuser has a rough surface with random surface variations. This creates spatially changing random angles of incidences for the laser beam. Since the transmittance and the reflectance of the incident beam depends upon the angle of incidence, the complex amplitude of the laser beam at the output face of the diffuser changes with polarization and hence changing the resulting speckle field. So a change in polarization state of the laser beam results in a change in the speckle pattern. This change in the speckle pattern was quantified by comparing it to a reference speckle pattern. This quantity can then be related to the rotation angle. The developed technique was applied to the measurement of small Faraday rotations in Quartz, when magnetic field was applied parallel to the direction of light propagation. From the value of correlation coefficient between the speckle pattern with and without the applied field we were able to measure rotation changes as low as 0.0066 degrees with less than 8% error. We also employed the technique with a cell phone camera to record speckle pattern. Detailed experimental results are presented in the paper.

8788-23, Session 5

Relation between vectorial source structure and coherence-polarization of light

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A polarization-based frequency shifting interferometry for inspecting transparent objects in microelectronics manufacturing

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In these days, semiconductor manufacturing technologies focus on high precision and miniaturization of electronic and mechanic components, and their assembly in one package. Final products, made by these fine manufacturing technologies, have been changing more complex than before. The in-line inspection for the product manufacturing requires precise inspection technology adequate for specified quality control in the manufacturing. According to this manufacturing technological trend, semiconductor packing technologies have been widely developed also because of increasing degree of integration of semiconductor. One of major packing technologies is the BGA(ball grid array)/CSP(chip scale package) assembly technology to flip the semiconductor die and bond it to micro PCBs. Conventional assembly methods flip the die, dip it to flux and bond it to micro PCBs. But recent methods rather print flux on PCBs rather than dipping semiconductor die into flux, and bond the semiconductor after that, because it results in the reduction of production time through processing parallelization.

In these processes, flux plays a critical role in the process dynamics of BGA/CSP package assembly. A vast range of defects in final assembly can be traced back to poor flux or paste deposition. For example, some of the defects in the final assembly derive from poor flux alignment with respect to the intended pads, insufficient thickness/amount of the flux material, excessive amount of flux, or from smearing. The detection of these pass/fail types of defects (attribute data) at an early stage of the process reduces the assembly cost significantly. Moreover, many manufacturers would agree that it is important to control the process of flux deposition by means of relevant measured variables to detect trends and prevent defects from occurring. This requires a system that is able to measure the key variables of the process (variable data). By providing real-time information on key process parameters, manufacturers can take corrective action and prevent scrap and production loss.

For this purpose, in this paper a polarization-based frequency shifting interferometer is proposed for three dimensional flux inspection in microelectronics manufacturing. FSI(frequency shifting interferometer) system, one of most promising optical surface measurement techniques, generally result in superior optical performance comparing with other three dimensional measuring methods as its hardware structure is fixed in operation and only the light frequency is scanned in specific spectral band without vertical scanning of the target surface or the objective lens. FSI system collects a set of images with interference fringes by changing the frequency of light source illuminated on target objects. Then, it transforms intensity data of acquired image into frequency information, and calculates the height profile of target objects with the help of frequency analysis based on FFT(fast Fourier transform).

The normal FSI system is good performance about specular surface (like semiconductor die). But, if there are transparent objects (like flux) on the surface, their optical polarization characteristics usually make the observed interference fringes degraded. When illuminated light reflects on the flux or penetrates the flux, the direction of polarization of light rotates depending on the polarization characteristic of the flux. The rotation of direction of polarization causes difficulty in measurement. So, a PFSI(Polarization-based Frequency Shifting Interferometer) system is proposed, which applies the polarization analysis method to the conventional FSI system.

First, the PFSI system is proposed for robust measurement to flux. It consists of tunable laser for light source, /4 plate in front of reference mirror, /4 plate in front of target object, polarizing beam splitter, polarizer in front of image sensor, polarizer in front of the fiber coupled light source, /2 plate between PBS and polarizer of the light source. Using the proposed system, low contrast problem of interference fringe due to polarization rotation of acquired fringe image can be solved by using polarization technique. Also, light distribution of object beam and reference beam can be controlled. So, reflected light intensities of the reference beam and object beam can be made similar for conspicuous interference signals.

Second, using PFSI system, the height of flux and the height of die...
of flux bottom side can be measured in the same system. In case of measuring the height of the flux, the multi-layer reflections are generated in the surface and bottom side of flux. Three interference signals are observed when transparent flux is deposited on the PCB surface: the interference signal A of the reflected light on the reference mirror and the reflected light on the flux surface, the interference signal B of the reflected light on the reference mirror and the reflected light on the flux bottom side, and the interference signal C of the reflected light on the flux surface and the reflected light on the flux bottom side. By light penetrates the flux, Signal A and signal B have different polarization characteristics. By controlling the polarization of the system, the height of flux and the height of bottom side of flux can be measured simultaneously.

Third, the signal processing acceleration method for fast height calculation is proposed for the PPSSI, based on parallel processing architecture, which consists of parallel processing hardware and software called GPU(Graphical Processing Unit) and CUDA(Compute Unified Device Architecture). As a result, the processing time reaches into takt time level of real-time processing.

Finally, the proposed system is evaluated in terms of accuracy and processing speed through a series of experiment and the obtained results show the effectiveness of the proposed system and method.

8788-25, Session 6

Fast and accurate line scanner based on white light interferometry

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White-light interferometry is a highly accurate technology for 3D measurements. It is mostly used for metrology purpose but is less common when it comes to in-line inspection within industrial production. The main reason is its high sensitivity to environmental vibrations and also to its limited speed: a large quantity of data needs to be acquired and processed in order to obtain a topographic measurement.

Heliotis developed a smart-pixel CMOS camera (Lock-in camera) which is specially suited for white-light interferometry. The demodulation of the interference signal is treated at the level of the pixel. Only the 2 values of the amplitude and phase of the modulated signal are returned for a chosen number of cycles. As a consequence vertical scan-speeds up to more than 40mm/s are reachable (one or two orders of magnitude faster than with standard camera). Another advantage of this high speed is to make the system more rugged against external vibrations.

For many industrial applications such as the inspection of wafer-bumps, surface of mechanical parts, solar-panels, etc. large areas need to be measured. In this case the instrument or the sample are displaced laterally and several measurements are stitched together. The scan speed of the system is then limited by the time needed to do stop and go lateral displacement.

A line-scanner using white light interferometry would combine the advantages of high precision and high speed allowed by a continuous scanning of the object. We will present a simple geometry to realize such a feature. The coherence plane of the interferometer and the object scanning direction are tilted by an angle . By doing so an advantage of our method really high speed measurements can be performed. We use a line scan camera providing 1024 pixels which acquires at a line rate of up to 57 kHz. This results in a number of 57 million measured height values per second. Using this setup an area 0.2 mm x 13.4 mm and height values in a range of 9 µm due to deviation from ideal axis movement could be measured in 1.1 seconds. The speed of the lateral movement is limited due to the used axis. Still the features of the object surface are preserved in the measurement results.

The feasibility of the method is demonstrated with a sinusoidal standard (100 µm pitch length, 1 µm peak-to-valley amplitude) and a plane measurement object. This enables to eliminate the measurement errors related to nonlinear movement of the used scan axis. We want to show that the collection of the interference data is possible in a way that we are able to later on add the actuated mirror to the setup and to collect height data from an in plane object.

References


8788-27, Session 6

Speed-up chromatic sensors by optimized optical filters

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This article proposes a changed optical setup for chromatic sensors. In detail, it is proposed to replace the commonly used spectrometer by a multispectral camera. The advantage of this approach is a significant reduction of acquired data. High-speed measurement systems that are no longer limited by the frame rate of a spectrometer become possible. The challenge of this approach is to keep the measurement resolution high. Results are presented that show, optimizing the filter transmission characteristics of a multispectral camera can lead to comparable
measurement resolution. In literature [1–4], the principle idea to use a multispectral camera is well known. However, the freedom of arbitrary filter designs has not yet been exploited, which is a precondition for high measurement resolution.

Instead, simple Gaussian-like filters are proposed [3]. Furthermore, it is fiber optical sensors [7] or the chromatic confocal triangulation sensor [8], which will be used within this paper as example application to apply the proposed method. The chromatic principle encodes measurement information as spectral information. Each distinguishable measurement value corresponds to a unique spectral distribution of the optical signal. Usually, a spectrometer is used to sample this spectrum and, afterwards, the measurement value is determined by signal processing. In contrast, a multispectral camera is proposed with a low number of optical filters. The optical signal is measured through this set of filters, which are optimized in terms of sensitivity and uniqueness. Hence, each distinguishable spectrum corresponds to a unique grey value vector. This approach can be regarded as a generalization of color vision, because a multispectral camera implicitly spans a multidimensional color space [5] and a grey value vector can be interpreted as a multidimensional color coordinate.

Based on a physical model of a multispectral camera a measurement sensitivity term is derived [6]. Special attention is paid to derive the sensitivity term invariant in terms of intensity changes. In this formulation, the sensitivity is not a function of the absolut radiance of the optical signal, but a function of the filter transmission characteristics. A merit function is proposed, which rates sensitivity of a multispectral camera. Another aspect is uniqueness of a measurement. The filter transmission characteristics must guarantee, that each grey value vector only encodes a single measurement value, even under noisy conditions. For this purpose, a second merit function is proposed which rates uniqueness.

As an example application, the proposed method is used to optimize a multispectral camera for a chromatic confocal triangulation sensor [8]. Preliminary results show, that five filters are sufficient to distinguish 6000 measurement values assuming 8-bit quantization and 400–850 nm spectral range. As optical signal a Gaussian-like spectrum is assumed with 5 nm FWHM. A shift of 0.08 nm (mean 0.08 nm, std 0.04 nm) of this optical signal causes a change of one quantization step. Furthermore, the false assignment probability is less than 0.0002%, assuming a standard camera noise model according [9]. 30 thin film layers per filter were used during optimization. A chromatic confocal triangulation sensor equipped with these optimized filters would have a vertical resolution of minimum 1.25 µm assuming a 6 mm measurement range. The nine filters can be arranged as macro pixels in a line scan camera, similar to a Bayer pattern. Then the high frame rates of line scan cameras are available. Theoretically, such a 3D sensor would be about ten times faster than the state of the art. In the final article, these results will be compared with the performance of a classical spectrometer approach.

SUMMARY

Preliminary results show, that optimized filters are capable to replace spectrometers commonly used within chromatic sensor concepts. The optimization of the measurement sensitivity ensures, that the measurement result does not significantly decrease, if a spectrometer is replaced by a multispectral camera. Using a multispectral camera offers high frame rates by reducing the amount of acquired data. The proposed method is a general approach to increase measurement speed of chromatic sensors.

REFERENCES

The proposed algorithm was tested by analysing different technical relevant surface topographies. In our paper, we demonstrate the performance of the algorithm and we compare the proposed algorithm to other known methods like the center of mass in particular.

8788-29, Session 7
Model-based assistance system for confocal measurements of rough surfaces
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Confocal sensors are well established in optical surface metrology and technology. Their performance can be both experimentally and theoretically. However most of the theoretical work has been based upon the assumption of locally flat or point like measurement objects. As confocal sensors have become more and more popular in industrial inspection of rough surfaces in recent years, severe limitations of the sensors and the performance of these systems are facing new challenges and standards. New sensors are required to operate under these conditions. We present an approach to generate a system to systematically guide the user of confocal measurement systems through the planning of an inspection task. We present an assistance system that provides the user with a set of proper sensor parameters for a given measurement task. In particular we propose to calculate a lateral resolution limit for confocal profilometry, that is different from conventional confocal measurements of biological samples or flat surfaces. In order to support our proposal, we present measurements of different roughness calibration standards, that were conducted with varying numerical aperture objectives on a custom build confocal microscope with rotating microlenses. As the surface profile of the roughness calibration standards is well defined we can easily compare the measurement results of these sensor configurations to each other. The parameter sets that are able to correctly measure the different surface profiles are compared to the predictions of our assistance system and the overall fitness of the assistance system is verified.


8788-30, Session 7
Parallelized chromatic confocal sensor systems
Matthias Hillenbrand, Adrian Grewe, Mohamed Bichra, Roman M. Kleindienst, Lucia Lorenz, Raoul Kirner, Robert Weiß, Stefan Sinzinger, Technische Univ. Ilmenau (Germany)

Chromatic confocal imaging systems represent a spectrally multiplexed realization of the confocal principle. For this purpose the laser source is replaced by a polychromatic illumination system and the objective lens is exchanged for a hyperchromatic lens. In contrast to classical lenses which are corrected for longitudinal chromatic aberration, hyperchromatic lenses are optimized to produce a well-defined amount of longitudinal chromatic aberration. As the focal length of the hyperchromatic lens is wavelength dependent, a single confocal object point is imaged to a line of spectrally separated foci along the direction of light propagation (z-axis) and only one wavelength will be in focus on the surface under test. The reflected or backscattered light passes the hyperchromatic lens a second time and only the wavelength in focus on the surface under test is also on focus on the pinhole or the fiber tip. Light of this specific wavelength passes the pinhole a second time or is coupled back into the fiber while all other wavelengths are subject to defocus and a strong attenuation. This leads to a significant peak in the spectral signal which is directly related to the distance between the hyperchromatic lens and the surface under test. In contrast to monochromatic confocal microscopes the specimen does not have to be scanned in z-direction but all z-values within the spectrally separated line of foci are evaluated in parallel. Thus, chromatic confocal sensor systems may offer a significantly higher measurement rate than classical confocal setups. Fiber-based commercial point sensors are available from different vendors (e.g. Stil S.A., Micro-Epsilon Messtechnik GmbH & Co. KG). The most common applications of chromatic confocal sensors are include non-contact distance measurements, layer and thickness measurements as well as surface microscopy.

In two recent publications we discussed the design of refractive, diffractive, as well as hybrid diffractive-refractive hyperchromatic lenses (Hillenbrand et al., “Hybrid hyperchromats for chromatic confocal sensor systems,” Advanced Optical Technologies 1, 187–194, 2012) and their application in chromatic confocal systems for hyperspectral imaging and chromatic confocal distance sensing (Hillenbrand et al., “Chromatic information coding in optical systems for hyperspectral imaging and chromatic confocal sensing.” Proc. SPIE 8550-13, 2012, invited). In the current paper we restrict our analysis to new types of parallelized chromatic confocal distance sensing systems that simultaneously evaluate several spatially separated sensors. The main advantages of these systems are cost reductions in comparison to solutions based on a series of single point sensors and a further increase of the evaluation speed. At the same time they are suitable for restricted industrial environments with just enough space for a single sensor but several measurement points.

One of our approaches to parallelized chromatic confocal imaging is based on the use of a pinhole array as replacement for the single pinhole in confocal point sensors. When imaged by the hyperchromatic lens all polychromatic quasi point sources are transformed into lines of foci which probe the object at different, spatially separated points. The backscattered or reflected signals are incident upon the same pinhole array a second time and alignment issues are avoided through self-alignment properties of the double pass setup. For each pinhole the peak wavelength of the spectral signal has to be evaluated to determine the distance between object under test and the pinhole. As the individual points that have to be analyzed are already spatially separated a straightforward combination of a diffractive grating or prism and an array detector is utilized to enable a measurement of the full surface topology with one single shot. In specific setups a lateral oscillation of the pinhole array can be applied to further increase the spatial resolution of the system similar to Nipkow disk based confocal microscopes. In comparison to point sensors the design of the hyperchromatic lens for an array imaging system is significantly more demanding. We specifically discuss the effects of field dependent aberrations arising from the full-field imaging setup. Furthermore, we point out the main parameters influencing the spectral and spatial resolution.

Significant factors limiting the speed of array-based chromatic confocal sensor systems are the frame rate of the CMOS or CCD sensor and the post-processing of the recorded signal. For high-speed multi-point measurements we present two new types of highly integrated chromatic confocal sensors. In both cases we use spectral multiplexing to evaluate a limited number of spatially separated points with one single spectrometer. In contrast to the array-imaging setup discussed before, not a full field but only specific field points have to be imaged with high optical resolution. Consequently we were able to reduce the system complexity and to develop compact hybrid diffractive-refractive setups. The conversion between the spatial and spectral channels is realized with segmented diffractive and refractive components.

With respect to both system types we discuss the benefits of
telecentric setups to the imaging of off-axis field points and of object surfaces which are tilted with respect to the sensor axis. Our discussions of the two different chromatic confocal imaging concepts are supported by experimental results.

8788-31, Session 7
Robust signal evaluation for Chromatic Confocal Spectral Interferometry
Tobias Boettcher, Institut für Technische Optik (Germany); Wolfram Lyda, Marc Gronle, Florian Mauch, Wolfgang Osten, Univ. Stuttgart (Germany)

As investigated in recent years, the combination of chromatic confocal microscopy (CCM) and spectral interferometry (SI) leads to a more robust hybrid sensor principle named chromatic confocal spectral interferometry (CCSI).

In CCM, one can easily achieve a measurement range up to 100 microns and more e.g. by use of a diffractive optical element (DOE). At the same time a suitable lateral and axial resolution is possible due to a high numerical aperture (NA). But the accuracy is reduced by self-imaging effects on curved mirror like surfaces causing artifacts in the confocal envelope. SI on the other hand is based on absolute evaluation of the optical path difference (OPD) and therefore robust against self-imaging. However, its axial measurement range is limited by the depth of focus, which is given by the NA. This leads to a trade-off between lateral resolution and axial measurement range.

CCSI combines the advantages of both, while circumventing most of their disadvantages by intelligent signal processing. The retrieved signal consists of an interferogram convolved with the sinc-shape of the CCM peak and is therefore heavily affected by the artifacts known from CCM, which are induced by the specimens curvature or discontinuities. However, one can use the phase information of the CCSI wavelet to overcome the problems of the envelope evaluation, given by the confocal contrast. Based on the OPD evaluation, the phase of the wavelet is decoupled from the envelope, giving a second information channel. Different approaches have been investigated to retrieve the phase information in a reliable way and it was shown, that a robust lock-in algorithm provides accurate results. Since the phase is wrapped, the proper fringe order has to be determined in case of discontinuities, steep gradients or measurement errors, which are exactly the points, where the envelope evaluation is also not reliable.

In this contribution we present an approach for a robust evaluation combining both, envelope and phase information to overcome these problems, i.e. reduce artifacts while gaining resolution. By this means we show latest experimental results from our combined CCM/CCSI demonstrator setup, which allows for direct comparison of both principles.

8788-32, Session 8
Measurement, visualization and analysis of extremely large data sets with a nanopositioning and nanomeasuring machine
Oliver Birli, Karl-Heinz Franke, Gerhard Linß, Torsten Machleidt, Eberhard Manske, Florian Schale, Hans-Christian Schwannecke, Erik Sparrer, Mathias Weiß, Technische Univ. Ilmenau (Germany)

Nanopositioning- and nanomeasuring machines (NPM-machines) developed at the Ilmenau University of Technology allow the measurement of micro- and nanostructures with nanometer precision in a measurement volume of 25 mm x 25 mm x 5 mm or 200 mm x 200 mm x 25 mm. Various visual, tactile or atomic force sensors can all be used to measure specimens. Atomic force sensors have emerged as a powerful tool in nanotechnology. Large-scale AFM measurements are very time-consuming and in fact impossible in a practical sense in the millimeter range due to low scanning speeds. A cascaded multi-sensor system can be used to implement a multi-scale measurement and testing strategy in the field of nanopositioning- and nanomeasuring machines. After capturing an overview image at the limit of optical resolution, the measured data are automatically scanned for interesting test areas that are suitable for a higher-resolution measurement. These “fields of interest” can subsequently be measured in the same NPM machine with individual AFM sensor scans.

The overview image is a complete series of individual images from a CCD camera microscope (currently 0.5 million pixels, resolution: 0.417 μm) generated at the NPM machine’s positioning accuracy level within acceptable response times. The individual camera images are merged into a complete overview image solely on the basis of the NPM positioning accuracy of the NPM machine without image data processing. Approximately 2.2 hours are required to fully acquire the entire 25 mm x 25 mm field, generating about 7230 individual images to be assembled automatically with nanometer precision. This process creates a 2.35 GB file containing 3.3 billion pixels.

The results involve extremely large data sets that cannot be handled by off-the-shelf software. To navigate in terabyte-sized data files quickly, preprocessing is done on the measured data to calculate intermediate images based on the principle of a visualization pyramid. This pyramid includes the measured data of the entire volume, prepared in the form of discrete measurement volumes (spatial tiles or cubes) with certain edge lengths at specific zoom levels. A structured file header contains all information about the tiles. When visualizing a specific image area, only the tiles (and the associated measured data) necessary for the current display and zoom range are loaded and shown. The 3D visualization as implemented is based on OpenGL.

The functionality of the closed process chain is demonstrated using a blob analysis for automatic selection of regions of interest on the specimen. As expected processing large amounts of data place particularly high demands on computing and software engineering.

8788-33, Session 8
Model-based, active inspection of three-dimensional objects using a multi-sensor measurement system
Marc Gronle, Wolfram Lyda, Wolfgang Osten, Univ. Stuttgart (Germany)

In the manufacturing process of components with complex three-dimensional surfaces, there is growing demand for consistent quality control, calling for fast, reliable and flexible inspection systems. Considering complex objects, it is a common situation, that this demand often cannot be met in a single measurement step. Instead, multiple and adapted inspection steps have to be applied to different sub-regions on the measurement object. Within these sub-regions, defects with varying characteristics, like the size or the general form of the artifact, need to be detected and analyzed. For example, while inspecting the surface of small gears, the side face or every tooth has to be searched for scratches while the upper edges are subject to dents in the micrometer range.

In order to realize such a manifold inspection task, a flexible multi-sensor measurement system can be used. It consists of a set of different sensors, each having individual characteristic properties. In total, they offer a wide diversity concerning their resolution, measurement speed or field size. Then, an optimization is used to choose the best sensor for each inspection step, such that the overall inspection process can be executed both within short time and with accurate result. Furthermore, individual sensors can also be used together in the sense of a multi-scale inspection process, such that the measurement speed of one single inspection step is highly increased. At first, the relevant region on the object’s surface is sampled by a fast, but coarse sensor in a lower scale. Afterwards, indicator functions will be used to determine sub-regions within the recently obtained data set, that are suspected to contain defects. Then, sensors measuring in finer scales, hence higher resolution, only have to iteratively analyze these sub-regions in order to accomplish the overall inspection task.

In this paper, we present a multi-sensor inspection strategy where the object under inspection is represented by a polygonal mesh structure. Using an initial overview measurement, the homogeneous transformation between the real object and its virtual model is determined. Then, the meshed model is divided into different functional sub-regions, where each region is assigned a set of different inspection steps, which contain both a certain class of defect and further
characteristic parameters. Based on this information, a suitable sensor or multi-scale sensor chain is selected that fits to the corresponding requirements. Using the local shape information of the model, the sensor is now positioned in order to acquire the necessary data. Finally, this data can be analyzed to either determine whether there is a defect or to indicate sub-regions where the inspection needs to be continued using a sensor measuring in any higher scale.

8788-34, Session 9

High-frequency optical fiber microphone for condition-based maintenance application

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Condition based maintenance (CBM) is a critical issue in industrial plants, and specifically relates to the monitoring procedures in large manufacturing plants operating under strict production efficiency constraints. In these circumstances, unexpected production stops due to damage and replacement of critical components have an immediate impact on production efficiency. However, many critical components including cogwheels, ball bearings, and rollers, have a quite predictable trend that can be estimated from their rotating sounds as an early failure sign. These peaks grow in intensity up to damage point. Our tests show that the FBG microphone is able to detect early failures, even in presence of a poor FBG mount, with higher accuracy than standard microphones, thanks to the strong signal processing. The output spectra are consistent with the failure model, and the superior SNR resilience improves the failure detection capability in CBM application.

8788-35, Session 9

A space-borne fiber-optic interrogator module based on narrow-band tunable laser diode for temperature monitoring in telecommunication satellites

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In this paper measurement results of the fiber-optic interrogator module for telecommunication satellite applications are presented. The final system will be verified as flight demonstrator during the German Heinrich Hertz mission. Fiber-optic sensing onboard satellites is a new concept allowing the implementation of novel satellite control and monitoring methods. Fiber-optic sensor bus architectures reduce integration cost by lowering the wiring effort, decreasing the required test time and by providing a flexible sensor network topology. The sensor interrogator features from fiber Bragg grating (FBG) based sensing. Benefits are intrinsic sensor distribution capability and the possibility to embed optical fibers in composite structures like tanks and satellite panels.

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We present a fiber optic extrinsic Fabry-Perot interferometer (EFPI) for temperature monitoring in high-pressure environments using an optical fiber sensor network. The EFPI module operates in low signal-to-noise (SNR) conditions, usually well below 0 dB. We exploit strong signal processing to deal with low SNR, restoring performances up to the usual microwave target. We employ a Kalman filter, employed as in channel pre-equalization in telecommunication systems, to mitigate the effect of background noise interfering the measurement. Then, with a Capon power spectral density estimator we retrieve frequency peaks even in low SNR conditions, obtaining much better performance than with FFT or other non-parametric algorithms usually employed in literature. The Capon algorithm has been suitably modified, through an eigendecomposition, to obtain a further increase of frequency peaks resolving.

For experimental validation, the sensing FBG has been mounted on a loudspeaker, fixed with scotch tape. This mount simulates a low-duty-cycle temperature compensation, according to the temperature range of the proposed application.
The white-light interrogation system is based on a high-speed spectrometer, a broadband source, and a 3 dB coupler to couple light in and out the probe. The proposed concept can be developed for any wavelength range; however, in order to take advantage of the availability of low-cost telecom fibers and devices, we implement the system in the third optical window. The broadband source is a (C+L)-band ASE generator, and a 1 kHz spectrometer operating in the 1520-1600 nm range is employed as receiver. The probe is assembled with standard single- and multi-mode telecom fibers (10/125 and 62.5/200 m size), sealed in a protective capillary with 200/220 μ m inner/outer diameter.

When pressure is applied on top of the diaphragm, the air-gap gets compressed according to a linear model, with a sensitivity inversely proportional to the third power of the diaphragm length. The fabrication process allows reducing the diaphragm thickness below 2 μ m; the typical obtained sensitivity is 2-15 nm/kPa (0.3 - 2.0 mmHg), with a >80% probe fabrication success rate. Further optimization of the diaphragm etching will allow consistently reducing the diaphragm thickness to 1 μ m, which is the optimum value for biomedical applications that operate in low-pressure regime.

The EFPI cavity is modeled through a scattering matrix approach. Compared to the standard three-beam analysis, the transmission matrix approach provides a more accurate explicit solution for the reflection spectrum from the FP cavity, and allows taking into account angles and changes of refractive index. A signal processing algorithm has been developed in order to estimate the length of air-gap, and therefore the applied pressure, online. The algorithm, based on a non-linear regression, interpolates the measured spectrum with the EFPI model function, returning the estimate of air-gap length. In order to discriminate between multiple peaks, a custom-made cost function has been developed in order for the regression routine to track the right peak, selecting the correct air-gap size. Repeated operation show that the nonlinear regression is extremely robust in low-pressure conditions, is noise-resilient and converges in a small number of iterations, which enables high-speed applications. Through this signal processing technique, we can expand the resolution of the interrogator and achieve a pressure resolution of 0.1-2.0 mmHg, depending on the diaphragm length resulting from fabrication. The system has been tested for pressure and pressure-temperature measurement in several conditions, in order to evaluate resolution, linearity and response speed; furthermore, as the sensor targets medical applications, we evaluate the capability to detect short pulsed signals, e.g. heartbeat, with a good reproduction of the pulse profile and repetition rate. The measurement system is based on a water pump built on a fluid reservoir, with a set of actuators that can dynamically regulate pressure; the EFPI sensor has been compared with a reference off-the-shelf fiber optics pressure probe. A second pressure chamber based on a cylindrical burette allows rapid pressure variations, and demonstrates instantaneous response: the speed of response is only limited by hardware sampling rate, and no significant hysteresis has been identified. Result of a test and validation, comparing the EFPI sensor with a commercial fiber-optic reference, will be shown in the final paper.

When EFPI is applied in conjunction with the FBG, for temperature compensation, pressure and temperature variations are simultaneously estimated from the dual estimation of air-gap and Bragg wavelength variations. As both diaphragm pressure/temperature is a linear system, a matrix structure allows compensation with target accuracy of 0.1°C.

8788-37, Session 9
Applications of tilted fiber Bragg grating in liquid parameters measurement
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The measurement of liquid parameter, such as the concentration, refractive index, liquid-level, diffusion process, etc, is of great importance in many widely dispersed applications, especially in the fields such as chemical, biomedical, environmental science, and so on. And due to the high sensitivity of the cladding modes of tilted fiber Bragg grating (TFBG) to liquid environment, it provides a new approach to the measurement of liquid parameter. This is because that the grating planes are angled by a few degrees relative to the plane perpendicular to the fiber axis, which enhances the coupling of light from the forward-propagating core mode to the backward-propagating cladding mode, and the cladding mode is guided by the interface between the cladding and the surrounding medium, then the parameters change in the medium adjacent to the fiber produces obvious spectral variation in the TFBG spectrum.

In this paper, the variations of the resonant wavelengths of three kinds of modes (core mode, ghost mode and cladding mode) and the normalized area enclosed by the upper and lower envelope curves of cladding modes of TFBG with the liquid refractive index are experimentally investigated. And then, a method for measuring liquid phase diffusion using a TFBG is proposed and experimentally demonstrated. Taking water-glycerol diffusion process as an example, the spectral evolution with the diffusion time is observed. And the distribution of the glycerol concentration in time and space can be obtained through the change of the normalized area enclosed by the upper and lower envelope curves of the cladding modes. Meanwhile, the application of TFBG in the liquid-level measurement is experimentally analyzed, and the coupling intensity, the resonant wavelength and the normalized area of the cladding mode linearly change with the height of the glycerol level, which shows different spectral variation with the glycerol concentration.

In addition, the comparative detection circuit which consists of one photodiode (PD) and another referenced PD (or using a precision reference voltage generator (PRVD)) and is employed to measure small variation of the TFBG transmission power in a strong background is designed and processed, and then the continuous change of the glycerol concentration due to the water-glycerol diffusion and index transients when the TFBG is immersed in the glycerol are monitored and experimentally analyzed. Compared with spectral measurement method, the scheme using the comparative detection about complicated data processing has simple structure, and can achieve fast and real-time measurement.

8788-38, Session 10
Experimental comparison of phase-shifting fringe projection and statistical pattern projection for active triangulation systems
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Active triangulation systems are widely used for precise, contact-free and fast measurements. Many different coding strategies have been invented to solve the correspondence problem. The quality of the measurement results depends on the accuracy of the pixel assignments. An imprecise correlation between two camera pixels leads to noisy 3D data. The most established projection sequence uses several phase shifted-patterns projected on the measurement object. Here, the number of projected patterns and also the fringe density are parameters that can be varied. This method is compared to an approach using statistical patterns. The main advantage of this coding strategy is the possibility of using a different kind of projection technique for the required illumination of the measurement scene. This makes it possible to configure high-speed 3D measurement systems. The amount of images and the spatial frequency can be varied in this method as well. Because of the increasing requirements on the measurement speed and accuracy, the methods have to be compared with respect to the quality of the measurement results and the measurement time or patterns needed to be projected. The measurements for the presented results are done with a fully calibrated high-resolution system. Each measurement at a single scene is done in a narrow time window with exactly the same setup. Hence, thermal drifts and variations in the measurement scene can be neglected. Additionally, the complete calculation process is done with the same software stack as for the calibration of the coding camera pixels. The experimental results show that both methods produce similar accuracy of the 3D-measurement data depending on the number of patterns used. In conclusion it can be stated that statistical pattern projection should be preferable applied for high-
speed 3D-measurements. For both systems, the accuracy at the same amount of images and same spatial frequency is similar. If the graycodes are omitted and only restricted 3D depths are of interest, the same accuracy can be reached for a smaller total amount of images with the phase-shifting technique.

8788-40, Session 10
High-speed 3D shape measurement using array projection
Stefan Heist, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Marcel Sieler, Fraunhofer IOF (Germany); Andreas Breitbarth, Peter Kühnstedt, Gunther Notni, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)
No abstract available.

8788-41, Session 10
Influence of the structured illumination frequency content on the correspondence assignment precision in stereophotogrammetry
Marcus Große, Institut of Applied Optics (Germany); Martin Schaffer, Bastian Harentdt, Richard M. Kowarschik, Friedrich-Schiller-Univ. Jena (Germany)

Stereophotogrammetric 3D shape measurement using structured illumination is an established class of methods for industrial inspection. One essential step in the measurement process for all stereophotogrammetric techniques is the assignment of corresponding points between the stereo views. As the purpose of the used structured illumination is to ease and improve the correspondence assignment, the choice of said sequence is of utmost importance. The precision of the correspondence assignment directly affects the noise of the final point cloud and therefore this assignment should be conducted with the highest precision possible. Depending on the chosen structured illumination sequence, different degrees of freedom for the pattern design exist and may affect the precision of the correspondence assignment and thus the noise of the 3d point cloud. In our contribution we want to discuss the influence of the frequency content of the structured illumination for a scheme employing bandlimited statistical patterns, which have been fruitfully used for highspeed applications in the past years. To evaluate the limits of the correspondence assignment accuracy we created a simple numerical signal-detector model. Using this model the correspondence assignment in dependence of the chosen structured illumination can be compared to ground truth-data. Furthermore, the noise of point clouds in real measurements is investigated to validate the results of the used simulation. Therefore, illumination sequences using different spatial frequency bands are created and projected onto a reference object. Afterwards, the noise of the resulting pointcloud is evaluated. The results indicate that it is advisable to optimize the pattern design depending on the used sensor and object properties.

8788-42, Session 10
High resolution measurements of filigree, inner geometries with endoscopic micro fringe projection
Christoph Ohrt, Markus Kästner, Eduard Reithmeier, Leibniz Univ. Hannover (Germany)

Fringe projection, as an areal kind of the triangulation measuring principle, nowadays covers a wide range of applications in dimensional metrology. From large scale bodywork measurements of free form geometries and gap measures in measuring areas in the m range, over high resolution measurements of small fields in µm [1] scales, to robot assisted multidimensional acquisition of complete 3D geometries in 360° in any direction [2], fringe projection provides fast holistic, accurate and precise sets of dimensional data of almost arbitrary geometries and shapes.

However there are still measurement applications that cannot be served by fringe projection. One is the accurate determination of filigree form elements in inner carrier geometries in forming tools of deep drawing or sheet metal forming [3] or internal gearings.

Since for these applications normally used tactile approaches turn out to be too slow to follow the trend of industrial quality management going into in-situ measurements or 100% control in the running production cycle, the idea of a flexible fibreoscopic fringe projector was generated that can be guided to the desired measuring field in an inner carrier geometry [4].

The paper, respectively the talk, will introduce a new endoscopic micro fringe projector, showing the special requirements of micro fringe projection in combination with coupling to flexible image fibre bundles. Several performed example applications such as measurements of deep drawing tools, will be shown and difficulties of certain geometries, such as internal gearings elements with steep flank gradients, will be discussed. Due to the miniaturisation of the fringe pattern into a 2 mm diameter fibre bundle and the decrease of resolution in the bundle, a cut in contrast has to be accepted. That leads to a fading of the sharp edges of black/white crossovers to sine like characteristics on the detection camera. Methods for the compensation of these artefacts in the beforehand made calibration and during the acquisition of the measurement data will be presented. The applications of the conventional grey code technique will be as well introduced and compared as the developing method of encoded phase shift [5]. In the current state the newly designed fringe projector is connected to a high resolution coordinate measurement machine (CMM). Measurement data and achievable resolutions of the connected systems will as well be presented as information about realiable measuring volumes.

It is clearly shown that fibreoscopic fringe projection, despite the drawbacks of miniature optics and decreased image resolution of the fibre, can fulfill the needs of high speed, areal measurements. Using CMM and stitching, even larger areas can be obtained with low errors.


8788-135, Session 10
Scanning fringe projection for fast 3D inspection
Marc Honegger, Michael Kahl, Sandra Trunz, Interstaatliche Hochschule für Technik Buchs NTB (Switzerland); Stefan Rinner, NTB Interstate University (Switzerland); Andreas Ettemeyer, Interstaatliche Hochschule für Technik Buchs NTB (Switzerland); Patrick Lambelet, Heliotis AG (Switzerland)

In an earlier paper we have described a concept for high speed 3D inspection with fringe projection technique. Goal is an inspection of 150 cm²/s and a lateral and vertical resolution of 10 m. We used a special CMOS camera with 300 x 300 px which can calculate the phase on board. Maximum frame rate of this camera is 1 Mio images/s. Focus of the first step of development had been a fringe projector, which is able to modulate the projected fringes with appropriate speed (up to 250 kHz, as we need 4 modulated images to determine the phase of the fringes).
In a second step the image acquisition part of the system has been developed. In case of 3D measurement with an area camera the camera resp. measuring object has to be moved stepwise in lateral direction to cover multiple acquisition areas of the measurement object. With our camera and the intended resolution, the field of view on the object is 3 x 3 mm2. Therefore, between each image the camera resp. the measuring object has to be moved laterally by 3 mm to cover the complete object. At the intended very high image acquisition rates the high accuracy of the system between each image will lead to unacceptable mechanical forces.

A continuous scanning process is easily obtained using a single line camera. In order to obtain a continuous scanning procedure and at the same time to use the performance of an area camera, a special lens system was developed.

In our configuration a measurement field of 120 mm (x-direction) x 3 mm (y-direction) is imaged onto the camera. In x-direction this field is imaged onto the 300 rows of the camera, giving a lateral resolution of 10 m. In y-direction the 120 mm object length is divided into 12'000 lines to reach the same resolution of 10 m. This is done with a micro lens array, placed right above the measuring object. With each camera shot 300 separated lines are imaged onto the chip. Between each of these 300 lines there is an empty space of ca. 0.4 mm, which is not imaged by the camera. Therefore, in principle, the camera is operating as 300 single line cameras operating in a distance of 0.4 mm. If the camera is moved in an inclined direction to the camera orientation over the object, the empty spaces can be recorded as well. Between each image the camera has to move in x- and y-direction. The movement has to be defined in a way that after 300 images the open spaces in y-direction are covered and in x-direction one complete field of view (3mm) is shifted. In this way, the complete surface can be scanned with constant camera speed covering a stripe with 120 mm width.

In this paper we will describe the complete system with focus on the image acquisition optics and camera. The test set-up is described and first test results will be given.

8788-43, Session 11
Measurement of aspheres and free-form surfaces in a non-null test interferometer: reconstruction of high-frequency errors
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The tilted wave interferometer is a non-null test interferometer for the measurement of aspheres and freeform surfaces without dedicated null-optics that uses an array of tilted waves to locally compensate the deviation of the surface from the spherical form. The concept allows for short measurement times of only a few minutes and high lateral resolution at the same time. The calculation of the surface error is performed by perturbation of a polynomial representation of the surface. Since we are also interested in higher frequency errors of the surface which cannot be described by a polynomial of finite order these errors are evaluated in an additional step. Since every wavefront only covers a small area of the surface the challenge here is to reconstruct the surface from the information that is distributed over the different patches. We will present the method that was developed for the reconstruction of these high frequency errors as well as measurement results of aspheres and freeform surfaces without rotational symmetry that were obtained by this method.

8788-44, Session 11
Non-contact profiling for high precision fast asphere topology measurement
Juergen Petter, Gernot Berger, Luphos GmbH (Germany)

Quality control in the fabrication of high precision optics these days needs nanometer accuracy. However, the fast growing number of optics with complex aspheric shape demands an adapted measurement method as existing metrology systems more and more reach their limits.

Tactile metrology systems are widely spread to determine the shape of a lens during or after fabrication. However, tactile measurements are slow and – especially on polished surfaces or plastic optics – severely can harm the surface. Parallel interferometers perform contactless measurements in the measurement range. However, their application is limited to surface shapes only close to a spherical shape; especially aspheric optics and optics with strongly changing slopes cannot be handled by those systems.

In this contribution the authors present a unique and highly flexible approach to measure spheric and aspheric optics. The principle idea is the combination of the flexibility of a scanning topology measurement system and the accuracy of a (contactless) interferometer. Based on a scanning point interferometer the system combines the high precision and the speed of an optical interferometer with the high form flexibility of a classical tactile scanning system.

A four axis scanning system ( R: radial axis, z: height axis, t: sensor tilt axis, c: object rotational axis) is used to guide the sensor along the radius of the object while the sensor is directed always perpendicular to the surface. Rotating the object during the scanning the complete topology of the object is scanned following a spiral path. With this scheme the system can measure rotational symmetric objects with almost unlimited spherical departure and with diameters from 2mm up to 420mm. Therefore, also objects with steep or strongly changing slopes such as “pancake” or “gull wing” objects can be measured straight forward.

To keep the high measurement accuracy even when using a scanning system, an interferometric concept is employed. By the use of three additional sensors the exact position of the object sensor is followed with respect to a fixed reference frame during the complete measurement process. This allows to reach an accuracy of less than +/-30nm topology error over the whole surface.

The core of the technology is a completely fiber based Multi-Wavelength-Interferometer. Four closely adjacent wavelengths are used to measure the same distance simultaneously. The analysis of the phase information of each single wavelength gives a distance information with interferometric accuracy. The combination of the phase information of the four wavelengths enables the creation of an absolute measurement range in which the position (or the change of the position) of the objects can be determined absolutely. This allows for following the measurement not only on polished but also on rough or even on discontinuous surfaces, such as ground lenses or lenses with diffractive structures.

As by this feature all the measurements (on rough and polished surfaces) can be done using one and the same system without any change in hardware or software a direct comparison of the influence of different fabrication steps is possible during production and after finishing of the object.

This contribution gives an insight into the functionality of the MWLI-sensor as well as into the concept of the reference system of the scanning metrology system. And of course a couple of different samples of the system in application are given.

8788-45, Session 11
Highly accurate surface maps from profilometer measurements
Katherine Medicus, Jessica Nelson, Optimax Systems Inc. (United States); Michael Mandina, Optimax Systems, Inc. (United States)

Profilometers are typically used to measure the surface shape of precision optical components. A profilometer measures a single line profile, from a probe moved laterally across the surface. From this height profile, the part’s overall shape and the surface irregularity (form error) can be determined. The main disadvantage of a profilometer is that it only creates a line profile, where a full surface map (2.5D measurement) is much more desirable. Interferometers, which can measure full surface maps on optical surfaces, are limited in their ability to measure highly aspheric and free-forms optical surfaces. In addition, interferometers are expensive and require a fully polished surface for measurement. Profilometers are less expensive and can be used on ground surfaces, and do not have a limit on the amount of aspheric departure. Depending on the profilometer type, they are limited by the measurable sag and lateral distance.
In the past, many aspheres and aspheric manufacturing processes were rotationally symmetric, leading to mainly rotationally symmetric errors, so a single profile was satisfactory to determine the surface error of the part. As manufacturing processes have improved and more non-symmetric-surfaces are needed, single profiles are not enough. Without this full surface error map, a full surface correction run cannot be done and accurate measurements of free-form, non-rotationally symmetric optical surfaces cannot be achieved.

We have developed an accurate method to transform multiple profilometer trace measurements to full surface measurements, with known uncertainties and limits. We have accomplished this by measuring multiple profiles and mathematically stitching those measurements together, resulting in a full surface map with an estimate of the uncertainty of the stitched map.

In our method, profilometer measurements are taken on the part at prescribed rotational (clocked) positions. The prescribed positions can be 3 (0 45 90 degrees), 4 (+ 135 degrees), or 6 (+ 60 120 degrees) positions. The required number of traces is determined by the typical tradeoff between accuracy and time required for measurement. After the profilometer traces are collected, the data is assembled into a mathematical program, where the measured heights are paced in their respective positions. This results in a height map that looks like the spokes of a wheel, with data along the spokes, but not between. This data is then fit to the (Fringe) Zernike polynomial set to determine the Zernike coefficients of the measured surface.

The number of traces taken determines the accuracy of the calculated surface (Zernikes). This accuracy was measured with two type simulations. First, using actual interferometer surface measurements, we simulated profiles at the prescribed positions, and then compared the calculated Zernikes to the full surface map Zernikes. Second, we simulated a full dataset with a prescribed set of Zernike coefficients, simulated the profiles at the prescribed positions, and then compared the calculated Zernikes to the prescribed value.

For the first simulations, using actual data (46 measurements, with peak to valley values varying from 0.03 μm to 0.25 μm), we can correctly predict the Zernike values when using 4 profiles to better than plus or minus 0.03 μm, with most values less than plus or minus 0.01 μm.

For the second set of simulations, we can correctly predict 26 of the 33 Zernike values to within 10% using 4 profiles. The other Zernike values have errors ranging from 20% to 100%. When 6 profiles (0 45 60 90 120 135 degrees) are used, all Zernike coefficients within the 4 to 36 range are well represented to within 10%. The Zernike values from simulated 3 profiles showed that only 10 Zernike terms (out of the 33) were within 10% of the expected value. Fifteen terms showed errors larger than 50%.

With these results, we can confidently say that we can stitch profilometer traces together to produce a full surface map that is accurate enough to perform full surface correction runs. This leads to more accurate aspheres and an ability to manufacture free-forms.

8788-47, Session 11

**Deflectometry vs. interferometry** (Invited Paper)

Gerd Haeusler, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Christian Faber, Univ. of Applied Sciences (Germany); Evelyn Olesch, Svenja Ettl, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

Quantitative deflectometry is a new tool to measure specular surfaces. The spectrum of measurable surfaces ranges from flat to freeform surfaces with steep slopes, with a size from millimeters [1] to several meters [2]. We will describe important properties of deflectometry and compare it with interferometry.

Deflectometry [3, 4] measures intrinsically the local slope (grad[z(x,y)]) of a surface z(x,y) under test. The shape can be found by integration [5] and the local curvature (refractive power) is calculated by differentiation. We will describe a few features of deflectometry, using examples:

The first example is the measurement of progressive eye glasses in the factory [6]:

Within 10 seconds, the slope at 1 Mio surface points is acquired. The precision of the measured slope is better than 8 arcsec, which is sufficient to calculate the local refractive power with an accuracy better than 10 mD over 3mm diameter (eye pupil). The shape trueness is in the range of 1μm. It is not necessary to position the eye glass properly to the sensor, positioning just by hand is sufficient.

The second example is the measurement of telescope mirrors for the Cherenkov Telescope Array (CTA). These mirrors have a diameter of about 1.5 m and a focal length in the range of 30 meters. The CTA consists of about 10.000 mirrors. The mirrors are fabricated by a low cost process: a glass or metal sheet is glued onto a honeycomb metal structure. We implemented a small footprint instrument that fits into a climate chamber, see Fig. 1.

The most important features of quantitative deflectometry are listed as follows: There are technical features such as simplicity and robustness against vibrations. There are physical features such as incoherence and the intrinsic sensitivity against local shape variations. And there are strategic features, the most important: Deflectometry does not display retrace errors. From this remarkable feature follows that the object does not need any precise positioning in the device and that we can measure a wide spectrum of complicated surfaces.

Of course, the trueness of the measurement or “global shape accuracy” needs thorough discussion: Deflectometry is the ideal method to measure local variations of the shape. Much more difficult is it, to achieve a good global accuracy (trueness) of the measurement. A global error or 100 nm for an object diameter of 100 mm, with a sag of 10 mm is very difficult to achieve. The required height dynamics would be 100.000:1. This is only possible because deflectometry intrinsically delivers the slope instead of the height. This means, we need integration to calculate the shape. Integration will strongly amplify low frequency measuring errors, while high frequency noise cancels. The source of low frequency errors is misalignment. For quantitative deflectometry of eye glasses, points within a volume of about 500x500x500 mm³ have to be localized with an accuracy better than about 20 μm. So the “real” difficulty of deflectometry is precise calibration. Presently, we achieve a global shape error of less than 500 nm for a planar mirror of 80 mm diameter. We developed a calibration method that can easily be applied by unexperienced users and that needs only a low quality calibration gauge. We aim for a method that does not need any calibration gauge at all.

We compare these results with interferometry. Interferometry is strongly superior over deflectometry, for simple surfaces such as spheres, planar surfaces and weakly aspheric surfaces. At those surfaces, interferometry will allow for nanometer trueness – under the assumption that the reference sphere is perfect and the object is perfectly positioned. For strongly aspheric surfaces, interferometric methods need assistance from auxiliary optics, computer generated holograms or from precise mechanics. The reason is that interferometry relies on normal ray incidence. This condition can be perfectly satisfied only for known objects and known auxiliary systems,
and for a perfect positioning of the object. This is the principal weakness of interferometry. A calibrated deflectometric system does not need any auxiliary system and does not need a precise positioning of the object.

The consequences are wide ranging. We illustrate this by the example of deflectometric measurements with a miniaturized Setup (Mini-PMD) within a diamond turning machine (Fig. 2): the work piece is manufactured and measured without unclamping. These measured data are used to start a second cycle, the correction turning. After the correction turning, the sample displays a shape trueness better than 300 nm. This result is only possible because the measuring device can be put into the machine or taken out just manually, and no accurate re-positioning is necessary, quite in contrast to interferometry.

The measuring results are as accurate as interferometric measurements, as shown in Fig. 3.

We summarize: the natural domain of interferometry is the measurement of “simple” and highly accurate surfaces, while deflectometry is the ideal tool for strongly aspheric or even free form surfaces, for a wide range of size.


8788-48, Session 12
Approach to the measurement of astronomical mirrors with new procedures
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The manufacturing of optical components more often requires grinding and polishing of non rotational symmetric aspheres or freeform surfaces. Although there are measurement techniques available for small diameters of some 10 mm the measuring of larger surfaces is not or only by extreme efforts feasible.

As larger parts – especially after the last manufacturing step – should not be transported, the used measurement technology should be applicable within the machine tool. The technical target of the project is the combination of different measurement methods in order to proof the accuracy of large (up to 800mm in diameter) optical surfaces for the final zonal correction polishing such as MRF. This could be established by using tactile methods and optical methods as they are described by different principles (confocal microscopy, interferometry, Shack-Hartmann-Sensors, deflectometry or others).

In this complementary combination the tactile system would be used to characterize the macro geometry and the non-tactile methods to measure the local geometry with high precision in several stages. The measurement of the global form of the optical parts together with high precision local information requires this hierarchical measurement setup. The stitching of local measurement patches will be based on the knowledge from previous stages about the global surface form.

Major tasks and work packages in realization are:
I. Mathematica and algorithmic combination of the different measurement methods by stitching of local measurement patches in order to get a high precision global form of the surface
II. Design and test on known surfaces by different metrology systems usable in a manufacturing surrounding
Several simulation results are obtained to study the influence of several points and the slopes of those points. On these methods different local errors are present. The first kind of methods is based on a path integral, in which the profile in a given point \( x(y) \) is obtained by a 1D integral from \( 0 \) to \( x \) followed by a 1D integral from \( x \) to \( y \). The second kind of methods is based on finite differences, along the integration paths, when local errors are present, so they are not recommended. Finite difference methods are more versatile, and their accuracy depends on the used interpolation methods. We will show that finite difference methods with cubic spline interpolation approximate the Fourier methods in a very wide range of frequencies and have less edge effects problems.

In both sensors, the profile is then obtained by integrating the gradient of the local tilt angle of the wave front \( \tan(\theta) \): \( d = f \tan(\theta) \). Then by measuring the shifts in both directions of the focal spots.

From the experiment results we show that the SCOTS can act as a large dynamic range, high precision, non-null test method for precision aspheric optics.

Methods to obtain the waveform profile from slope measurements

Alfonso Moreno, Manuel Espinola, José Martínez, Juan Campos, Univ. Autònoma de Barcelona (Spain)

There are many optical metrological techniques to determine the profile of a surface or a wave-front. A group of them are based on the measurements of the profile slopes, like deflectometry or wave-front sensors.

Deflectometry an incident light beam is reflected by the surface under test. The angle between the incident and reflected beam is twice the local tilt angle of the surface. By measuring this angle, the local tilt of the surface is determined. From this measure the local slope of the surface is determined. By scanning the surface in a regular bi-dimensional grid the sampled slopes in these points are measured.

A Shack–Hartmann sensor consists on an array of micro lenses and a CCD detector located on the focal plane of the lenses. When a plane wave front arrives to the lens array, the local wave fronts limited by each lens are focused on the CCD camera. When a general wave front arrives to the lens array, each local wave front presents a different local tilt, and in consequence, the corresponding focal spot is shifted a distance \( d \) with respect to the plane wave front. The shift is proportional to the focal length of the lens and to the tangent of the local tilt angle of the wave front (tan(\( \theta \))): \( d = f \tan(\theta) \). Then by measuring these shifts (the local slope \( \tan(\theta) \) ) of the wave front can be determined. Note that the lens array performs a two dimensional scan of the wave front. Then the slopes in both directions are obtained by measuring the shifts in both directions of the focal spots.

In both sensors, the profile is then obtained by integrating the gradient information provided by the measurements. The used integration method influences the quality of the obtained results.

In this work we compare the performance of different bi-dimensional integration methods to obtain the profile from the slopes, and we propose some new methods. The first kind of methods is based on a path integral, in which the profile in a given point \( x(y) \) is obtained by a 1D integral from \( 0 \) to \( x \) followed by a 1D integral from \( x \) to \( y \). The second kind of methods is based on finite differences, where the profile in a point is related with the profile in the neighbor points and the slopes of those points. On these methods different interpolations can be used. Finally, the third kind of methods is based on Fourier domain integration.

Several simulation results are obtained to study the influence of several parameters:

- The integration errors as a function of spatial frequency of the signal are studied by simulating sinusoidal functions with different frequencies.
- Local slope errors are simulated by introducing impulse errors on the simulated slopes.
- Random noise is simulated by adding to the simulated slopes random white noise with different standard deviations.
- Edge effects, could be especially important if Fourier methods due to the non-periodicity of the signals.

Fourier domain methods could be considered as the gold standard, they suffer from edge effects because the signals are not periodic. Moreover they can only be applied when regular Cartesian sampling is used. These edge effects can be reduced by extending the signal and using iterative methods, and by extrapolating the signal to the extended domain, imposing a periodic final signal. Path integral methods create artifacts along the integration paths, when local errors are present, so they are not recommended. Finite difference methods are more versatile, and their accuracy depends on the used interpolation methods. We will show that finite difference methods with cubic spline interpolation approximate the Fourier methods in a very wide range of frequencies and have less edge effects problems.

Moiré deflectometry under incoherent illumination: 3D profiler for specular surfaces

Tomohiro Hirose, Tsunaji Kitayama, Toyota Central R&D Labs., Inc. (Japan)

In the production of automobiles, optical 3-D profiler for specular surface is indispensable for the reverse-engineering and the quality-control of specular products such as an automobile body, designed parts and molds.

A variety of 3-D measuring methods have been proposed, such as laser triangulation [1], fringe projection [2], white-light interferometry [3], classical interferometry [4], and deflectometry [5-6]. Diffuse surfaces such as human skin and ceramics are readily measurable by laser triangulation and fringe projection. Glossy surfaces are also measurable if we make use of these methods carefully. For specular surfaces, interferometry [3-4] or moiré deflectometry under laser illumination [5-6] are mainly utilized. However, these methods make time-consuming when we try to measure a complex curved specular surface including deeply curved, continuously modulated and discontinuous shape.

Phase measuring deflectometry (PMD) proposed by M.Knauer et.al. is a promising technique for a 3D specular profiler [7]. This method measure surface slope of an object by observing reflected fringe patterns produced on the liquid crystal display (LCD) in the distance. Since the phase shift distribution depends not only on the height but also on the slope at each measurement point, they obtain two variables separately by using a calibrated stereo camera through the stereo matching procedure. Several researchers have proposed improvements relating to device configurations, signal processes and its applications [8-13].

In PMD, we could not figure out the slope variation only from the phase shift distribution. To clarify the slope, first of all, the distance between the surface and the fringe pattern must be known accurately. Therefore, before measuring the surface, we need three-step calibrations for “camera pixel”, “fringe pattern” and “geometric calibration”. These multistep calibrations are complicated and also can be a cause of systematic errors.

Here we present a method based on moiré deflectometry for measuring a specular surface shape. We made use of pairs of Ronchi gratings with incoherent illumination. The Ronchi gratings are translated in order to modulate a spatial frequency of the moiré produced by the superposition of the gratings. A calibrated stereo camera observed the moiré reflected off a specular object. This method intrinsically has no ambiguity of slope and the measurement. And we need only the camera calibration. Furthermore, the 2D phase unwrapping is not needed. Therefore, our method has a potential to develop into a 3D profiler for complex specular surface.
A lateral sensor for the alignment of two formation-flying satellites

Stéphane Roose, Yvan G. Stockman, Univ. de Liège (Belgium); Zoran Sodnik, European Space Research and Technology Ctr. (Netherlands)

The lateral sensor is a system able to measure the lateral position between two satellites. It bridges the gap between the alignment accuracy achieved with the radio frequency metrology, and the alignment accuracy required to start the high-precision optical metrology (fine-lateral and longitudinal sensor).

This project concerns the demonstration of formation flying technologies for future European scientific and application missions of the EUROPEAN SPACE AGENCY.

Technological developments enabling formation flying have already been initiated and some precursor missions already cover part of the related technologies, for example SMART-2.

The lateral sensor developed at Centre Spatial de Liège (CSL) is based on a camera (CMOS detector) a telecentric lens designed at CSL, a fibre-coupled laser-diode bar and a corner cube.

The fibre-coupled laser-diode bar emits a diverging beam, from the master spacecraft to a slave spacecraft. A corner cube located on the slave spacecraft sends the light back. This light is captured by the telecentric lens and camera (build by Deltatec Liège-B). A lateral shift of the corner cube is seen on the camera as an image displacement.

Real time centroidisation algorithms will allow tracking the image position and feed the on-board computer with this information via a RS422 link, allowing further position stabilisation. The imaging system needs to operate in a depth of field from 25 m to 250 m.

Because of the large depth of operation, all lateral system performances are angular ones.

The system is build to meet:

• Tracking capability for a spot moving @ 0.5 arcdeg/sec
• Spot detection with the sun in the field of view
• Centroidisation accuracy: 0.1 camera pixels (3.5 arcsec)
• Absolute calibration accuracy: 0.14 camera pixels (5 arcsec)

In order to comply with these requirements, the following features were implemented:

• The camera allows quick read-out of sub-windows of interest (in 1 ms).
• The detector captures the images. An electronic unit records the images and localizes the bright spot (return image from the corner cube).
• Implementation of a “slow detection mode”, which allows to discriminate sun from moving image

The system is a standalone unit. Once connected to an unregulated 28V power-supply, it delivers, after spot detection, pixel coordinates to the RS422 link at a 10 Hz rate. Its average power consumption is 8W.

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are many mobile elements in remote places, and check its work while moving is not possible by contact methods. This paper describes the electro-optics automation system longevity test valve to adjust the flow of toxic fluids. The system is designed for the dynamic measurement of the piston in the cylinder valve. It consists of a valve, a motor, and a label, located on the controlled piston. The camera includes a special lighting system (based on LEDs), lens and CMOS high-resolution rolling shutter sensor. The described system measures the position of the image label placed on the piston valve with a frequency about 100 Hz and accuracy about 0.05 mm. Piston moving has amplitude 10 mm and speed up to 14 mm per second. Basis on the system measurement and additional data such as a number of work cycles of the valve, conclusions about valve degree of depreciation is produced. In particular, the parameters piston movements (such as its range of motion, trajectory, speed, acceleration) are determined. The use of such systems allows automating the longevity tests such devices.

Two algorithm for image processing based on joint multiple images processing are described in this article. The main systematic and random errors are also analyzed and ways for its compensation are proposed. The paper describes the results of mathematical modeling conducted in Zemax for different labels. In addition, the article also describes laboratory bench designed for the system analysis. The paper presents the results of acceptance tests.

8788-81, Session PS

Precision inspection of micro components flatness by Moiré interferometry
Sadeg Meguellati, Aissa Manallah, Univ. Ferhat Abbas de Sétif (Algeria)

The automation, speed and precision in the quality control of surface shape require the development of control methods suitable for this purpose. The technique proposed in this paper provides a quality control component surface flatness by non-destructive and contactless way, with high resolution and increased sensitivity. The control is done in real time and instantaneously on all inspected surface. The accuracy of components geometry is the one of parameters which influences precision of the function. Moiré topography is full-field optical technique in which the shape of object surfaces is measured by means of geometric interference between two identical line gratings. The technique has found various applications in diverse fields, from biomedical to industrial and scientific applications. In many industrial metrology applications, contactless and non-destructive shape measurement is a desirable tool for, quality control and contour mapping. This method of optical scanning presented in this paper is used for precision measurement deformation in shape or absolute forms in comparison with a reference component form, of optical or mechanical components, on surfaces that are of the order of few mm2 and more. The principle of the method is to project the image of the source grating to palpate optically surface to be inspected, after reflection; the image of the source grating is printed by the object topography and is then projected onto the plane of reference grating for generate moiré fringe for defects detection. The optical device used allows a significant dimensional surface magnification of up to 1000 times the area inspected for micro-surfaces, which allows easy processing and reaches an exceptional nanometric imprecision of measurements. According to the measurement principle, the sensitivity for displacement measurement using moiré technique depends on the frequency grating, for increase the detection resolution. This measurement technique can be used advantageously to measure the deformations generated by the production process or constraints on functional parts and the influence of these variations on the function. Then, optical and geometrical principle, on which it is based, can be used for automated inspection of industrially produced goods. It can also be used for dimensional control when, for example, to quantify the error as to whether a piece is good or rubbish. It then suffices to compare a figure of moiré fringes with another previously recorded from a piece considered standard; which saves time, money and accuracy. This optical device control has advantageous features allows non-destructive and contactless testing, real time speed inspection and measurement; possibility of image tracking in motion analysis and surface deformation, high spatial resolution and high sensitivity may vary depending on the importance of defects to be measured.
algorithms is presented. 3D information is shown in auto-focus images and 3D profiles. It is also described a method for the determination of the diameter of the bonding wire. In a very similar manner PCB track measurements were accomplished. From 2D and 3D track profiles mean and standard deviations of its width and thickness were measured. Results form both applications are used to show the limitations imposed by less spatial sampling rate which is related to positioning resolution of the sample.

8788-98, Session PS

**Design of omnidirectional camera lens system with catadioptric system**

Jae Heung Jo, Sangon Lee, Hyeon Jin Seo, Hannam Univ. (Korea, Republic of); Jung Hwan Lee, Joon Mo Kim, JM Tech Co., Ltd. (Korea, Republic of)

Optical vision systems have developed from wide field of view to all direction field of view on some purpose, such as security, surveillance, teleconferencing and etc. An omnidirectional image is an image with 360 degrees field of view in the horizontal plane and wide field in the vertical plane. The fish-eye lens and the multiple cameras are typically used to get the omnidirectional image. In this paper, we designed an omnidirectional camera lens system (OCLS) for small size, low cost, ease of fabrication and high resolution.

We choose the catadioptric method to construct the omnidirectional vision system by combining lenses and mirrors together. The OCLS is composed of one convex mirror with central hole, one flat mirror and correction lens system with three single lenses and an achromatic doublet. The OCLS is optimized to short height less than 50 mm, for no constraint of space and to attach to a 3.27 mega pixels high resolution digital camera module with a 1/2.8 inch size CMOS digital image sensor.

The optical design of OCLS covers from 37 degree to 107 degree vertical field of view, total view range is 70 degrees including upper range 57 degrees and lower range 13 degrees, by two mirrors which are coated by aluminum. The range of wavelength is visible and weights of wavelength are same weights at 486 nm, 558 nm and 656 nm. The object distance is 7 m, almost infinite distance for the OCLS, and the focal length is 1 mm set on the CCD camera module. The primary convex mirror (M1) is the 23 mm diameter clear aperture mirror with a 4 mm diameter central hole. The 16 mm secondary flat mirror (M2) is located 32.5 mm from M1 along the z-axis. The optical design was composed of five lenses, including the achromatic doublet, as the aberration corrector and the focus compensator. N-BK7 and SF2 are chosen for optical materials of the OCLS with design considerations of ease of fabrication and cost. The image shape is torus and the image size is 2.92 mm from 107 degrees field and 1.34 mm from 37 degrees field which fits to 2080 x 1553 array CMOS image sensor with 2.5 size pixel. The optical performance of the OCLS with the MTF including all fields, 0.0, 0.5, 0.7, and 1.0 degree, has more than 0.5 at 150 cycles/mm frequency.

Opto-mechanical design of the OCLS is considered optical performance, stiffness, ease of fabrication and cost. Under the consideration, black anodized aluminum is used for mechanical material. Opto-mechanical structures of the OCLS are composed of the M1 assembly, the M2 assembly, the assembly of lenses and the body of the OCLS. The components of the M1 assembly are the primary convex mirror and the tripod spacer. The M2 assembly includes the secondary mirror and its barrel and is places on the top of the tripod spacer in the M1 assembly. The assembly of lenses, 3 single lenses and an achromatic doublet, are mounted on one lens barrel for ease of alignment and the lens barrel is placed under the M1 to control the defocus of the image. The M1 assembly assembled with the M2 assembly fixes on the top of the body of the OCLS. The bottom of its body is made to fix on the camera module.

The omnidirectional camera lens system is designed by catadioptric system to cover 360 degrees field of view in the horizontal plane and 70 degrees field in the vertical plane. The dimensional sizes of the OCLS are the 45.3 mm short height and 32 mm diameter width for less constraint of space. The overall performance of the OCLS well meets the specification of the optical design to the CMOS image sensor with 2.5 size pixel as well.

8788-99, Session PS

**Dual view x-ray inspection system for foreign objects detection in canned food**

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X-ray inspection technique for foreign objects in food products can determine and mark the presence of contaminants within the product by using image process and pattern recognition technique on the X-ray transmission images. This paper presents the two beams X-ray inspection technique for foreign objects in food via analyzing the weak point of the traditional single beam X-ray inspection technique. In addition, a prototype with the new technique is developed in accordance with glass splinter’s detection within the food jar (glass jar especially) which is a typical tickler. Some algorithms such as: adaptive image segmentation based on contour tracking, nonlinear arctan function transform and etc., are applied to improve image quality and achieve effective inspection results. The false recognition rate is effectively reduced and the detection sensitivity is highly enhanced. Finally the actual test results of this prototype are given.

8788-101, Session PS

**Absolute scale-based imaging position encoder with submicron accuracy**

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Study is devoted to the analysis of spatial distribution of the light that was reflected by a retroreflector. The features of design, choice and use of tetrahedral reflectors (corner cube prisms) and cat’s-eye reflectors are described. Mathematical expressions were achieved for energy distribution analysis in the autoreflection scheme. Zemax simulations were made to study the influence of beam and image deformation (caused by these reflectors). It was shown that the error value gains with the degree of image defocusing. Theoretical calculations and simulations are supported by experimental tests with autoreflection shift control system. The result of the study is a detail comparison table of tetrahedral and cat’s-eye reflectors with recommendations and limitations of use for alignment control.

8788-102, Session PS

**CCD camera-based analysis of thin film growth in industrial PACVD processes**

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In this paper we present a method for the characterization of (semitransparent) thin film growth during PACVD processes (plasma assisted chemical vapour deposition) based on the analysis of thermal radiation by means of near-infrared imaging. We use a standard CCD camera with a near infrared band-pass filter (1030 nm, FWHM 10nm) as thermal imaging device. The spectral sensitivity of a Si-CCD sensor at 1 m is sufficient to allow the imaging of thermal radiation at temperatures above approx. 400 °C, whereas light emissions from plasma discharges (which are mainly occurring in the visible range of the electromagnetic spectrum) barely affect the image formation. Due to interference effects during thin film growth, characteristic emissivity signal variations can be observed which allow a very detailed spatio-temporal analysis of growth characteristics (e.g. growth rates). The field of PACVD based metallic surface coating has found widespread
industrial application in recent years (i.e. to improve wear and corrosion resistance of wear pieces or to specifically change specific surface properties like color appearance), however industrial process control of such surface modifications is still a demanding task. It is shown that near-infrared pyrometry/thermography is a promising approach for process monitoring with the potential for industrial application as a very simple measurement setup can be used (i.e. there is no need for additional modifications or reconstruction of the plasma chamber, as the camera can simply be attached to the inspection window on top of the reactor).

Our analysis is based on the measurement of surface emissivities. Thus, a blind hole on the specimen surface is used as radiation reference. Assuming a certain ratio between diameter and depth, this hole exerts almost ideal blackbody radiation i.e. the emissivity within this drill hole is very close to 1 and does not change during the surface modification process. The emissivity of the surface can simply be determined as the ratio between measured surface intensity and the blackbody reference intensity, ensuring reliable emissivity values even under slightly varying temperature conditions during the plasma process. The imaging software allows the definition of several regions of interest (ROIs) in the image where the mean intensity is measured and divided by the blackbody reference intensity in video real time, visualizing the temporal evolution of emissivity at different spatial positions of the specimen surface. Additionally, image-/signal processing (e.g. based on wavelet denoising) is applied to further improve signal quality. Finally, signal analysis methods like empirical mode decomposition and Hilbert filtering are applied to derive growth curves from the measured interference signals.

Exemplarily, results of various thin film processes are presented (e.g. thermal iron oxide films, silicon based thin films) showing the potential of the proposed approach for in-situ process monitoring.

8788-103, Session PS
Towards superresolution imaging with optical vortex scanning microscope
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Optical vortex scanning microscope (OVSM) is a system in which sample is scanned by a beam carrying optical vortex (vortex beam). The vortex beam possess a special point where the phase is undetermined. This vortex point is stable and survives the scattering from the object. Due to scattering the vortex point changes its position. The first idea was to change the location of vortex point. Unfortunately the position changes of the vortex point are not characteristic enough to read the surface topography, unless very simple samples are measured (like a single phase step, for example). At this point the new idea was necessary to save the OVSM project. The two changes introduced into the start design of the OVSM opened the new possibilities. The first one was to move the observation plane just behind the object plane. In the previous solution the observation plane was fixed at some distance from the object plane – so the far field diffraction image was recorded and analyzed [1,2]. Now the object plane is imaged to see the phase distribution of the optical vortex just after passing the object. The second invention is to apply the scanning by moving the vortex lens [3,4]. When the vortex lens is moved the optical vortex moves inside the focused beam at highly reduce range. This movement is very characteristic and the vortex becomes highly sensitive when moving the vortex lens. Both changes open new possibilities to the microscopic imaging by OVSM. In our contribution we discuss all these aspects of the new version of the OVSM. We also present our first measurements of simple phase objects.

References

8788-132, Session PS
Surface normal deblurring caused by conveyor movement for fast surface inspection
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These days there are many real-time 3D measurement systems. Those method has finite exposure time, then the motion blur is inevitable in principle. We developed a motion deblurring technique in surface orientation images using a correlation image sensor for 1D movement by belt conveyor.

This imaging system consists of two components: one is ring-shaped modulation illumination for encoding surface orientation into the amplitude and phase of the reflected light, and the other is the three-phase correlation image sensor (3PCIS) for demodulating the amplitude and phase of reflected light. The higher spatial frequency components, which is lost by motion are captured by modulation imaging using correlation image sensor. The reconstruction algorithm is proposed for modulation imaging picture which is complex value image representing surface orientation.

We applied wiener filtering method and weighted integral method proposed by us to optical flow constraint in surface orientation, and then still normal vector image is successfully reconstructed.

In the presentation, we will compare the above two reconstruction algorithms.

8788-72, Session PS
Low-coherence interferometry for thin-film thickness profile measurement
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Thin films are widely used for various purposes and precise measurements of film thickness especially in a non-destructive way are crucial to ensure the intended functions of thin films for the in-line high-speed inspection of microelectronics devices being mass-produced in the semiconductors and flat panel displays industries. Our work is devoted to suggest low-coherence interferometry to measure the top surface height as well as the thickness of a thin-film structure which enables us to reconstruct 3D tomographical view of the target. The described methods here are based on a spectrally resolved interferometric method being implemented through a dispersive scheme of low-coherence interferometry equipped with a line-scan spectral imaging device. And the main idea or key point of our proposed methods is to make it possible the decoupled measurements of the top surface and film thickness at the same time. It measures film thickness independently by analyzing the self-interference signal occurred among the multi-reflected beam from the thin films and extracts the surface profile by taking into account the pre-measured film thickness. In this paper we describe several powerful methods to separate the information of top surface height profile and film thickness from a complex mixture of overlapped interference signals. Our methods are also verified by measuring and testing several thin-film layered structures.
Amongst the different types of profilometers that exist today, such as SPS, the Interferometric Fringe Scanning Interferometry (WLSI), is an important optical technique that is now widely used in the measurement of surface roughness and microscopic surface shape. SPS has the advantages of being rapid, non-destructive and applicable to many different types of surfaces. The technique is based on the scanning of a series of white light interference fringes over the depth of the roughness to be measured and using signal processing along the x-axis at each pixel to determine the centre of the fringe envelope and thus the corresponding height of the surface at each point in the image. Many different types of algorithms have been proposed to find the fringe envelope, such as those using the centroid detection [1], peak fringe intensity detection [2], demodulation [3], FFT [4], wavelets [5] and signal correlation [6]. An efficient, but little used algorithm is that based on the measurement of the fringe visibility or signal modulation, known as the five-sample adaptive (FSA) algorithm [7]. The algorithm is derived from the well-known 5 step phase shifting technique, in which a phase shift of /2 is used between each image. The algorithm can be represented as a second-order nonlinear filter derived from Teager-Kaiser methods [8]. The algorithm is compact and very efficient in terms of computational time, showing high accuracy for envelope detection in the presence of fringe stepper errors. In [9] we presented the use of this algorithm in the measurement of rough layers of synthetic hydroxyapatite, a biomaterial used in implants and in [10] we used it for its compactness in cable logic for high speed 4D microscopy of moving surfaces. In this paper we present the implementation of the FSA algorithm in a practical measuring system for static surface roughness measurement. One of the key aspects of its successful use is the design of the envelope peak detection method. Different envelope peak detection techniques are demonstrated using either spline interpolation or local phase measurement. We show how in practical cases of different types of surfaces, the right choice of envelope peak detection is essential for minimising measurement artefacts. For example, the local phase measurement technique can give a nanometric axial sensitivity on mirror-like surfaces, but not on slighly rough surfaces where phase artefacts of up to /2 can appear. On rougher surfaces, spline interpolation is more robust, giving an axial sensitivity of 10-20 nm in the best of cases. The reaction of the algorithm to different configurations of wave filtering and the results compared with a commercial interferometer and AFM. We demonstrate the robustness of the implemented FSA technique in these different applications and show its performance and limits.

References
Static and (quasi)dynamic calibration of stroboscopic scanning white light interferometer

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Scanning white light interferometry is used to characterize out of plane features and motion in N(IME)EMS devices. For traceability the interferometers must be calibrated prior to use. The main challenge in this calibration is to have a reference device whose out-of-plane displacements are precisely reproducible when submitted to standard loadings. We use a flat mirror attached to a piezoelectric transducer for static and (quasi)dynamic calibration of a stroboscopic scanning white light interferometer. First we calibrated the piezo-scanned flexure guided stage (Queensgate Instruments, type NPS-Z-15B) using a symmetric differential heterodyne laser interferometer developed at the Centre for Metrology and Accreditation (MIKES) - Finland. This 633 nm He-Ne laser device features linearity and noise in the subnanometre to picometre level. The uncertainty of the piezo stage motion calibration was 1-10 nm in the measurements with the calibration setup. Then we used the stage as a transfer artifact to calibrate our stroboscopic scanning white light interferometer (SSWLI) equipped with a halogen lamp (Philips, type 6958) and a light emitting diode (Cree, type XML-16) pulsed at 200 Hz with 3% duty cycle. We measured the static position and (quasi)dynamic motion of the attached mirror relative to a reference surface. The results show the proposed methodology could be applied for SSWLI calibration.

Temperature sensing by modulating phase of optical fiber

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The development of temperature sensing based on modulating phase of optical fibers has been an active research topic in the context of fiber optic sensing. In this paper, a form of interferometer to measure temperature is made using single-mode optical fibers. The light from the two fibers interferes to form a series of bright and dark fringes when the optical path lengths of the two arms are nearly equal within the coherence length of the source. A change in the relative phase of the light from one fiber with respect to the other is observed as a displacement of the fringe pattern, a phase change causing a displacement of one fringe. The phase of the light leaving a fiber can be changed by dimensional or index of refraction changes in the fiber. Looking along a certain ray impinging onto the cylindrical surface, the Zernike polynomials are neither orthogonal over rectangular area nor do they represent balanced aberrations and misalignment aberrations. Hence, their unique utility is lost. In this case, a new set of polynomials is needed to fit the misalignment aberrations introduced by the cylindrical surface. In this paper, a flexible strategy to carry out misalignment removal for the interferometric measurement of the cylindrical surface is proposed.

Calibration of misalignment aberrations in cylindrical surface interferometric measurement

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Misalignment of the test surface with respect to its ideal position relative to the interferometer coordinate system can significantly influence the measurement results. For rotational symmetric surfaces such as plane and spherical with least-square technique to obtain the unwrapped phase maps. The residuals show that the misalignment aberrations can be removed by directly set the corresponding Zernike coefficients as zero. For the non-rotational symmetric optics such as cylindrical surface, the Zernike polynomials are neither orthogonal over rectangular area nor do they represent balanced aberrations and misalignment aberrations. Hence, their unique utility is lost. In this case, a new set of polynomials is needed to fit the misalignment aberrations introduced by the cylindrical surface. In this paper, a flexible strategy to carry out misalignment removal for the interferometric measurement of the cylindrical surface is proposed. A general cylindrical object has up to four adjustment-sensitive degrees of freedom resulting in misalignment aberrations containing in the measured phase data. The misalignment parameters are tip/tilt, defocus and clock. Provided that all misalignment parameters are sufficiently small, the linear approximation model can be used to describe the misalignment aberrations of the cylindrical wavefront. The first consequence of linear approximation is that we can write the misalignment aberrations as a linear superposition of individual contributions. The second consequence of linear approximation is the factorization of the individual contributions. This means that in linear approximation each misalignment aberration can be written as a specific misalignment function that is simply multiplied by the corresponding misalignment parameter. After fitting of the misalignment functions to the unwrapped phase data with least-square technique, the misalignment aberrations, introduced by the cylindrical wavefront tilt, tip, defocus, and clock, were subtracted from the measurement result. The residuals show that the misalignment aberrations can be removed with the proposed method. In addition, a set of fringe pattern images and two-dimension color figures representing the misalignment aberrations have been plotted, which can be used to guide the fine alignment in the interferometric testing of cylindrical surface. The experiment has been carried out to further validate the proposed calibration technique. The certain misalignments with wavefront tilt, defocus, clock are introduced in the measurement, in which interferograms are adjust to a straight fringe pattern and a curved fringe pattern respectively. After removing the misalignment aberrations with the derived polynomials, the comparisons were implemented over these results. The residuals show that this technique can provide a feasible way to lower the requirement on the adjustment in the measurement of cylindrical surface, while retaining good accuracy and repeatability.
The impact of polarization on metrology performance of the lateral shearing interferometer

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The semiconductor industry is aggressively pushed to produce smaller and smaller feature size from their existing base of lithography system, wavefront aberration should be derived by comparing ideal and real wavefronts at the wafer plane of a high resolution lithography system. We propose the IIW5 (Integrated Interferometer Wavefront Sensor) system. On the base of traditional lateral shearing interferometer, tow-dimensional phase-shifting shearing interferometry and vectorial optical analysis are used in this paper. By adjusting polarization state and polarization distribution, the metrology accuracy of the wavefront aberration of the system, which is significant for the modern semiconductor industry, is greatly increased.

Reaching accuracies of Lambda/100 with the Three-Flat-Test

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Usually every measurement relies on a reference which has a higher quality than the test-piece. A higher resolution usually demands a better reference, as the errors introduced by the reference have to be small in comparison to the test-piece. But in special cases reference and test-piece can be of the same quality. In the Three-Flat-Test three flats A, B and C are used, with all flats being of the same quality. The practical implementation in a Fizeau-interferometer uses the back-reflex of the reference surface and the primary reflex of the subject to be tested. Kuechel showed that using function-decomposition and five measurements the Three-Flat-Problem can be solved in approximation. His algorithm needs four normal measurements \( W_1 = A(x,y) + B(-x,y), \) \( W_2 = A(x,y) + C(-x,y), \) \( W_3 = C(x,y) + B(-x,y), \) \( W_4 = C(-x,y) + B(-x,y) \) and a special measurement \( W_5 = A(x,y) + B(x,y). \) In the fifth measurement surface B is rotated continuously with respect to surface A. Continuous measurements are not realistic however. Kuechel showed that for a standard size CCD array of 640 to 480 pixels 20 rotations are enough s.t. the residual error drops below an acceptable value. Using his algorithm an interferometric-measurement accuracy on the order of \( \text{lambda}/100 \) is likely. In the simulation part both fractal and Zernike surfaces A, B and C were generated. The former representing high, the ladder low frequency errors. These surfaces were used to simulate the measurements W1, W2, W3, W4 and W5. Applying the algorithm both fractal and Zernike original surfaces could be retrieved. In a first practical test the algorithm retrieved the wavefront errors of three ZYGO transmission flats. The three flats had given accuracies of \( A = \text{lambda}/15, B = \text{lambda}/15 \) and \( C = \text{lambda}/20. \) The cavity between reference and test flat was chosen to be \( 3 \text{cm} \) in the Fizeau-Interferometer to minimize external error sources. For measurement W5, 20 rotations of surface B were used. The application of the algorithm resulted in accuracies of \( A_a = \text{lambda}/39, B_a = \text{lambda}/42 \) and \( C_a = \text{lambda}/40. \) This implies that all surfaces could be more accurately determined than given by the manufacturer! To finally approve these results the transmission flats have to be measured using another method, e.g. deflectometry. A rotation stage which can be turned more precisely and transmission flats of known better quality are however expected to lead to the measurement of higher accuracies in the range of \( \text{lambda}/100. \) Hence this procedure is likely to allow for cheap and fast calibration of transmission flats.

In the manuscript Kuechel's solution to the Three-Flat-Test will be shown, its MATLAB implementation sketched and a simulation and the first run in praxis demonstrated.
wave shape. Secondly, measurement for a surface with shape error was demonstrated. In this case, the shape error was composed on the SLM as a simulation. A flat mirror was placed as a target. It was normal to the optical axis. In the first turn, phase map of interference fringe was detected. In the next turn, the detected phase map was overlaid on the SLM and phase of interference fringe was measured. In this time, the phase map was almost flat. It means that the defect of the shape was successfully compensated. We think that it could be measured for the shape with more complex or more inclined shape by some numbers of iteration.

8788-115, Session PS

Automatic unit for measuring refractive index of air based on Ciddor equation and its verification using direct interferometric measurement method


In scanning probe microscopy laser interferometers are usually used for measuring the position of the probe tip with a metrological traceability. As the most of the AFM setups are designed to work under standard atmospheric conditions the changes of the refractive index of air have an influence to measured values of the length with 1.0e6×(4) relatively. In order to achieve better accuracies the refractive index of air has to be monitored continuously and its instantaneous value has to be used for compensating the lengths measured by all of the interferometric axes. In the presented work we developed a new concept of an electronic unit which is able to monitor the refractive index of air on basis of measurement of ambient atmospheric conditions: temperature, humidity, pressure of the air and the CO2 concentration. The data processing is based on Ciddor equation for calculating the refractive index of air. The important advantage of the unit is a very low power consumption of the electronics so the unit causes only negligible temperature effects to the measured environment. The accuracy of the indirect measuring method employed by the unit was verified. We tested the accuracy in comparison with a direct method of measuring refractive index of air based on an evacuable cell placed at the measuring arm of a laser interferometer. An experimental setup used for verification is presented together with a set of measurements describing the performance. The resulting accuracy of the smart electronic unit falls to the 4.1 exp(-7) relatively.

8788-120, Session PS

Wavelength modulation-based method for interference phase detection with reduced optical complexity

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Although the laser interferometry represents the most precise class of techniques in the field of precise measurement of geometrical quantities, its wide use in measurement systems is still accompanied by many unresolved challenges. One of these challenges is the complexity of underlying optical systems. We present a novel approach to the interference phase detection -- fringe subdivision -- in the homodyne laser interferometry that aims at reduction of the optical complexity while the resolution is preserved. Our method employs a series of computational steps (synchronous detection, mixing, scale linearization, quadrature signal phase adjustment) to infer a pair of signals in quadrature that allows to determine the interference phase with a sub-nanometre resolution from an interference signal from a non-polarising interferometer sampled by a single photodetector. The complexity trade-off is the use of laser beam with frequency modulation capability.

The method was experimentally evaluated on a Michelson interferometer-based free-space setup and its performance has been compared to a traditional homodyne detection method. The results indicate the method is a feasible alternative for the traditional homodyne detection in case it performs with optical stability (< 0.5 nm standard deviation), especially where the optical setup complexity is principal issue and the modulation of laser beam is not a heavy burden, for instance in multi-axis measurement systems or laser diode based systems. The authors wish to express thanks for the support of the GACR, project GAP102/10/1813, the research intent RVO: 68081731 and EU supported projects No. CZ.1.05/2.1.00/01.0017 and CZ.1.07/2.3.00/30.0054. Experimental tasks were supported by the Ministry of Industry and Commerce, project FR-TI2/705.

8788-126, Session PS

Precision positioning with suppression of the influence of refractive index of air


We present an interferometric technique based on differential interferometry setup for measurement in the subnanometer scale in atmospheric conditions. One of the important limiting factors in any optical measurements are fluctuations of the refractive index of air representing a source of uncertainty traditionally compensated when the index is evaluated indirectly from the physical parameters of the atmosphere. Our proposal is based on the concept of overdetermined interferometric setup where a reference length is derived from a mechanical frame made from a material with very low thermal coefficient on the 1E-8 level. The technique allows to track the variations of the refractive index of air on-line directly in the line of the measuring beam and to compensate for the fluctuations. The optical setup consists of three interferometers sharing the same beam path where two measure differentially the displacement while the third evaluates the changes in the measuring range acting as a tracking refractometer. The principle is demonstrated on an experimental setup and a set of measurements describing the performance is presented.

8788-78, Session PS

Real-time visualization and analysis of airflow field by use of digital holography

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The analysis and measurement of airflow field is very important in fluid dynamics. For airflow, smoke particles can be added to visually observe the turbulence phenomena by particle tracking technology, but the effect of smoke particles to follow the high speed airflow will reduce the measurement accuracy. In recent years, with the advantage of non-contact, non-destructive, fast and full-field measurement, digital holography has been widely applied in many fields, such as deformation and vibration analysis, particle characterization, refractive index measurement, and so on. In this paper, we present a method to measure the airflow field by use of digital holography. A small wind tunnel model made of acrylic glass is built to control the velocity and direction of airflow. Different shapes of samples such as aircraft wing and cylinder are set in the wind tunnel model to produce different forms of flow field. With a Mach-Zehnder interferometer setup, a series of digital holograms carrying the information of airflow filed distributions in different states are recorded by CCD camera and corresponding holographic images are numerically reconstructed from the holograms in different states by computer. Then we can conveniently obtain the velocity or pressure information of the airflow deduced from the quantitative phase information of holographic images and visually display the airflow field in the form of a movie. The theory and experiment results show that digital holography is a robust and feasible approach for real-time visualization and analysis of airflow field.
8788-79, Session PS

**Visual and dynamic measurement of temperature fields by use of digital holographic interferometry**

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The measurement of temperature field distribution in transparent media is an attracting subject in many research fields. Optical holographic interferometry, with its advantages of full-filed visualization, non-destruction, non-inversion and high-resolution, provides an effective approach for this measurement, but the complicated wet chemical process of the holographic plates and personal estimation of the holographic interferograms limit its practical applications, in particular for in-situ, dynamical and quantitative measurement. Different from the traditional optical holographic interferometry, the recently developed digital holographic interferometry allows recording the hologram using digitally imaging devices such as CCD, and reconstructing the holographic image by numerically simulating beam diffraction, so it can well overcome former limitations. In transparent medium, the temperature change will induce a corresponding refractive index change and thus lead to the phase distribution and variation of the object wavefronts passing through the medium. One of the most important advantages of digital holographic interferometry is that it can directly obtain the complex amplitude distribution of the object wavefront in different states by dynamically recording a series of holograms of the object field in different time, so that more impersonally measure the detail information of the object field, such as the refractive index distribution and variation in transparent media. In this paper, we introduce the principles and summarize the applications on dynamically measuring the temperature field distribution by using digital holographic interferometry with specially designed experimental setups, such as the temperature distributions and variations corresponding to Rayleigh-Benard convection, heat conduction process in glass samples, heating process of the oil in container, flame filed, cooling process of heat radiator and so on. The experimental results are in good agreement with that of the theoretic simulation. This work is supported by the National Natural Science Foundation of China (Grant No. 61077008 and No. 61127011), and the Strategic Pioneer Program on Space Science, Chinese Academic Sciences (Grant No. XDA04070200).

8788-104, Session PS

**Image quality improvement using speckle method in digital holography by means of multi-mode fiber**

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We present an image quality improvement using the speckle method in an in-line digital holography by means of a multi-mode fiber. In the proposed method, we use the speckle field emitted from the multi-mode fiber as both the reference wave and the wavefront illuminating the object. To capture multiple holograms, the speckle fields are changed by vibrating the multi-mode fiber using a vibrator. This method has an advantage in that the alignment of an optical setup becomes easy due to the introduction of an optical fiber and the speckle method can be readily performed by means of a vibrator.

8788-107, Session PS

**Tilted objects EFI in digital holography by two different numerical approaches**

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Limited depth of field (DOF) is one main shortage for many optical imaging systems. This is a limitation that precludes to get in focus, in a single plane, objects that are located at different distances, but that fall in the same field of view. In optical systems such as microscopes, the depth of field is reduced as much as greater is the requirement for a high magnification and to obtain an extended focus image (EFI) of these objects remains one of the major challenges. The EFI construction is an important issue, even in the digital holography and, over the years, various viable solutions have been suggested. In this work we propose and compare two different approaches to build the EFI of holograms recorded on a tilted plane. In the first case, a simplified three-dimensional (3D) formulation of the angular spectrum method (ASM) is proposed. It allows to generate the entire stack of propagated images in a single shot. Starting from this dataset and through simple masking operations, we are able to reconstruct the EFI of objects with a 3D extension. This method can be easily used in practice because it is quite versatile. Through the proper definition of a suitable mask, it can be used for very different setting situations. Moreover, the full stack of propagated images carries in itself a high information content and the possibility to obtain and handle it at once could be very advantageous for many application fields.

In the second approach, a numerical cubic phase plate (CPP) is included into the reconstruction process of digital holograms with the aim to enhancing DOF of optical imaging system. The idea comes from the practice of placing a special phase plate in the aperture stop of a coherent optical system. This causes the phase of the optical field to be focus invariant over a significantly larger range than the focal range of a standard optical system. Here we investigate how the CCP works for coherent light imaging systems in DH microscopy. In particular, inserting a numerical CPP during the reconstructing process, we demonstrate that it is possible to increase the optical coherence of the optical system. Working in this way, to obtain an EFI of tilted objects in a single shot and without further processing. This offers the advantage of dispensing with the use of real optical components and related complex fabrication process that require precise design to fabricate continuous cubic phase plate with high phase deviation.

Theoretical formulations of the two approaches are supported by experimental evidences. In particular, these proposed procedures are applied to digitally process the holograms of differently tilted objects providing EFI images of them. Then, in order to allow a correct method assessment, some objective parameters are introduced, and also a comparison between the obtained results with those achieved from more traditional strategies is executed. The obtained results show that the proposed strategies allow to reconstruct effectively an EFI from holograms recorded on an inclined plane; furthermore, they are comparable and coherent with other reconstruction methods, used for validation. Ultimately, although no strategy can be used indifferently on all cases, the proposed techniques produce results equivalent to other methods, and their implementations are easy and direct, and with only few drawbacks.

8788-109, Session PS

**Non-Bayesian noise reduction in digital holography by random resampling masks**

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Digital Holography (DH) is a well assessed technique allowing amplitude imaging and quantitative phase-contrast mapping at both microscopic and macroscopic scale. Unfortunately, due to the coherence of the emitting laser source and disturbances affecting the recording system, the quality of holographic reconstructions can be severely degraded by a mixture of both speckle and incoherent additive noise. Bayesian approaches can be adopted to improve the image quality by reducing the incoherent noise contribution, but some prior knowledge of the noise statistics is required. Thus, the performance of these methods varies depending on the hologram being processed. Moreover, the accuracy of any noise estimation worsens in presence of low Signal-to-Noise Ratio (SNR). Alternately,
quality improvement is achievable by speckle reduction. Spatial smoothing reduces the speckle at the cost of a deterministic resolution loss. On the other hand, the incoherent combination of multiple holographic reconstructions of the same object can keep the image contrast unaltered while reducing the noise. In this framework, diversity is obtainable e.g. combining holograms recorded at different wavelengths, angle or polarization. However, in these cases a complex ad-hoc set-up is needed to provide uncorrelated noise patterns.

Hence, a non-Bayesian strategy to reduce the overall noise content in DH with one single hologram is an highly wanted goal.

Some early works appeared in the 70’s by F. T. S. Yu and E. Y. Wang where a moving aperture was employed to perform a random sampling on the hologram plane. Although this idea showed interesting potentials, constraints due to the complexity of the mask implementation limited the number of obtainable images and the acquisition process was slow. Here we propose a simple and fast one-shot technique which significantly reduces the incoherent noise contribution with no prior knowledge of its statistics. The idea is to apply a set of binary random masks to the acquired hologram in order to obtain multiple reconstructions with uncorrelated noise. In this way we perform a random resampling of the same hologram, which can be seen as a sort of numerical simulation of the random diffuser of Yu and Wang’s work. The incoherent combination of the obtained reconstructions returns a Multi-Look (ML) output where the uncorrelated noise is much reduced with respect to the unprocessed Single-Look (SL) image. Since this is a one-shot technique, the acquisition process is fast and simple and no data capture diversity has to be provided. Moreover, we directly extrapolate the useful signal avoiding the noise estimation. Hence, the method works, independently on the processed hologram, also in case of very low SNR and when no prior noise information is available.

Experiments have been performed on noisy off-axis holograms showing the effectiveness of the proposed method. In particular, we tested two different stacks of binary masks and a comparative analysis has been carried out. As a consequence of the noise mitigation, the image contrast on the edges improves, whereas in homogeneous areas the gray level distribution exhibits a smoother trend, which in turn results in a visible image enhancement. A quantitative performance evaluation has been performed in terms of noise contrast, whose results indicate an improvement close to the theoretical bound. It is remarkable that, differently from smoothing methods, this is achieved while preserving the resolution of the SL image.

Digital holographic microscopy for the study of nano-fibers

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The advantages of digital holographic microscopy to record not only the intensity but also the optical phase are employed here. The experimental arrangement comprises a Mach-Zehnder type interferometer with a microscopic objective of magnification 100x. The used camera is a 5 Mpixel Allied Vision Guppy Pro F-503 with a pixel pitch of 2.2 μm. The lateral magnification is set to about 200x using MLL-STD-150A 1951 USAF resolution test target.

The dimensions of the used aggregated natural cellulose nanowisker fibers are in the range of some hundreds of nanometers, which are positioned in the front of the microscopic objective using a 3D translation stage in the object arm of the holographic setup. The recorded off-axis holograms are refocused using the angular spectrum method. The reconstructed complex field is used to calculate optical phase and intensity distributions of the object at different reconstructions depths. The dimensions and orientation of the fibers can be evaluated by reconstructing the optical field at different depths. Then, the shape and textures along the aggregated natural cellulose nanowisker fiber can be presented in 3D space. Further, the refractive index profile of the fibers can be calculated.

Digital holographic tomography is a new 3-D refractive index imaging technology which is developed in recent years. It is the outcome of the combination of digital holography and computed tomography. Based on the projection reconstruction principle of computed tomography, the 3-D structure of the phase object can be reconstructed cross-section by cross-section, by recording holograms resulting from the interference between the object wave and the reference wave under various angles of illumination. It is especially suitable for the integrated measurement of refractive index distribution and geometric structure of the cylindrically symmetric object.

In this work, we report the experimental results of geometric parameters measurement of the micro-capillary by use of digital holographic tomography. Considering the micro-capillary has the cylindrically symmetric structure, we use single phase data under zero incidence angles to simulate all measured field phase data under different angles. Tomography of the micro-capillary is performed by filtered back-projection algorithm and Fourier diffraction algorithm respectively to reconstruct the 3-D map of refractive index. According to the 3-D map of refractive index, we can further get the geometric dimensions of the micro-capillary.

The experimental setup is shown in Fig. 1. The system is analogous to a Mach-Zehnder interferometer. The object to be measured is a micro-capillary (the reference parameters provided by manufacturers: the inner diameter in the range of 0.9–1.1 mm and wall thickness in the range of 0.1–0.15 mm). Fig. 2 shows the reconstructed image of cross-section of the micro-capillary by the filtered back-projection algorithm. The inner diameter and the wall thickness are obtained as about 0.949mm and 0.225mm, which are outside the ranges provided by manufacturers. Fig. 3 shows the reconstructed image of cross-section of the micro-capillary by the Fourier diffraction algorithm with the Flytov approximation. The inner diameter and the wall thickness are obtained as about 1.105mm and 0.148mm, which are closer to the ranges of parameters given by the manufacturer. Experimental results show that, comparing with the filtered back-projection reconstruction, diffraction tomography based on the Flytov approximation better respects the dimensions of the micro-capillary. It provides a new way for the real-time and online measurement of tiny weakly-diffracting objects having a cylindrically symmetric structure such as the micro-capillary.

Stimulated LIF studied using pulsed digital holography and modelling

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A frequency tripled Q-switched Nd:YAG laser (wavelength 355 nm, pulse duration 12 ns) has been used to pump Coumarin 153 dye solution in ethanol. The laser induced fluorescence (LIF) spectrum has been recorded using a spectrometer at different dye concentrations. The frequency doubled 532 nm beam from the same laser is used as a probe beam to pass through the excited volume of the dye. Because of stimulated emission an increase of the probe (532 nm) beam energy is recorded and a reduction of the spontaneous fluorescence spectrum intensity is observed. A model was developed that approaches the trend of the gain as a function of the probe beam energy at low dye concentrations (less than 0.08 g/L). The stimulated LIF is further recorded using digital holography. Digital holograms were recorded for different dye concentrations using collimated laser light (532 nm) passed through the dye volume. Two holograms without and with the UV laser beam were recorded. Intensity maps were calculated from the recorded digital holograms and are used to calculate the gain of the green laser beam due to the stimulated fluorescence emission which is coupled to the dye concentration. The gain of the coherent 532 nm beam is seen in the intensity maps and its value is about 40% for a dye concentration of 0.32 g/L and decreases with the decrease of the dye concentration. The results show that pulsed digital holography can be coupled to the stimulated LIF effect for imaging fluorescent species.
8788-73, Session PS

Analysis of method of 3D shape reconstruction using scanning deflectometry
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Many measurement methods were developed for 3D surface topography of specular surfaces in recent years, which may find many applications in different parts of science, engineering, and biomedicine. The existing measurement and evaluation methods are based on different physical principles, both in a contact and noncontact operation mode. There are mainly two classes of noncontact methods for specular surface measurements: interferometry and deflectometry. In many cases it is difficult to apply interferometry in the testing of surface shape. Interferometric approaches permit measuring specular surfaces with a very high accuracy and resolution, but these are not suitable for measuring a greatly curved or a large scale surface. As a promising alternative, optical deflectometric techniques make possible to overcome the shortcomings of interferometric techniques. In recent years deflectometry has been investigated by many researchers, which led to the development of different deflectometric techniques, such as Moire deflectometry, Ronchi method, phase measuring deflectometry using structured illumination of the surface, laser scanning deflectometric techniques, etc. The reconstruction of a specular surface shape by means of deflectometric methods is a challenging task. These deflectometric techniques calculate the slope distribution of the surface, and finally the 3-D shape is usually obtained by numerically integrating the slope distribution.

This work presents a new scanning deflectometric approach to solving a 3D surface reconstruction problem, which is based on measurements of a surface gradient of optically smooth surfaces. It is shown that a description of this problem leads to a nonlinear partial differential equation (PDE) of the first order. Due to the fact, that the general solution of this differential equation cannot be found in an explicit form, the differential equation must be solved numerically. Several methods exist how to solve this nonlinear differential equation. An universal method is to write the of the differential equation as a sum of certain basis functions and then to find the coefficients in the sum in order to satisfy the differential equation as well as possible. The method for effective finding of the solution of this differential equation is proposed, which is based on the transform of the problem of PDE solving to the optimization problem. The three-dimensional shape of the measured surface is approximated by a suitable mathematical function, whose coefficients can be found by nonlinear optimization techniques. We describe different types of surface description for the shape reconstruction and a numerical simulation of the presented method is performed. The reconstruction process is analyzed by computer simulations and presented on several examples. The performed analysis confirms a robustness of the reconstruction method and a good possibility for measurements and reconstruction of the shape of spherical and aspheric surfaces.

8788-90, Session PS

Optical resolution measurement system for small lens by using slanted-slit method
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For the optical resolution measurement, the Modulation Transfer Function (MTF) is widely applied. In this paper, we will present the research result of our developed optical resolution measurement system with slanted slit method for small lens. The MTF is built up by the Fourier's transformation of the Line-Spread Function (LSF) that is acquired by analyzing the projected dark-bright image of the measured lens. In order to obtain a smooth LSF, we propose a slanted slit method. And the slanted slit lets a part of the collimated light transmit through the measured lens, and a dark-bright slit-image is projected on a CCD-camera. For a proper choice of the region of interest (ROI), a smooth LSF with dense sampled data can be formed by arranging pixels according to their distances to the slanted slit. And these sampled data of the LSF can effectively eliminate the aliasing effect through the digital processing and furthermore can accurately derive the MTF. The influences of the angle of the slanted slit and the ROI-choice on the performance of the proposed optical resolution measurement system are thoroughly studied. The accuracy of the developed processing algorithm is experimentally verified by using the statistic factors GR&R and STD-error. Based on a calibrated lens, our developed processing system and algorithm can achieve the industrial level with GR&R of 27% and STD-error of 8%.

8788-91, Session PS

A compensation method of large aperture optical lens for gravity deformation
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Now the design and manufacture of large aperture optical lenses are increasing emphasis on the influence of the gravity deformation of optical system. A compensation method of large aperture optical lens for gravity deformation is presented in this paper. The method analyses in advance and predicts the gravity deformation to compensate it in the processing stage. Taking the difficulties of machining into consideration, the spherical compensation mode is adopted and the compensation accuracy is given. The wave aberration caused by gravity deformation between surface before and after the compensation are compared and it proves that this method can effectively reduce the influence of gravity deformation though advance compensation.

8788-111, Session PS

Design and experiment of testing an off-axis aspheric surface by computer generated hologram
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To test an off-axis aspheric surface in high precision, a multiple combined computer generated hologram (CGH) is designed and fabrication. Multiple combined CGH which is a hologram including different areas with different purposes can not only measure off-axis aspheric surface, but also align every element in test system. The design methods of test CGH and alignment CGH were deduced in detail. Ray trace and B-spline were used to devise test CGH, reflection CGH was used to align interferometer and CGH, and hologram alignment mark was used to align CGH and off-axis aspheric surface. A design example was given to test an off-axis paraboloid with 50mm aperture and 35mm off-axis distance. Meanwhile, this CGH was fabricated and this paraboloid was measured by it. The test result (PV=0.304 RMS=0.050 ) is matched well with the outcome verified by autocollimation (PV=0.343 RMS=0.051 ). At last, we analyze and solve the noise in the CGH test result. It proves that these designs are correct and this method can test off-axis aspheric surface in high precision.

8788-119, Session PS

Efficient testing methodologies for microcameras in a gigapixel imaging system
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Multiscale parallel imaging with a wide field of view (FOV)–based on a monocentric optical design–may potentially change our visual perception in diverse applications, including sport broadcast, wide-field microscopy, astronomical studies, and security surveillance. Recently demonstrated AWARE-2 is a gigapixel camera consisting of an objective lens and 98 microcameras spherically arranged to capture sub-images of an entire scene from 120°-by-50° FOV, thereby expanding the capabilities of current imaging systems.
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and computational image processing forms a final composite image of 0.96 gigapixels. As each microcamera adjusts exposure, gain, and focus, a true parallel imaging with a high dynamic range is obtained. In the optical design of AWARE cameras, spherical aberration due to the objective lens is avoided by being corrected by micro-optics (optics in microcameras), achieving imaging performance near the diffraction limit. Therefore, a key to successful imaging performance of AWARE cameras is to ensure consistent manufacturing quality of micro-optics. In order to meet this objective, the next generation AWARE-10 cameras designed to capture 5 gigapixel images, we have developed two methodologies: an objective lens simulator and two-dimensional analysis using a dot grid chart.

The objective lens simulator is auxiliary optics equivalent to the actual objective lens used in AWARE-10 cameras, emulating the same aberration but requiring a test chart distance as short as 46 cm. (The AWARE-10 objective lens projects 30 m in infinite object distance.) The simulator is designed by tracing rays forward through the simulator and backward through the AWARE-10 objective lens, following the basic optical principle that the ideal simulator should make the output from the objective lens a plane wave, since the objective lens of the AWARE-10 cameras projects an infinite conjugate. Replacing the objective lens in the micro-optic testing, the objective lens simulator enables imaging testing procedures in the confined lab environment without requiring a long object distance. Furthermore, the objective lens simulator—designed with auxiliary lenses—enables testing not only the on-axis of micro-optics but also the off-axis imaging performance. By analyzing sagittal and tangential modulation transfer function on the off axis at and/or through the focus with slanted edges, micro-optic testers can gain an in-depth knowledge of aberrations and assess the optics. The simulation provides an on-the-shelf solution for those who are easily constructed without involving any custom lenses.

The next methodology which we have developed utilizes a precisely fabricated dot grid chart as in a single experimental setup and two-dimensionally extracts critical optical properties such as veiling glare index, distortion, magnification, and modulation transfer function over the entire field corresponding to a microcamera. Optical characterizations of different properties often require different experimental apparatus; for instance, modulation transfer function by slanted edge, bar target at various spatial frequencies, or laser speckle, veiling glare index with a light trap and an integrating sphere, distortion by a pattern of straight lines or dots in grid. Therefore, reduction of complication in the measurements should offer immediate convenience for the performance validation process. Our proposed metrology requires one experimental apparatus and only two images obtained, one with and the other without a dot grid chart. To compute veiling glare index that quantifies stray light into micro-optics, the image without the dot grid is divided by that with the dot grid, pixel by pixel. This method detects the darkness inside each dot and maps the veiling glare index over the image plane. Because the dots used in this method are fabricated to precisely known dimensions of diameter and spacing, we measure the optical distortion and magnification. Analyzing the edges of each dot, the modulation transfer function is calculated.

In this presentation, we comprehensively describe the principles of these methodologies and discuss the experimental measurements with our AWARE micro-optics. We believe that such procedures will facilitate quality control and speed up the manufacturing process of AWARE systems.

8788-74, Session PS

CO2 laser photoacoustic spectrometry: sensitivity and drift analysis

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Photoacoustic spectrometry (PAS) offers high sensitivity and broad dynamic range, permitting monitoring of concentrations from trace values to the saturation level. PAS has been used as an in situ method for observation of actual concentrations combined with high spatial and time resolution. PAS is based on the photoacoustic effect and in conjunction with lasers has already been used in monitoring of industrial trace gas components at ppb concentrations. It has been proven that the characteristic of laser frequency/wavelength stability is crucially important for evaluation of micro-optics performance when the function principle is based on photoacoustic spectrometry. In particular, the long-term stability range, corresponding to noise in the hundreds of hertz to kilohertz bandwidth, strongly affects the measurement final accuracy of the reported measurement rates. The reported trace gas measurements performed by the eddy correlation technique and we determined the time domain stability criterion for laminar and turbulent flows measured in the street canyon model. The preliminary evaluation of the instrument performance was performed by in situ measurement of O3 and CH4 light pollutant concentrations. Further, the instrument has been adapted to in situ measurements of C2H5OCH3 trace gas concentrations. We have determined optimal averaging times for C2H5OCH3 measured by CO2 laser PAS at static operation connected to wind tunnel. The Allan and Hadamard variance methods were used for detection analysis. The CO2 laser operated at room temperature, approx. at 25 °C. The average output power was in the range of 1-10 mW. The used PAS was connected with the low-speed wind tunnel (cross section 150 cm x 150 cm) for the measurement. The low-speed wind tunnel enabled the simulation of pollution by wind thanks to a taking place wind pattern. The street canyon model was used for measuring of turbulent and laminar flows with street orientation axis perpendicular to the direction of the reference flow over the canyon walls. Street canyon model used approx. 60 cm wide, with walls of houses about 15 cm high. Line-source pollution was placed at the bottom of the street at 16 houses in the street. The line-source pollution has been created using a set of silicone hoses sealed at both ends by steel balls and filled with 98.8% ethanol. Leakage of ethanol through the walls of tubing at a constant temperature created a defined generation of gaseous pollution inside the canyon. Individual permeating tubes allowed generating ethanol concentration high enough for spectroscopic detection. Continuous monitoring of the atmosphere inside the canyon was provided by a photoacoustic gas analyzer. A discreetly tunable 12CO2-laser with internal modulation was used as a source of radiation. The laser was emitted in the spectral range 10-11 m on the 9P22 laser emission line, which was used for both calibration apparatus and for the analysis. Measurements were checked by using a spectrum analyzer. Optimal laser modulation frequency of approximation f = 1.2 kHz was found experimentally. At this frequency, the value of detected photoacoustic signal that was generated using the same calibration standard, was the highest. The laser radiation, after passing photoacoustic cell, was aimed at a pyroelectric detector active area, and its intensity was thus controlled. The cylindrical photoacoustic cell (inner diameter 8 mm length 380 mm) was made of stainless steel with a diameter and a thickness of approx. 30 °C. Acoustic wave was detected by the absorption cell using an electret microphone placed in the middle of the full length of the absorption cell. Measured modulated signal was demodulated by lock-in nanovoltmeter. The measured concentration of the ethanol was generated by the permeable ethylene permeation method. A sample ethylene permeation method. A sample ethylene permeation tube was filled with light pollutant; company: Sigma Aldrich; purity: 99.8% was used as a permeation standard. Flow of the buffer gas through the chamber were regulated at different flow rates (0.8 – not presented, 1 and 1.2 m/s), and were pumped into the photoacoustic cell together with the measured sample. From the cell it was directed into the pump through a flow rate regulator. Dependence of both values of Allan and Hadamard variances on different degrees of flow turbulence was evaluated for the sample pollutant ethanol. The approach used in the study of the influence of turbulence on the optimal averaging time for minimum detectable concentrations has been described. Several measurement series were made to determine the optimum modulation amplitude and frequency. The stability test of experimental set-up made with the CO2 laser at different sample concentration and flows. The data were collected over period of 1000 2000 s. This data was analyzed by the Allan variance method. Results of these analyses show a dependence, indicating a white noise behavior. The detection limit could, therefore, be slightly improved with a longer integration time. During the 1000 to 2000 s period of the Allan and Hadamard variance measurement the emission wave-length of the CO2 laser was stable. The contribution will detail the laser performance of the used PAS including sensitivity and stability analysis by Allan and Hadamard variance measurements. We have analyzed different combinations of mass flows. This concept has been used to characterize accuracy of spectroscopic data in the time domain. We have then applied this analysis to different values of Allan and Hadamard variances.
Development of program package for investigation and modeling of carbon nanostructures in diamond like carbon films with the help of Raman scattering and infrared absorption spectra line resolving

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In recent period the interests to the nanostructures have been growing which is related to their unique physical properties. Especially carbon nanostructures can possess wide range optical, electrical and mechanical properties. They can be electrically insulating or conductive, optically transparent or opaque, mechanically hard or soft. Some typical examples of nanostructures which have great interest are quantum dots, quantum wires, quantum wells, nanotubes, nanowires, fullerenes etc. Each of the aforementioned structures has various types of modifications. For instance, quantum dots can be spherical, pyramidal, cylindrical, ellipsoidal, lens – shaped etc., but nanotubes can be multiwall, single wall and etc. All the above mentioned structures are obtained experimentally and can be observed by different experimental equipments. Carbon nanotubes are stretched cylindrical structures from a few nanometers to a few centimeters of length. They consist of a one or few convoluted to the tube hexagonal graphite planes and usually they finish with the half spherical head. Nanotubes are mainly classified according to the convolution of graphic planes. The way of convolution is determined with the help of two numbers n and m which determine the resolving of the convolution direction to the translation vector of graphic net. According to the n and m parameters nanotubes are classified to the “straight”, “armchair”, “zigzag” and spring types. In reality nanotubes often are obtained as multilayer systems which can be represented as a few single layer nanotubes, which are incorporated to each other (Russian dolls).

Because of the variety of nanostructures some serious methods are needed for investigation which are being developed and modified discontinuously. The prospective and powerful methods of nanostructures’ investigation are the data extraction from their Raman Spectra and Fourier Transform Infrared Spectroscopy (FTIR) which allow to determine types of chemical bonds and their ratios which are present in Diamond Like Carbon (DLC) films. G (1581 sm-1) and D (1355 sm-1) lines are known in Raman spectra for appropriately ordered and disordered carbon structures. Some compounds can lead to the shift of D line in spectra. The ratio of the integral intensities of G and D lines (IG/ID) in graphitic grain structures linearly increases with the grain size decrement. In this way IG/ID ratio can be used in estimation the linear sizes of clusters or crystals which will be used in our models. With the analogy of graphitic lines in DLC films D and G lines are also observed. Compared with the ordered graphite the above mentioned lines of DLC films’ lines are wider which is related to the complicated structure of the films. Different types of clusters with different quantities are present in the in the structure of DLC films. Big quantities of these clusters are in the deformation a state which also leads to the widening of the two lines. Different types of nanotubes and fullerenes can also be present in the structure of DLC films depending on the obtaining technology. All these facts are making the analysis of spectra complicated for the technologists, experimentators and engineers. The developed program takes into account all the configurations of the above represented structures and contribution of each component is determined.

The database is created in which characteristic lines for carbon based components of investigating material present. Hence many varieties of probable versions for components in nanostructures are considered and their Raman and FTIR spectra characteristic lines are imported in database. Algorithm is made in the way that the spectra data from any type of Raman and FTIR spectrometers is imported automatically without the human help. After the data import, a line and component distribution is done all over the spectra. Obtained results are compared with the database and knowledgebase with the help of which further analysis are realized. As well as the components’ names, their appropriate vibration and absorption wavelengths with their presence probabilities are represented in the user interface in the form of chart and simultaneously the names of components also appear in the imported graphics to make the process more visual. The determination of vibration and absorption integral intensities with the help of determined lines is done which has a huge importance in investigating the spectra of carbon nanostructures. The nanocluster sizes are estimated. The determination of nanocluster concentration with the help of intensity relations is made as well.

Laser welding control by monitoring of plasma

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Laser as a source of intensive monochromatic light beam is implemented to industrial welding systems due to its advantages in comparison with classic methods, for example high processing speed, narrow heat affected zone, deep penetration, non-contact process, full automation and reproducibility, precise control of the energy input by spot diameter settings, flexibility and many others. On the other hand, high processing speed causes too high cooling velocity and tendency to micro-cracks can occurred, narrow laser spot requires very strict tolerances to weld joint arrangement and precise coincidence of the spot centre with gap between welded parts.

Keyhole mode welding is a typical industrial application of high power continuous lasers or high energy pulsed lasers. During the deep penetration laser welding plasma can be generated above the keyhole. In gases such as argon, oxygen, helium and their special mixtures are used for plasma reduction. On the other hand, thanks to the plasma plume presence, welding process can be controlled on-line by means of plasma intensity measurement.

Optical laser processing parameters are usually recorded in laser beam according to sort and thickness of material, optimal focus length is chosen and focus plane is correctly positioned in reference to material surface, but some defects could be caused by laser power decreasing due to active medium ageing, contamination on optics, impurities in gas nozzle, de-alignment of optic elements. Also material can contain surface impurities, internal micro pores or mechanical micro defects, weld arrangement can be out of tolerances or improperly fixed. Finally, shielding gas flow can be too high or too low, have bad composition or direction. Various on-line monitoring methods have been developed (optical sensing, acoustic emissions, spectral analysis of plasma, etc.) in research centers all over the world and are reported in science literature. Goal of them is to enable promptly operator action to avoid enormous economical losses if un-expected defect is detected, such as lack of penetration, seam oxidation, pores, cracks, shift of weld line, etc.

Our laboratory has been participated in project CLET - Closed Loop Control of the Laser Welding Process through the Measurement of Plasma as responsible partner for developed system testing both in the laboratory with pulsed Nd:YAG laser and in the real welding facility with high power continual CO2 laser.

Control system is based on the electron temperature computation from the relative intensities of couple of emission lines belong to certain metal ion present in plasma plume. Electronic temperature dependence on laser power was experimentally verified and closed loop control system is developed now by project partners to ensure optimal depth of penetration by means of optimal power setting according actually measured electron temperature.

Our experiment was realized within the longitudinal welding of a tube using AISI 304 stainless steel sheet with thickness 1.3 mm and width 33.35 mm rolled to the outer diameter 12 mm. Measuring line was placed in the facility Vatrans Zlin, Czech republic. Ocean Optics HR2000+ spectrometer with fiber optic connector and collimating lens fixed in optimal position with regard to welding point are used. Spectrometer was connected to a notebook via USB connection offering high-speed communication as well as power.

At first, several couples of emission lines were tested to acquire a good signal at actual welding conditions in facility. Then power calibration was made within the interval 1950 W to 4000 W with step about 300 W to obtain electron temperature dependence on increasing power. Samples were prepared for microanalysis to measure depth
of penetration, weld area dimension and quality dependence on laser power by laser confocal microscope. From measured values implied that in region between 80 % and 100 % optimal power full penetrations are achieved, differences only in re-melted area dimension due to increasing heat input were found. Welding above 100 % optimal power is not recommended avoiding thermal distortion of the tube.

Numerical model of the re-melted area cross section was made to display temperature distribution dependence on increasing power. Red area represents temperature higher or equal to 1700 K, the orange one represent heat affected zone to 1020 K. Full penetration is achieved from 80 % Popt, above 100 % Popt dimensions of melted area increased and risk of weld humping or deformation threatens.

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8788-112, Session PS

Spectral monitoring of toluene and ethanol in gasoline blends using Fourier-Transform Raman spectroscopy

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The combination of fossil-derived fuels with ethanol and methanol has acquired relevance and attention in several countries in recent years. This trend is strongly affected by market prices, constant geopolitical events, new sustainability policies, new laws and regulations, etc. Beside bio-fuels, these materials also include different additives as anti-shock agents and as octane enhancer. Some of the chemical compounds in these additives may have harmful properties for both environment and public health (besides the inherent properties, like volatility).

We present detailed Raman spectral information from toluene and ethanol contained in samples of E10 gasoline-ethanol blends. The spectral information has been extracted by using a robust, high resolution Fourier-Transform Raman spectrometer (FT-Raman) prototype. This spectral information has been also compared with Raman spectra from pure additives and with standard Raman lines in order to validate its accuracy in frequency.

The spectral information is presented in the range of 0 cm⁻¹ to 3500 cm⁻¹ with a resolution of 1.66 cm⁻¹. This allows resolving tight adjacent Raman lines like the ones observed around 1000 cm⁻¹ and 1030 cm⁻¹ in toluene.

The Raman spectra obtained shows a reduced frequency deviation when compared to standard Raman spectra from different calibration materials.

The FT-Raman spectrometer prototype used for the analysis consists basically of a Michelson interferometer and a self-designed photon counter cooled down on a Peltier element arrangement. The light coupling is achieved with conventional 62.5/125 m multimode fibers. This FT-Raman setup is able to extract high resolution and frequency precise Raman spectra from the additives in the fuels analyzed. The proposed prototype has no additional complex hardware components or costly software modules. The mechanical and thermal disturbances affecting the FT-Raman system are mathematically compensated by accurately extracting the optical path information of the Michelson interferometer. This is accomplished by generating an additional interference pattern with a = 632.8 nm Helium-Neon laser (HeNe laser). It enables the FT-Raman system to perform reliable and clean spectral measurements from the materials under observation.

8788-113, Session PS

Reflection, transmission and color measurement system for the online quality control of float glass coating process

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Over the past century there has been a dramatic increase in the demand for float glass in many fields of industry. In order to satisfy this trend, many new glass factories have been built. Today, most of the float glass factories have a melting furnace with a production output of 150-180 tons of the float glass per day. Usually, 10 to 30 % of produced float glass is coated with various coatings for different purposes. Solar energy panels, LCD displays, energy saving architectural glass require very sensitive and precise quality control procedures. This is why quality control of the coatings is one of the most current issues during the process of float glass manufacturing.

Generally, the width of the produced float glass is in the range of 3.5-5 m and the average speed of the production is a few meters per minute. Traditionally, in order to control the quality of the produced glass, an operator cuts pieces of glass with dimensions of about 20-30 cm in width and the measure of the ribbon in length. Reflectance and color coordinates of each 10 cm of the piece are measured by means of a handheld spectrophotometer. If there is a large deviation, the sample glass sheet is cut into 10 or more smaller equal pieces and examined in laboratory for detailed analysis. This process is repeated every hour.

In this way, if there is a large deviation in the parameters of the coatings, establishing the reason and troubleshooting take a relatively long time, which results in a significant loss of productivity. At the same time, when the coating color is changed to a new one, the process of matching, in which the new color has to fully correspond to the required color parameters, takes a very long time.

In this work we describe a system designed for the online control of reflectivity, transmittance and color coordinates of the coatings during the glass production process. In addition to being fully automated and more flexible when used in the process of changing the color of coatings, the system allows for very fast reaction to any coating nonuniformity.

The working principle of the system is based on the measurement of the spectral characteristics of reflectivity and transmittance of the coatings within the 400-700 nm spectrophotometer spectral range during the online coating process.

The measurement unit consists of two microspectrometers (one for the measurements of the spectral characteristics of the reference source, and the other for the measurements of the reflectance spectrum), illumination head (consisting of one white 1W LED and collimating lenses), stabilized power supply, microprocessor and 18 bits precision ADC. The use of the reference channel allows us to stabilize the intensity of the incident light up to 10⁻⁴ level. The accuracy of the measurement of reflectivity coefficient in laboratory conditions was in range of ±0.001. However, in the measurements in the factory environment, due to the vibration of the glass ribbon on the conveyor, the measurement error was about ±0.005.

The system performs measurements with frequencies of 20-30 Hz. So, there is a sufficient amount of data for averaging and thus compensating of the errors originated from the vibration of the glass ribbon. Generally, in most production processes, the allowable limits of the deviations of the reflectivity, transmittance and color parameters are within ±3 % of the nominal value, which is higher than the capability of the system in a real factory environment. Consequently, the system allows for an immediately reaction to any deviation of the parameters of the coating process from the nominal values and sends a warning to the operator.

The number of measuring units depends on the width of the glass ribbon. We assessed that one measuring unit per each 25-30 cm width of the glass strip is sufficient to satisfy the required reflectance and color measurement demands. Therefore, in order to control the useful width of 360 cm of the glass strip, we have utilized 13 measuring units along the conveyor width.

While generally the non-uniform areas of the coatings can be expanded in large areas, for the measurement of the transmittance a few number of measurement units are sufficient. At the same time, in this unit for the measurement of the transmittance we have used only one spectrophotometer, i.e. performed single channel measurement. This is because for the transmittance unit reference channel, we can use correction data from the reference channel of the reflectance
Automated hardware and software complex for extended light sources verification

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Of late years developments in lighting technologies occupy a leading position in the innovation sphere. Newest lighting systems, for example LED-based systems, are developed and are demanded not only because of low power consumption and long service life that distinguishes them from other light sources. Multicomponent light sources are of great interest in connection with ample opportunities existence to create specialized lighting devices (with the required spectrum, light intensity, radiation pattern, color etc.), controlled light sources too. However, the development of such device is impossible without careful verification of parameters and characteristics both lighting device all in all and emitting elements used for its creation.

There are many different systems and devices for research and certification parameters of varied light sources. But none of them does not allow realizing the simultaneous analysis of the spatial illumination distribution and spectral and color illumination characteristics in the three-dimensional space, as well as the power settings of extended light sources. This paper deals with automated hardware and software system for the simultaneous determination of the spectral characteristics and color parameters of lighting from extended light source (both single- and multicomponent) in three-dimensional space, as well as its illumination uniformity for certain parameters of power supply. In addition the paper describes experimental researches results of varied light sources types with different shape, order of the emitting elements location, spectrums and the energy characteristics of the illumination.

The experimental dependences were being compared with theoretical models that describe both the uniformity of illumination distribution from tested light source and its spectral (color) characteristics in the area of analysis for certain parameters of power supply. Mentioned models take into account the basic laws of the formation of luminous flux for different types of extended light sources.

Results of our work can be used in the development and quality control:
- in the radiation sources manufacture;
- of multicomponent light sources (linear, circular, etc) for optical-electronic systems of high accuracy;
- of adaptive light sources (changing spectral and color light characteristics) used for color analysis of different objects and effects.

This paper is a continuation of works associated with the creation of specialized illumination devices for optical-electronic systems, devices and systems of industrial control, as well as the relevant automated devices for measurement and control of parameters and characteristics of the lighting sources various types.

Three-axis optic-electronic autocollimation system for the inspection of large-scale objects

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The inspection of large-scale objects in industry, science and power engineering calls for the determination of angular and linear displacements of respective loaded elements: engine seating, bridge spans, dam pylons, dock walls, reservoirs, radiotelescope axles. For estimation the state of such objects the high-precision measurements of angular tilts and deformation with an error within one arc second in a
range to several tens of arc minutes are necessary. Optic-electronic autocollimators for non-contact measurements are used effectively. The autocollimation system comprises the autocollimator on a rigid base and the optical reflector on the inspected object.

Deformations of the object are determined by three angular dimensions simultaneously. They are pitch, yaw and roll angle. The ordinary autocollimator uses the plane mirror as reflector. This autocollimation mean measures only two classical tilt angles: yaw and pitch for rather small range.

The second disadvantage of the ordinary autocollimator with plane mirror as reflector is the relatively short work distance between base and inspected object. The reason is the shift of the reflected beam in the plane of the entrance pupil of the receiver objective after mirror rotation. As result at the same distance the reflected beam does not ingress into the objective and working distance is less than 4...5 meters, which is insufficient in many practical cases.

The autocollimator for three dimensions measuring the yaw, pitch and roll angle deformations is researched. The structure shape of optical reflector for three dimensions measuring is the glass prism tetrahedron with non-planar facets. Two reflecting facets are the plane and third facet is the cylinder fragment.

The collimated beam reflects from three facets of the optical reflector and returns to the objective of autocollimator. The tetrahedron reflector with the cylinder fragment transforms the collimated beam into the beam with ribbon structure.

As result the reflected beam forms the image as two intersecting line segments into the matrix photo receiver at focal plane of the autocollimator objective.

After inspected object deformations parameters of image are changed. The size of horizontal segment varies in proportion to pitch angle, the full image rotates relatively to the centre as the roll angle and the angle between the horizontal and vertical segments varies directly as the yaw angle.

These parameters of the image are calculated after processing of image and the pitch, yaw and roll rotations of the object are determined.

As addition the ribbon reflected beam allows setting the autocollimator on a rigid base and reflector on inspected object.

The great attention during the research is paid to the experimental approval of the theoretical results. The experimental setup of the autocollimator is designed.

The main parameters are: infrared emission diode by power 15 mWt as sources of radiation; the objective by focal length 260 mm as aperture of receiver video-camera, the CMOS matrix receiver by type OV05620 Color CMOS QSGXGA with 2592*1944 pixels and one pixel size (2.2*2.2) micrometers produced Omni Vision as image analyzer. The experimental measuring error of the yaw and pitch angle is 1 arc seconds at the angular region 30 arc minutes and the measuring error of the roll angle is 5 arc seconds at the angular region 5 degree.

8788-93, Session PS

Optical measurement system applied to continuous displacement monitoring of long-span suspension bridges

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This paper focuses on the design and development of an optical measurement system applied to continuous displacement monitoring of long-span suspension bridges. In this type of large-scale engineering structures, the knowledge of the tridimensional amplitude of the displacement – namely in the main span of the stiffness girder – is a key element for structural analysis and safety conformity assessment (supported on the bridge design requirements and historical behavior records). Therefore, actual displacement measurement has a relevant impact on the safe mobility of persons and goods, requiring a high level of confidence which can only be operationally achieved by traceable and accurate dimensional measurements.

In recent years, several solutions – global navigation satellite systems and microwave interferometric systems – have been proposed to monitor long-span suspension bridges. However, such measurement systems are still partially limited in terms of measurement accuracy, since most of the long-span suspension bridges are composed of metallic elements that create multi-path effects (i.e., non-desired multiple signal reflections in the structure), strongly affecting the displacement range which can reach up to one meter amplitude, specially, in the vertical direction.

The authors propose and design an optical measurement system to accurately determine tridimensional displacement in the main span of a suspension bridge, based on off-the-shelf digital cameras with CCD sensors and long-focal-length lenses, computer image processing and active targets composed by LEDs. This approach combines the main advantages of the above mentioned systems – day/night operation, low cost and simplicity.
non-contact and long distance measurement, real-time monitoring and high measurement range – and is not affected by multi-path effect. The main limitations may be associated to atmospheric phenomena due to heavy fog or rain in the optical propagation path, turbulence effects or refraction index variation in the vertical direction.

This paper describes the optical measurement system in terms of architecture and main elements, geometrical and radiometric characteristics of the digital cameras and active targets for the following set of operational specifications: observation distance close to 500 meters, dynamic measurement range up to one meter in amplitude and frequency below one hertz, instrumental measurement uncertainty of ten millimeters and resolution of one millimeter.

In its minimum configuration, the proposed optical measurement system comprises one digital camera (600 mm focal-length lens, 7.4 m pixel size and 1920 x 1080 pixels) installed beneath the main span main span of the stiffness girder and four active targets in one of the tower’s foundation. The photogrammetric approach is based on the pinhole camera model, corrected by lens distortion (after intrinsic parameterization). Since the relative positions of the four active targets are known (by previous metrological characterization) and precautions are taken to eliminate significant induced dynamic behavior – mainly by wind exposure in the generator’s foundation – the active light set allows materializing a “world” coordinate system aligned with the bridge longitudinal, transversal and vertical directions. The approach assumes a rigid connection between the observation camera and the bridge structure so that the flexible bridge’s dynamic characteristics are decoupled from the response of the bridge displacement, therefore, special attention must be given to the camera/bridge mechanical coupling in order to avoid high frequency vibrations induced by wind or transmitted through the local connection of the bridge structure to the camera support.

The metrological characterization of the optical measurement system is a two steps process. The first step concerns the camera’s laboratory intrinsic parameterization, which determines both the estimates and corresponding measurement uncertainties for the focal length, principal point coordinates and distortion parameters quantities. The second step refers to the in situ metrological calibration process, whereby a 3D measurement reference framework is used in order to establish a comparison between the dynamic displacement estimate, given by the optical measurement system, and the reference values in specified monitoring conditions. The proposed calibration method should ensure that the observation camera is rigidly placed on the bridge anchorage and that the four targets set on the closest tower’s foundation. The four targets set is rigidly connected to the measurement reference standard prototype, which consists of an electrical linear actuator (previously subjected to metrological characterization) that applies a linear displacement to the targets in desired directions.

Since the optical measurement system is intended to be used for continuous structural monitoring, this paper also addresses the environmental conditions and their contributions to the measurement uncertainty. The influence of atmospheric phenomena such as refraction and turbulence are analyzed and experimental research activity developed in this context is mentioned. In addition, the relationship between the camera’s exposure time and short (night and day effect) and long term (weather season) influence on target’s image quality is also considered and analyzed.

Throughout this study, the main sources of uncertainty related to the measurement instrument and method are identified, quantified and accounted in the displacement measurement uncertainty budget in order to determine the accuracy of the proposed optical measurement applied to long span suspension bridge monitoring. Analytical and functional approaches, such as the least-squares method, the uncertainty propagation law and the Monte Carlo method are used for the measurement uncertainty propagation, from input quantities to the tridimensional displacement output quantity.

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Research of auto-collimating angular deformation measurement system for large-size objects control

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Autocollimating systems are widely used for determination of angular position of large-size objects relative to the base, for example, correction of non-homological primary mirror deformation of a radio telescope. Adjustment of the mirror shape to the theoretical parabolic surface is possible only through measurement of deviation of a normal to reflector surface from its nominal position in points under control. This challenge implies the problem of measuring the relative position between two objects. One of two objects is taken as the base object (its position is fixed), while the other (the object under control) can move relative to first one. The measurement system includes an optical-electronic autocollimator mounted on the base object, and an optical system attached to the object whose angular position is under control.

Such an optical-electronic system enables to control the object’s position relative to two axes normal to the optical axis of the autocollimator (pitch axe and yaw axe – another term is «collimation» axes) and relative to the optical axis of autocollimator itself (roll axe), i.e. an angle position of the object can be measured relative to tree orthogonal axes.

For this purpose we chose a tree-axis autocollimator with increased roll...
angle measurement sensitivity. A tetrahedral reflector, which has the deviation from 90° in two dihedral angles between reflecting sides, is chosen as a control element in this autocollimator. The incident optical beam going along the axis of the autocollimator is divided into two parts of beams by the control element. One of these parts can be used for roll angle measurement. Both of the beams in the pair for roll angle measurement have an angle with the autocollimator objective axis, which is equal to transmission coefficient between angle of rotation of the control element at the roll angle and deviation of the reflected beam from its initial direction. This angle determines the sensitivity of roll angle measurements. Increasing of sensitivity of the angle for a standard autocollimator with a small field angle is provided with reflection from a flat mirror. Thus beam reflected from the tetrahedral reflector passes through the receiving objective and having reflected from the mirror comes back to the tetrahedral reflector. After second reflection from tetrahedral reflector the image of the mark is formed in the focal plane of the autocollimator objective. Pitch and yaw angles are measured with a part of the beam reflected from the front side of the tetrahedral reflector as if it reflected from autocollimator mirror. If the object coupled with the tetrahedral reflector rotates at small angles 1, 2, 3 relate to axes OX, OY, OZ, the image of the mark shifts at a value proportional to the rotation angle.

In the implementation of the autocollimator the mirror offset was about 100 mm, so that the value of the angle is determined as about 0.1 Rad. The sensitivity of roll angle measurement was about 2 ± 0.2 Rad, then significantly exceed sensitivity of roll angle measurement in scheme without re-reflected beam. At the laboratory of the Dept. of Optical-Electronic Devices and Systems, Saint-Petersburg National Research University of Information Technologies, Mechanics and Optics a prototype of an angle deformation control system for large-size objects based on free-axis autocollimator scheme was fabricated. The prototype of the measurement system consists of an autocollimator, a tetrahedral reflector mounted on a rotation stage (it provides rotation angles 1, 2 between the collimation axis OX, OY and roll angle 3 at the axis OZ), a personal computer, power supply for a radiation source of the autocollimator (a laser diode), ammeter, an optical bench, a visual autocollimator with a flat mirror for rotation stage angle position control, power supply for a radiation source of the visual autocollimator.

Static characteristics linearity of the autocollimating system was proved in the experimental investigation. The RMS was 20° while measuring a roll angle within the range of measured angles ±25°, and 3° while measuring a pitch and yaw angles within the range of measured angles ±1°. Metrological characteristics we got from the experiment correspond with qualifying standards for angle deformation measurement systems for large-size objects and particularity for modern radiometric sensors.

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Iterative improvements to the surface error of a 1.7 metre aluminium reflector

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The Large Millimeter Telescope (LMT) is a 50-metre (currently 32-m) diameter single-dish telescope optimized for astronomical observations at millimeter wavelengths (0.85 mm < λ < 4 mm). The telescope is located on the summit (at an altitude of 4,600 m or 15,000 ft) of the dormant volcano Sierra Negra, situated within the Pico de Orizaba National Park in the Mexican state of Puebla, where the median wind-speed is 5 m/s, and the median temperature is around 0°C with a diurnal variation of about 5°C. During initial observing runs, the LMT makes use of a 2.5 metre hyperbolobic secondary reflector constructed of cast and machined aluminium. The current observing instruments are illuminated by the central 1.7 metres of this mirror. Following the first light campaign in 2011 a program of improvements to the reflector surface has been carried out with the aim of reducing the surface RMS error of the inner 1.7m to within limits for acceptable image quality during the next observing season, in line with major improvements to the primary reflector surface.

Throughout all stages of the process, the mirror surface was measured using a laser tracker, with initial maps taken by scanning the tracker target over the surface at high spatial resolution. Hence the overall RMS of the full surface was in excess of 200 microns, the central area of interest was in excess of 60 microns. The final goal of the program was...
to achieve 40 microns or better in this central area. Initial surface maps showed a major low area on the mirror surface covering many tens of square centimeters, plus several smaller high spots. It was decided to remove as many of the positive areas as possible by sanding down the surface high spots, since elimination of the depressions would require excessive removal of material. Sanding was carried out by hand using 6 inch discs on an orbital sander. Frequent pauses were made to take repeat surface measurements with the tracker. As the work progressed, additional maps were taken at progressively higher resolution, to check for convergence of the calculated rms errors. Maps for the final iterations were repeated for distinct scan patterns to check for systematic variance.

A total of 22 grinding iterations were interspersed with tracker measurements at differing spatial resolutions, allowing the RMS surface error to be reduced from 63 to 35 microns. Sanding periods lasted from 15 seconds to 4 minutes at each sanding spot, while tracker measurements took approximately 15-20 minutes to acquire from 600 data points (low spatial frequency) to 6800 points at high resolution.

Since the aluminum mirror is mounted to the telescope support structure at 6 points, an important part of the metrology procedure is to verify surface error repeatability following the mounting and dismounting of the mirror. Before starting the program to sand the mirror surface, mounting tests were carried out using shims beneath individual mount points to investigate the possibility of making improvements to the RMS surface error using controlled distortions of the mirror body.

In this paper we present details of the surface improvement program with emphasis on the assurance of metrology integrity throughout the process. We discuss data fitting to the desired hyperbolic shape, data sampling strategies, methods for identifying sanding zones, and tracker performance outside of operating environment specifications.

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Camera-based curvature measurement of a large incandescent object
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In steel industry incandescent objects can be found in hot strip rolling processes, for example. In hot strip rolling the transfer bar has a tendency to curve during reversible roughing. The curvature is called camber and it can be caused by uneven slab temperature, unsymmetrical slab dimensions or unsuitable rolling parameters, for example. High camber value complicates hot strip rolling causing poor quality or even cobble sets off by the transfer bar colliding with the entry guides of the finishing train. These issues cause inescapable economic losses due to increased amounts of rejection and downtime.

During the rolling process, the roller operator needs to know the amount of strip camber in order to adjust the roll gap with the intention of straightening the transfer bar. The goal of this work was to implement a low-cost machine vision system to help the operator to estimate the amount of strip camber during the rolling process. The machine vision system composing of a single camera, a standard PC-computer (Intel Core i5 processor, 4 GB of RAM) and a LabVIEW written program determines the magnitude and direction of camber and presents the results both in numerical and graphical form on the computer screen. The roller operator can use either the displayed camera values or the live video feed from the previous pass (or both of these) to decide the next roll gap adjustments.

The imaging components of the measurement system are selected according to the industrial environment and to the accuracy requirement (camera: GigE, 5 MP, 15 fps, 2/3” image sensor, high shock and vibration resistance; lens: 10 MP, 2/3”, 25 mm, f/1.8; filter: hot mirror 700 nm). The lens aperture is set close to minimum size and the camera’s exposure time to 10 ms. The camera is placed in the rougher’s exit side above coil box looking into the roll bite so that the whole 55 meters long rolling table is covered with the single camera field-of-view. The system is calibrated by using eight (8) pairs of LED light sources, which are manually positioned on the rolling table forming two straight lines and having known lateral distance to the LED light sources, which are manually positioned on the rolling camera field-of-view. The system is calibrated by using eight (8) pairs that the whole 55 meters long rolling table is covered with the single hot mirror 700 nm). The lens aperture is set close to minimum size and presents the results both in numerical and graphical form on the computer screen. The roller operator can use either the displayed camera values or the live video feed from the previous pass (or both of these) to decide the next roll gap adjustments.
uncertainty and relative uncertainty of the profile measurements were estimated. The absolute uncertainty is indicative of the quality of the measurement method. For this reason we introduced the relative uncertainty, calculated in relation to the absolute value of the defect obtained from the iterative method that we adopted. Inside every scanning, the absolute uncertainty increases from the trough towards the extremities. On the contrary, the relative uncertainty decreases from the centre towards the trough ends.

The causes of the curvature defect can be multiple and should be analyzed in detail. A possible reason of the wrong curvature can be due to the fixing of the mirror to its support that could generate an elastic deformation of the inferior and superior extremities. Another possible cause could be connected to the edge effects due to the different distribution of the mechanical tension between extrados and intrados of the mentioned zones.

8788-94, Session PS

Small angle light scattering for a glass fibre diameter characterization
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The aim of the paper is to discuss the concept of a method for non-invasive characterization of a glass fibre diameter. Thin, flexible glass fibres have become the most versatile industrial materials used in various branches of technology and industry, such as telecommunications, sensor-technology and composite materials.

The method involves the use of light as a non-invasive measurement tool and thus, is potentially fast and accurate from simple pass/fail quality check to detailed evaluation of the fibre diameter. Measurements performed on the scattered field are intended to prove cause-effect relationship in order to quantitatively and unambiguously determine diameter of the fibre. What is important, the inverse analysis is applied to the data recorded at a small angle.

Most scattering techniques use laser radiation as a measurement tool. When a beam of laser light is scattered by a transparent or partially transparent particle, multiple phenomena occur which influence the small angle regime. The incident radiation is diffracted by the particle, reflected from its surface, refracted and scattered many times in its structure. What is more, axial symmetry and regularity of the interface between the particle and the environment contribute to the formation of standing waves and, in consequence, resonance phenomena strongly influence the scattered field. Although both, physical as well as mathematical interpretation of the scattered field is possible using the exact Maxwell equations, e.g. within the framework of Lorenz-Mie theory, it is a difficult task to find a cause-effect link between measurement data and physical properties of the particle.

The essence of the measurement method promoted throughout this paper is to influence the spectral properties of the incident light in such a way to obtain the scattered field easy to explain from the physical point of view and, in consequence, straightforward to describe mathematically. It may be shown, that through the use of low-coherence radiation, the interpretation of the field scattered at a small angle is reduced to simple rules of diffraction based on the geometrical optics. In fact, scattering components specific to scattering of coherent radiation are suppressed. The most attractive feature of diffraction, however, is fact that it is insensitive to the refractive properties of the glass fibre (refractive index profile, minor inclusions and air bubbles). Optical Fourier transform configuration of the measurement setup is also realizable.

The method of low-coherent light scattering will be verified by means of numerical experiments for the case of a glass fibre with diameter ranging from 10 to 150 microns. Part of the analysis will be also devoted to demonstrate how refractive properties of the fibre influence the field scattered at a small angle. To obtain the fibre diameter, direct and reverse mathematical concepts will be introduced on the foundation of the Huygens-Fresnel integral. An empirical research will be aimed to demonstrate some achievements in the formation and analysis of the filed scattered on 125 µm optical fibre.

8788-105, Session PS

Measurement of residual stress fields in FHPP welding: a comparison between DSPI combined with hole-drilling and neutron diffraction
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This paper shows a portable device to measure mainly residual stress fields outside the optical bench. This system combines the traditional hole drilling technique with Digital Speckle Pattern Interferometry. The novel feature of this device is the high degree of compaction since only one base supports simultaneously the measurement module and the hole-drilling device. The portable device allows the measurement of non-uniform residual stresses in accordance with the ASTM standard. In oil and gas offshore industries, alternative welding procedures among them, the friction hydro pillaring processing (FHPH) is highlighted and nowadays is an important maintenance tool since it has the capability to produce structure repairs without risk of explosions. In this process a hole is drilled and filled with a consumable rod of the same material. The rod, which could be cylindrical or conical, is rotated and pressed against the hole, leading to frictional heating. In order to assess features about the residual stress distribution generated by the weld into the rod as well as into the base material around the rod, welded samples were evaluated by neutron diffraction and by the hole drilling technique having a comparison between them. For the hole drilling technique some layers were removed by using electrical discharge machining (EDM) after diffraction measurements in order to assess the bulk stress distribution. Results have shown a good agreement between techniques.

8788-108, Session PS

Deformation measurement of centimeter-sized objects by sequentially recorded intensity patterns
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Sequentially recorded intensity patterns reflected from a coherently illuminated diffuse object can be used to reconstruct the complex amplitude of the scattered beam. Several iterative phase retrieval algorithms are known in the literature to obtain the initially unknown phase from these longitudinally displaced intensity patterns. The algorithms are mostly based on iterative methods, but deterministic methods also exist. The core of the methods is relatively simple: recording the speckle field at different positions along an optical axis. To assure the faster rate of convergence, 10-20 intensity patterns are recorded. Thanks to the sufficient speckle intensity variation between the measurement planes the phase retrieval is usually possible by converging numerical calculation.

One possible way to check the result of phase retrieval is numerical focusing, when the reconstructed wave shows a focused image of the object at a proper plane. The cross-correlation between the calculated intensity distribution and the ideal image can also be used to characterize the quality of the reconstruction.

The volume speckle field is recorded in equal-interval planes with a high resolution CCD/CMOS camera, whose position can be changed along the optical axis by precision motorized stage. It should be noted that although the optical arrangement is simple and the laser power is effectively utilized, there are two major drawbacks of the method: the expensive precision stage and because the limited speed of the stage, the relatively long exposure time. The Nyquist sampling condition must be satisfied as well, so the camera must resolve speckle patterns. This results in an increased object-to-camera distance for larger objects, as usual in digital holography.

When two sequences are recorded in two different states of a centimeter-sized object in optical setups that are similar to digital holographic interferometry - but omitting the reference wave - displacement, deformation, or shape measurement is theoretically
possible. To do this, the retrieved phase pattern should contain precise information not only about the intensities and locations of the point sources of the object surface, but their relative phase as well.

In the measurements not only the requirement of strict mechanical precision is important, but the object to camera distance range, uniform or variable field, speckle field characteristics, and phase forming characteristics of the used imaging lens has major influence on the quality of the fringe pattern. Experiments were done using an as large as 5x5 cm sized deformable object to demonstrate major effects and give proposals to reach higher quality measurements.

An alternative solution for reference-free shape and deformation measurement is using set of sequentially recorded objective speckle patterns scattered from the investigated object. This method can measure the deformation field or the shape of the object with lower precision, like speckle photography. Our major goal was a comparative analysis of these methods to determine their sensitivity and measuring range. It was demonstrated experimentally, that the sequentially recorded images of relatively large objects can be used for deformation measurement. Different algorithms were used for the reconstruction (e.g. iterative Gerchberg-Saxton method), their effects and differences were analyzed.

According to the demonstrated interferograms, no restriction is present to the type of deformation, but the limiting aperture of the CCD camera or the imaging lens may cause reduced speckle correlation between the two retrieved waves. Results of simulation are also presented to visualize theoretical limits for different methods.

Energetic sensitivity of optical-electronic systems based on polychromatic optical equisignal zone
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Nowadays means of optical-electronic remote control are widely used in industry, construction, geodesy, etc. They enable to achieve high performance and accuracy while positioning elements under control at large distance. There are instruments based on optical equisignal zone (OEZ) which can perform this task.

Such a system contains a transmitter forming the base plane, and a receiver, which determines its position relatively to the base plane. The base plane is created by two light sources (e.g. LEDs) modulated with different frequencies, radiating in the same direction. Thus irradiance of two fields divided by the projection of the base plane is formed in the plane of the sensor. The difference between fluxes coming on the plane of the sensor (so-called differential flux) results in the signal of the receiver, indicating the direction the receiver is to move. The receiver is attached to an element under control so that it becomes possible to keep the element in required position.

It is known that air refraction caused by temperature gradient leads in one of the largest error in optical-electronic systems. Considering that rays are bended by heated atmosphere in a different way according to their wavelength, it is possible to found the position of each ray on the sensor. At present the research of formation of the polychromatic OEZ is being held, as applying light sources of different wavelength would enable to eliminate air refraction influence using a special processing algorithm, and thus to reduce the error of positioning and increase its accuracy. For such an application it is recommended to use light sources with the difference between wavelengths as large as possible (e.g. a blue/UV source and red/IR one) since the larger the difference of wavelengths the more precisely the difference in position of rays may be determined.

Sensitivity of the receiver to the lateral displacement is determined by energetic sensitivity of the whole system, i.e. the relation of differential flux to the displacement it causes. Earlier this term was applied only to monochromatic radiation. Because of dispersion in lenses of the objective the relation of energetic sensitivity on the distance is different for wave-lengths used, and the response of the receiver depends on them, too. Thus the term of energetic sensitivity should be revised for the polychromatic case.

The new term is referred to as effective energetic sensitivity, which would consider terms of equation of energetic sensitivity as the function of the wavelength and take into account the response of the receiver sensor to radiation of chosen wavelengths. So it shows the effective sensitivity of the system.

The research demonstrated that effective energetic sensitivity may be used as a criterion while choosing components of an optical-electronic system.

Design and analysis of a low-cost compensated POF displacement sensor for industrial applications
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We present a non-contact low-displacement sensor based on plastic optical fiber (POF), with reflectivity compensation feature, designed for industrial applications.

Fiber optic sensors (FOS) target a broad range of industrial applications, because of their intrinsic advantages over standard technologies, including immunity to electromagnetic interferences, impossibility to start or propagate fires, low optical attenuation that enables remote monitoring, and miniature lightweight shape. Among FOS, POF sensors own key features that make them strategically competitive: they are the lowest cost for any FOS architecture, they can be easily handled even by non-expert users thanks to simple connectors and visible light, they have a lower Young modulus that results in bending tolerance. On the other hand POF have a higher attenuation, limiting the cable length up to a few hundred meters.

The proposed system is based on bifurcated fiber bundle (BFB) approach. A 650-nm LED is used as light source, coupled to a polymethyl-methacrilate (PMMA) POF fiber with core diameter 1.0 mm and NA = 0.47 through a 50/50 coupler. The output of the coupler (TX fiber) is used both for illuminating the target, and for collecting the backreflected power. A bundle of N RX fibers, in addition to the TX channel, is also used to collect the backreflection from target surface, so that (N+1) channels are assembled. The fibers are grouped into a single bundle structure, and coated with black paper to avoid cross-talk; the bundle is then placed at distance d from the target surface. The optical signal from each channel is recorded with a receiver that includes a Si photodiode, a trans-impedance amplifier and a post-amplification stage with adjustable gain. The LED source is directly modulated with frequency fmod (0.8-1.2 kHz) generated through an arbitrary waveform generator, in order to clear off stray light and interferences; thus, a lock-in-amplifier (LIA) is employed to demodulate the signal and extract the output signal dependent on displacement d. Data acquisition is performed with a high-speed DAQ card programmed in LabVIEW.

In industrial applications, compensation of target reflectivity and power drifts is a key issue. In typical working conditions, target reflectivity may change over time due to day/night or light/dark shift, shadowing, dust deposition, yellowing, or aging. In these conditions the standard POF sensors fail as the backreflected power depends on changes of target reflectance. We implement a compensation technique that, exploiting the several fibers compensating the bundles, computes a normalized ratio of fiber outputs and returns a compensation function that is independent on both input power and target reflectivity.

In order to evaluate system performance, we develop a Monte Carlo (MC) ray-tracing simulation that allows us arbitrarily changing any radiation, fiber positioning, target reflectivity, and propagation parameters. MC outlines an excellent benchmark for the system analysis as it allows selecting fiber rotations, target rotations, target non-uniform reflectivity, diffusivity of target surface, and radiation pattern. This allows drawing quantitative analysis of system tolerance and resilience to non-ideal conditions, but also returns bundle design guidelines in order to maximize performances.

Experimental results will be reported in the final paper. The compensation of target reflectivity has been tested by using a set of targets with different material and reflectivity.

Diffusive targets have been simulated by using paper with different color, with a reflectivity of 20% to 50% at red wavelength; as reflective targets we have employed opaque metal, tin foil, and a mirror.
Both RX and TX outputs represent a close match with the MC model. TX output is superposed to a constant value due to the non-ideal directivity of the 50/50 POF coupler; once removing the offset, the voltage tends to zero for long displacement. By computing the compensation functions, the dependence on the reflectivity of the target is correctly removed, at least on the short range 0 – 1.2 mm. On this range, we estimate an uncertainty of 5 m to 10 m, with an approximate additional 2 m/mm for each percent of target reflectivity variation.

8788-125, Session PS

Turbine-blade tip clearance and tip timing measurements using an optical fiber bundle sensor

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When it comes to measuring blade-tip clearance or blade-tip timing, reflective intensity modulated optical fiber sensors have overcome capacitive, inductive or discharging traditional limitations of probe sensors. These include limited frequency response or the requirement of electricity-conducting blades. This paper presents signals and results corresponding to the third stage of a multistage turbine rig, obtained from a transonic wind-tunnel test. The probe is based on a trifurcated bundle of optical fibers that is mounted on turbine casing. This bundle eliminates the influence of intensity variations of the light source and also the influence of blade surface reflectivity [1]. It is composed of a central illuminating fiber and two concentric rings of receiving fibers that collect the light reflected from the blade. A laser is used to insert light into the illuminating fiber, which is then transmitted to the blade. Two photodetectors turn the reflected light signal from the receiving rings into voltage. The electrical signals are acquired and saved by a high-sample-rate oscilloscope. Tip clearance measurements require sensor calibration, in order to convert the ratio of the signals provided by each ring of receiving fibers into distance [2]. In the case of tip timing measurements, only one of the signals is considered, which serves us to get the arrival time of the blade. The system provides the necessary data to obtain the traveling wave spectrum, which presents the average vibration amplitude of the blades based on EO+ND response. The differences between the real and theoretical arrival times are obtained for each blade. The deflections obtained from these time differences are used to perform a FFT, which gives the spectrum. In the case of tip clearance measurement, a precise method to get the distance between the casing and the blade is being developed. The results demonstrate the suitability of the optical fiber bundle to achieve tip clearance and tip timing measurements in turbine rig testing facilities and suggest the possibility of performing these measurements in real turbines under real working conditions.

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Tape measuring system using linear encoder and digital camera

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The calibration of line standards such as survey tape and rigid rule is usually performed by a comparison method. The reference and measurement tapes are stretched side by side and the length difference between two graduations is measured. This comparison method requires a reference tape, which is traceable to length unit. Therefore several national metrology laboratories (NMLs) had designed and constructed their absolute measuring systems to calibrate the reference tape. Their tape measuring systems usually use the laser interferometer for measuring the displacement. These systems required the temperature controlled room and the environmental conditions measuring system such as air temperature, pressure and humidity. This kind of absolute tape measuring system is so complicate and expensive that it is generally used at the primary calibration laboratory such as NML.

We have designed and constructed a 3 m tape measuring system for measuring the working grade tape. The system consists of the main body with linear stage and linear encoder, the optical microscope with digital camera, and the computer (tablet PC). The base of the system is a aluminum profile with length of 3.2 m, height of 0.09 m and width of 0.18 m. The linear stage and linear encoder are fixed on the aluminum profile. This long stage is moving by hand. The second short stage driven by micrometer is fixed on the carriage of the long linear stage, and the optical microscope with digital camera and the computer are on the this short stage. The linear encoder counts the moving distance of the linear stage with a resolution of 1 µm and this distance is transferred to the computer. The image of the graduation of the tape is captured by the CCD camera of optical microscope and transferred to the PC through USB. The computer automatically determines the center of the graduation by image processing technique and reads the moving distance of the linear stage. As a result, the computer can calculate the interval between the graduations of the tape. In order to determine the center of the graduation, we use three different algorithms. First, the image profile over specified threshold level is fitted in even order polynomial and the axis of the polynomial is used as the center of the line. Second, the left side and right side areas at the center of the image profile are calculated so that two areas are same. Third, the left and right edges of the image profile are determined at every intensity level of the image and the center of the graduation is calculated as an average of the centers of the left and right edges at all intensity levels. The difference between distances determined by three center detection algorithms depends on image quality and is usually less than 10 µm. In order to achieve the high accuracy, the linear encoder should be calibrated using the laser interferometer or the rigid steel rule. This encoder is fixed on the linear stage and the encoder is stored at the computer and the computer compensates its reading value.

Even though the tape measuring system has a very simple structure, it has an enough accuracy to calibrate the working grade tape. The expanded uncertainty of the system is smaller than (30 + 15 * 10^-6 L) µm. Here L is the measuring distance of tape and the unit is µm. At this system, the long distance measuring instruments such as ultrasonic distance meter or laser displacement sensor can be also calibrated.

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Optical profilometer using laser based conical triangulation for inspection of inner geometry of corroded pipes in cylindrical coordinates

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An axis-symmetrical optical laser triangulation system was developed by the authors to measure the inner geometry of long pipes used in the oil industry. It has a special optical configuration able to acquire shape information of the inner geometry of a section of a pipe from a single plane frame. A collimated laser beam is delivered to the tip of a 45° conical mirror. The laser light is reflected in such a way that a radial light sheet is formed and intercepts the inner geometry and forms a bright laser line on a section of the inspected pipe. A camera acquires the image of the light line through a wide angle lens. An odrometer-based triggering system is used to shot the camera.
to acquire a set of equally spaced images at high speed while the device is moved along the pipe’s axis. Image processing is done at a 45 Hz rate using a high speed Graphic Processing Unit. The measured geometry is analyzed to identify corrosion damages. The measured geometrical alignment is graphically presented using virtual reality techniques and devices as 3D glasses and head-mounted displays. The paper describes the measurement principles, calibration strategies, laboratory evaluation of the developed device, as well as, a practical example of a corroded pipe used in an industrial gas production plant.

Active retroreflector with in situ beam analysis to measure the rotational orientation in conjunction with a laser tracker

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High precision optical non-contact position measurement is a key technology in modern engineering. Laser trackers (LT) can determine accurately x-y-z coordinates of passive retroreflectors. Next-generation systems answer the additional need to measure an object’s rotational orientation (pitch, yaw, roll). To date, these devices are based either on photogrammetry or on enhanced retroreflectors. However, photogrammetry relies on costly camera systems and time-consuming image processing. Enhanced retroreflectors analyze the LT’s beam but are restricted in roll angle measurements.

In the past we have presented a new method to measure all six degrees of freedom in conjunction with a LT. Now we dramatically optimized the method and designed a new prototype, e.g. taking into consideration optical alignment, reduced power loss, highly optimized measuring signals, better accuracy and higher resolution.

The basic principle is to directly analyze the orientation to the LT’s beam path by outcoupling laser radiation on detectors. The optical design is inspired by a cat’s eye retroreflector equipped with an integrated beam splitter layer where the laser beam is partially reflected two times. This creates two laser beams for further analysis. The first beam represents the incident beam; the second the reflected beam. From the path, the two laser beams take through the retroreflector, the rotational orientation of the device can be inferred.

The accuracy of a laser tracker highly depends on the quality of the used retroreflector. Therefore the optical components of our prototype were aligned with an optical measurement setup to maintain the laser tracker’s accuracy. Power loss of the laser beam is an unwanted property too. Therefore, we adapted the integrated metallic-dielectric beam splitter layer to strongly reduce power loss and the influence of the laser beam’s angle of incidence on the beam splitter ratio.

A big advantage of the design is the possibility to measure the roll angle Rx decoupled from the pitch Ry and yaw angle Rz. This is possible by exploiting the symmetric property of the optical setup. One detector is placed in the mirrored beam path at the center of symmetry C’ to measure the roll angle. The source of the signal is the beam offset d. A second detector is placed near to the mirrored focal point F’, where the beam offset is approaching zero. This allows measuring the pitch and yaw angle without influence of the beam offset d.

The system’s raw signals are distorted by a superposition of different effects like misalignment, nonlinearity of the detectors, optical aberration and temperature influences. Therefore, in order to determine the actual orientation of the device, it is essential to calibrate the system. We tested a calibration procedure that can easily be implemented into a microcontroller. It is based on supporting grid points measured with a reference system.

To test and develop our designs and the calibration procedure we programmed a simulation tool based on Wolfram Mathematica 8.0. The simulation model includes all relevant parameters of the system. The results provided the foundation for the subsequent implementation.

A proof of concept prototype has been designed with a specified measuring range of 360° for roll angle measurements and ±12° for pitch and yaw angle respectively. The performance of the system regarding the point stability yielded a standard deviation of 62 nm. A further characterization is in progress and will be presented within this publication.

A FPGA board is used to control and read the ADC which digitized the laser spot positions and additional sensors. The simultaneous sampling ADC reads data at a sampling rate of 200 kSPS with a resolution of 18-bit. The FPGA allows averaging to gain a higher resolution and noise reduction. In addition to the hardware implementation, more functions can be implemented as well as software, running on an embedded processor in the FPGA.

We anticipate our method to facilitate simple and cost-effective six degrees of freedom measurements. Furthermore, for industrial applications wide customizations are possible, e.g. adaptation of measuring range, optimization of accuracy, and system miniaturization.

Automated control of robotic camera tacheometers for measurements of industrial large scale objects

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An automated approach for the tacheometer measurements needed in the dimensional control of the industrial large scale objects is proposed. There are two new contributions in the approach: the automated extraction of the vital points and the automated fine aiming of a tacheometer. The accuracy and the reliability has been evaluated and promising results have been obtained.

1. INTRODUCTION

The modern robotic tacheometers equipped with digital cameras (called also imaging total stations) and capable to measure reflectorless offer new possibilities to gather 3d data [2]-[6]. We have developed an automated approach for the tacheometer measurements needed in the dimensional control of industrial large scale objects.

2. DESCRIPTION OF THE APPROACH

The proposed approach proceeds through the following steps: First the coordinates of the vital points are automatically extracted from the computer aided design (CAD) data (contribution 1). The extracted design coordinates are then used to steer the tacheometer to point out to the designed location of the points, one after another. However, due to the deviations between the designed and the actual location of the points, the aiming need to be adjusted. We propose to utilize an automated dynamic image-based look-and-move type [1] servoing architecture for this fine aiming of the tacheometer (contribution 2).

After the successful fine aiming, the actual coordinates of the point in question can be automatically measured by using the measuring functionalities of the tacheometer.

3. EVALUATION OF THE APPROACH

The validity of the automatically extracted points was studied by comparing the points extracted to the points actually measured by the measurement crews of two shipyards in four different and real measurement cases. Promising results were obtained: on average 97% of the actually measured points were indeed proposed to be measured by the software.

The accuracy of the image based fine aiming was evaluated by steering a Topcon IS -tacheometer both automatically and manually to a corner of an iron sheet. It was noted that the automated approach succeeded well: the deviations of the results obtained with the automatic approach were similar to the deviations of the results obtained manually.

The functionality of the image analysis part of the approach was studied by imaging three different kind of steel structures (typical for ship building) with the tacheometer camera from different distances and viewing angles (in laboratory environment). Each structure was imaged either five or ten times so the point to be measured was in different location in the field-of-view of the camera. Three different temprone matching methods were evaluated and promising results especially with a perspective deformable matching approach were obtained: The image analysis approach failed only in one case and even in this case the failure was noted to be due to the problems in the illumination.

4. CONCLUSIONS
The automatic vital point extraction method was observed to be operational. It was also noted to be easily tunable for the needs of different kind of dimensional inspection tasks. Also the control method used for the image based fine aiming was noted to be feasible. The accuracy of the control method was comparable to manual measurements. Therefore the reliability of the image processing step of the control method was high in the laboratory tests. The functionality of the approach in real environment should and will be validated in the near future.

REFERENCES


Development of alignment-guidance device for grooved roll mill using parallel projection imaging technique

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We have developed the quantitative guidance system for precise alignment of the grooved rolls which is used for finisher rolling of the bar steel products. Grooved rollers in finisher rolling mill are required to have symmetrical arrangement and have a specified gaps, because these arrangement factor affect roundness of steel bar product used for precision machine components such as bearing.

As a former method of grooved roll setup procedure, operators used to insert a standard bar to check visually the state of biting of the bar by the grooved rolls. However, this method sometimes caused personal dependencies or lack of repeatability.

The developed system consists of the combination of parallel light projection and imaging optics of specific design, silhouette image processing technique (edge detection) to detect cross sectional profiles for each of grooved rolls, and the searching algorithm for determination of the center position of groove arc of each of rolls. The system adopts back light illumination imaging (silhouette imaging method). However, because both projection and imaging lenses have to be designed with low numerical aperture (i.e., low optical resolution) to prevent unnecessary irradiation from the inner structure of roll mill housing, the silhouette transition around the edge of the grooved roll in acquired silhouette is rather ambiguous. Therefore we developed curve-fitting and algebraic edge detection algorithm to recover the resolution of the profiles. On determination of the center of the groove (and shape part of the grooved roll), we developed a geometric voting method which can determine the actual position of the groove by knowing exact radius, interval of the arc among the profile of the roll. Finally we calculate and display the relative offset of the center points each of grooved rolls on the PC. The system does not contain mechanical moving structure, which sometimes cause unavoidable measurement uncertainty or system maintenance costs. We present experimental results to check accuracy as follows; (1) Comparison of cross-sectional profile of the culver roll acquired through the edge detection algorithm and by scanning laser distancemeter showed good coincidence, (2)The displacement of the culver roll in radial direction is followed in good precision by the developed roll-center detection algorithm, while the position in axial direction was kept within 0.05mm. Thus the developed system should be seen as method enough for practical roll alignment procedure, and helps the factory operators to tune the rolling mill rapidly and precisely.

Photogrammetry based system for the measurement of cylindrical forgings axis straightness

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Dimension measurement of hot large forgings is necessary for process control and product quality. Conventional non-contact optical measurement methods are not applicable, mainly because of high temperature and large dimensions. A novel approach to the simultaneous measurement of cylindrical forgings axis straightness, based on the principle of photogrammetry and edge detection, is described in this paper. Proposed system is developed under laboratory conditions, but the actual conditions of steel production are also considered.

Demands on the measurement system were set by Company. The system should be able to detect axis straightness deviations higher than 5 mm (system accuracy has to be better than 5 mm). Cylindrical forgings are 4 to 20 m long with diameter up to 1.4 m. Measurement approach is based on the assumption that the actual shape of the cylindrical forging can be determined (in the simplest case) from four boundary curves which lie in two mutually perpendicular planes. Four boundary curves can be obtained by detecting forging edges in two images. Due to the big length of the forgings, image matching method is used to create panoramic images.

Accuracy of the system is determined by measurement sensitivity (minimum detectable size) and measurement deviations, such as deviations resulting from edge detection and deviations resulting from the optical system, which cannot be eliminated by calibration etc. The first step was choice of cameras for actual and experimental conditions and verification the achievable accuracy. Validation of the proposed method was carried out on cylindrical rods with a length up to 1 m and at ambient temperature. The exact position of the cameras was determined by metric calibration. Camera calibration should be performed for the actual conditions of the measurement i.e. in the actual working distance, with chosen focal length and aperture. Due to the fact that the field of view of the proposed system must be very wide (if real conditions are considered), the calibration was simplified to 1D issue. 1D calibration (with one-directional field of markers) was performed by using tape measure.

A crucial step for the function of the proposed system is the choice of the edge detection method, which will ensure precise extraction of the forgings’ boundary curves. The chosen method has to be appropriate for measurement of the hot and normal temperature forgings, which is not an easy task. Common edge detection methods extract edges in the whole image, however, in this issue only two boundary curves are required. Therefore, automated edge detection based on median filter was proposed. The method validates the luminance value of each point of the analyzed cross section. Outputs of the measurement are two charts for each panoramic image, were actual shape of the axis is plotted. Overall maximal deflection is listed in table. Evaluation of this method was performed on 10 samples. Each cylindrical rod was also measured by industrial fringe projection scanner Atos III Triple Scan in order to verify the accuracy of the proposed system. 3D scanning was performed with 320 mm measuring volume (i.e. 320x240x240 mm), with measuring point distance of 0.095 mm. Digitized rod in the form of a polygonal mesh was used to create cross-sections, which were imported in IGES format to the 3D CAD software. Standard CAD tools were used to measure actual axes of each rod and compared with results of the proposed method.

Despite the positive results, additional measurements must be performed to determine the repeatability of the measurement and thus precision of the system. The crucial step for the verification of this measurement approach will be determination of the measurement accuracy under high temperatures.
Light scattering techniques for efficient surface quality control (Invited Paper)

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Today’s technological development places ever increasing demands on high-precision optical surfaces. New manufacturing techniques generate such surfaces even for large and curved optical components. Hence, there is an urgent need for measurement tools which allow a sensitive but also fast and easy quality inspection. To meet these requirements, several light scattering techniques have been developed at Fraunhofer IOF. In this talk, instruments as well as data analysis methods are presented. It is demonstrated how e.g. information on roughness, defects and homogeneity can be obtained from such measurements. Examples of applications are discussed for diamond-turned and polished surfaces as well as for multilayer coatings with roughness levels ranging from below 1 nm to several nanometers rms. Besides single gratings and other optical components, one of the main results will be the introduction of in-die systems which will be presented which enable rapid, robust yet high resolution measurements close to manufacturing processes.

Sub-nanometer in-die overlay metrology: measurement and simulation at the edge of finiteness

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The drive in optical lithography to push for smaller overlay targets is two-fold: on the one hand, metrology space consumption needs to be minimized to maximize device real estate on the semiconductor wafers. On the other hand, down-scaling of the device feature size following the ITRS roadmap requires aggressive overlay budgets. Higher order intra-field grid corrections are considered necessary to accomplish this. This is not possible only with scribe-lane metrology and subsequent extrapolation to within the die. Therefore, the overlay needs to be measured in-die. This requires small targets that fit in between the product structures. In such in-die applications, it is important that the overlay measurement is unaffected by the device structures surrounding the target. Furthermore, for process reasons the metrology target layout should be compatible with the neighboring device structures. In this publication, the challenges of sub-nanometer in-die overlay metrology are addressed, supported with measurements and simulations.

The technique used to perform the overlay measurements, is called micro-Diffraction-Based-Overlay (µDBO) technology. The µDBO technology is based on polarized and angle-resolved optical scatterometry. The measured angle-resolved diffraction pattern that is reflected by a lithographically defined semiconductor structure, such as a grating, is very sensitive for the asymmetry in this structure. The µDBO technology uses a stacked grating structure named µDBO-target on the wafer. The lateral position-difference (= overlay) of the top-grating with respect to the bottom-grating translates the overlay between the two layers into a stack asymmetry. This stack asymmetry is then detected as an asymmetry in the higher orders of the angle-resolved diffraction pattern. At the detector, images are measured for which single diffraction orders are optically filtered from this diffraction pattern. Furthermore, the grating-environment contribution to the transmitted pattern is filtered out. As such, the µDBO technology is able to measure each individual grating or other selected area on the semiconductor product wafer for a single diffraction order. The asymmetry computation higher orders is then a measure for the overlay. In this, a known ‘overlay-bias’ that is programmed in advance on the reticle, serves as an on-wafer calibration of the asymmetry signal. The measurements are performed on µDBO targets that have a size of 10 x 10 µm². These targets include 2 x- and 2 y-biased gratings, where the individual gratings are 5 x 5 µm². The target design optimally uses the available metrology target area with a dense line-space pattern in both layers of the stack, thereby optimizing for the signal-to-noise ratio. Imposed by the diffraction of light, the illumination spot is larger than the gratings as well as larger than the target. Still, measurement results show that in-die targets in product environment are measurable for overlay, with excellent correlation with nearby 40 x 160 µm² reference targets. Furthermore, an expected scaling of the measurement noise with the inverse of the square-root of the contributing grating area is observed. Dynamic reproducibility values of 3-sigma ≤ 0.3 nm are achievable for the 10 x 10 µm² targets in a product environment.

In order to optimize the µDBO-target design, a partial coherent simulation model is developed. This simulation model includes diffraction effects, the sensor properties and the interaction with the wafer. The simulation model allows for the understanding of the physics and estimation of effects, for example related to the optical sensor, the finite size of the µDBO targets, and the influence of the proximity of neighboring devices on the overlay measurement. Furthermore, it allows for the optimization of the µDBO technology. Simulation results will be presented in support of the µDBO technology.

Concluding, supported by measurements and simulations, the new µDBO technology allows for accurate in-die overlay metrology on small gratings.

Nanometrology of periodic nanopillar arrays by means of light scattering

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Part of the EU-funded IMPRESS project [1] is a case study on the anti reflective housing for photovoltaic modules. The latter will contain moth eye-like textured structures, which will be embedded in the solar cell device for efficiency increase. The functional nanostructures with sub- m lateral and height dimensions, which are periodic in both Cartesian directions, are manufactured using micro-injection moulding. An inline metrology tool needs to be developed in order to assure the specified quality of the large-area functional nanostructure during the manufacturing process. This paper gives a short overview about the nanometrology concept and the progress in the scattering simulations.

Introduction

Nanostructured surfaces are subject to research and, increasingly, gain more importance in industrial applications. Nanoscale structuring allows for the creation of functional surfaces, which can be used for, as considered here, the optimization of the optical properties of solar cell components. A fast and reliable inline metrology such as inverse scatterometry [2,3,4] needs to be developed in order to control the manufacturing process of large-area nanostructures.

Nanometrology concept

Inverse scatterometry is based on physical modeling of polarized light scattering from the periodic nanostructured surface. It should be noted that inverse scatterometry is dedicated to retrieve the parameterized nanostructure, which closely resembles the real nanotopography. The latter cannot directly be reconstructed from this optical measurement. The workflow in this concept is as following:

- Experimental determine efficiency of sample
- Simulate efficiency maps
- Retrieve error map (difference between experimental and simulated value)
- Reconstruct total error
- Gain unambiguous solution (inverse problem solved)

Thus the simulated data are employed to retrieve the characteristic parameters of the periodic structure from measured light intensities in different reflection and diffraction geometries.

Nanostucture model

In the physical model, the structure is built up with a unit cell, which consists of a cylindrical nanopillar with two characteristic parameters, radius and height, with nominal values of R=250 nm and H=1000 nm. The unit cells are arrayed in 2D with a lattice constant of 800 nm in both Cartesian directions. Light scattering from this model structure is...
calculated using the finite elements method. In order to setup the metrology concept along the workflow mentioned above, the scattering efficiencies of different diffraction orders are calculated for both, TE and TM, polarizations for monochromatic illumination (=670 nm) with a fixed angle of incidence (=17.5°). These simulations are performed for the nominal characteristic parameter values, which are assumed to exhibit a variation of ±12%, i.e., R=250 nm ± 30 nm and H=1000 nm ± 120 nm. Following this procedure, scattering efficiency maps are generated for different experimental configurations.

The maps show e.g. that a ±12% variation of the characteristic parameters is accompanied with a variation of the efficiency by approximately one order of magnitude, with overall lower scattering signal levels for the diffraction orders TE(1,0) and TM(1,0) than for the specular reflections TE(0,0) and TM(0,0).

The idea of the concept presented here is to find an unambiguous solution for the characteristic parameters by the comparison of possible solutions for a measured efficiency, which are contained in each efficiency map. The squared relative difference in this function generates a map, which contrasts possible solutions of the inverse problem by forming lines in the map (iso-efficiency lines). Thus, there are many combinations of radius and height, whose efficiencies are equal (i.e. for SRD=0) or very close to the model structure. In principle, more complex nanostructures can be addressed by a tailored combination of wavelengths, polarizations, incidence angles and diffraction orders, if the individual effects on the efficiency are known.

Conclusions

A nanometrology concept, based on inverse scatterometry, is proposed for the determination of the characteristic parameters of a special periodically structured surface: a two-dimensional nanopillar array. The validity of the concept is demonstrated in an emulated experiment, which retrieves the nominal height and radius values of the nanostructure. The sensitivity of this model-based approach was investigated in detail and compared with measurements of nanostructured samples, whose nominal parameters have to be close to the model structure. In principle, more complex nanostructures can be addressed by a tailored combination of wavelengths, polarizations, incidence angles and diffraction orders, if the individual effects on the sensitivity are known.

8788-60, Session 14

Phase information in coherent Fourier scatterometry

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Introduction: We show how extra measurements in Coherent Fourier Scatterometry (CFS) using a focused spot from a coherent source of illumination can lead to phase information. The focused spot is scanned laterally over the grating such that there is an overlap between consecutive scanning positions. Far field intensity is recorded for each scan position and consequently the phase information can be directly extracted from a series of intensity maps. An analytic relation is used to derive the phase difference between the diffracted orders from the far field intensity maps.

Phase Analysis: Let us assume an infinitely long grating which is periodic in the x direction with a given period. The shape of the grating is defined by the period, midCD, height and sidewall angles. Lateral displacement of the initial scanning position of the focused field with respect to the grating is described by an addition parameter bias. We choose the center (midCD/2) of the grating as zero bias. The lateral shift in the grating manifests itself in the scattered far field as the phase change in the individual diffracted order.

The introduction of constant phase shift in the non zero diffracted order with the translation of the grating can be treated as the case in shear interferometry. Here the zeroth order beam acts as the reference beam. In most applications, the grating pitch is preferred to be small enough, such that there exists only few propagating diffracted orders on the detector. For the analysis here, we consider grating pitch such that there is overlap for m values; and in exit pupil. The far field intensity maps are recorded for the set of incident and output polarization settings of the incident field and the scattered field from the grating, respectively. With phase shift between the consecutive scanning positions, the phase difference map for can be derived by the four frame . The phase difference between the orthogonal polarization in the far field for identical input polarization can also be obtained by the right choice of polarizer for the incident field and the diffracted field before the detector.

Results and conclusions:

For the simulations, the nominal values of grating parameters (midCD, height, SWA, bias) are defined and then one of the parameters is allowed to vary from its nominal values, while others are kept constant at their nominal values. The nominal value of grating parameters are given by pitch nominal: =450 nm, height: 130 nm, SWA: 90 degrees, midCD is half the pitch nominal. Result shows the sensitivity to the grating parameter midCD for high numerical aperture (NA:0.9) system for all in and out polarization combinations. We observe that the sensitivity is maximum for X incident and X output polarization. Similar behavior is observed for the other grating parameters.

In conclusion, the applicability of temporal phase shifting in coherent Fourier scatterometry with scanning spot is derived and analyzed. The results of the simulations are validated with experiments.

8788-61, Session 14

Revisiting parallel catadioptric goniophotometers

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A thorough knowledge of the angular distribution of light scattered by an illuminated surface under different angles is essential in numerous industrial and research applications. Traditionally, the angular distribution of a reflected or transmitted light flux as function of the illumination angle, described by the Bidirectional Scattering Distribution Function (BSDF), is measured with a point-by-point scanning goniophotometer. The major drawback of such an instrument is its impractically long acquisition time, especially when high angular resolution over a wide range and numerous incidence angles are required. Orders of magnitude faster measurements can be achieved by simultaneously measuring light flux in all scattered directions. This radically different approach requires a device capable of imaging the far-field distribution of light scattered by a sample onto a relatively small two-dimensional sensor array. Such an angular-to-spatial mapping function can be realized with a so-called parallel goniophotometer. An important category of parallel goniophotometers, which we designate catadioptric mapping goniophotometer (CMG), relies on the combination of a lens system with a reflector of parabolic or ellipsoidal shape. The key advantages of a CMG are high throughput and negligible stray light. Their performance and limitations, whose assessment and quantification is not trivial, are very sensitive to the overall design, in particular the properties of the lens system. To our knowledge, the design rules for a reliable CMG still need to be formally established.

In this contribution, we revisit the existing CMG designs, which are all based on the same working principle. Depending on the design, the lens system must comply with very different requirements in terms of size and acceptance angle. Our theoretical considerations reveal that a CMG must incorporate a lens system nearly free of grid distortion, which is possibly for a lens with a thin symmetrical profile smaller than 0.5. However, existing CMG designs that exploit a fisheye camera obviously do not comply with this crucial design rule. To demonstrate the limitations inherent to such devices, we developed specific raytracing tools in MATLAB and modelled the key features of a typical CMG incorporating a fisheye lens. The simulation results revealed significant artefacts in the angular-to-spatial mapping function that severely bias the measurements. To investigate the implication of our design rule on the design of a CMG, we performed raytracing calculations for a parametric study accounting for the angular resolution, the sample size and the reflector size and ellipticity. The simulations provide quantitative insights into the key parameters for a CMG design free of artifacts, while maintaining a reasonable size and using a standard lens system. Our investigation reveals that the design of a CMG with an angular resolution better than 3° requires a reflector with an ellipticity ranging between 0.6 and 0.85 for a sample size relative to the ellipse size (major semi-axis) ranging
Metrology solutions using optical scatterometry for advanced CMOS: III-V and Germanium multi-gate field-effect transistors

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New materials and novel device structures are needed to overcome the challenges faced by Si Complementary Metal-Oxide Semiconductor Technology. Novel channel materials, such as III-V compound semiconductors and Germanium with high electron and hole carrier mobility, are attractive candidates to replace strained Si-n- and p-channels, respectively, for logic applications beyond the 16 nm node [1]. Three-dimensional device architectures, such as multiple-gate FETs (MuGFETs) or FinFETs, have higher scalability than their single gate counterparts since the multiple-gates help to achieve better electrostatic control in the body and therefore reduce the short-channel effects. Scatterometry Optical Critical Dimension (OCD) measurement provides fast, accurate and non-destructive metrology solutions to monitor process variations in semiconductor fabrication process. In OCD measurements, diffracted light signal from a periodic structure is collected and analyzed. CD, structural profile and film stack information can then be accurately determined using computational modeling techniques based on Rigorous Coupled Wave Analysis (RCWA).

In this work, we report metrology solutions using scatterometry OCD characterization on advanced CMOS: novel gate-last In0.53Ga0.47As n-channel FinFET with self-aligned Molybdenum (Mo) contacts [2] and Ge p-channel FinFET formed on Germanium-on-Insulator (GOI) substrate. Key critical process steps during the fabrication of these advanced transistors were identified for process monitor using scatterometry OCD measurement to improve final yield. We also further explore OCD characterization on these critical process steps using normal incidence spectroscopic reflectometry (SR), spectroscopic ellipsometry (SE), and combined SR-SE technologies. Excellent correlation with both SEM and TEM and high measurement precision were achieved by employing OCD characterization, confirming scatterometry OCD as a promising metrology technique for next generation multi-gate transistor with novel channel material.

The fabrication process flow of gate-last In0.53Ga0.47As n-channel FinFET with self-aligned Molybdenum contacts is summarized in Figure 1 (a). OCD characterization can be integrated to monitor key process variations during the following critical fabrication processes in the front-end-of-the-line (FEOL): channel definition, removal of Molybdenum and n++ In0.53Ga0.47As for channel opening, lithographic patterning and dry etching of Fin and Gate structures. Figure 1(b) plots the transistor drain current ID during on-state biasing condition with VG of 1.0 V and VD of -1.0 V as a function of LG from 140 nm to 160 nm. As previously described in Equation (1), ID is inversely proportional to LG. In addition, ID increases with larger WFin. Process monitor using scatterometry OCD is important as these parameters show strong impact to the device performance.

Figure 4(a) illustrates the cross-sectional view of the OCD model for the Ge fin structure after dry etching process. The key process variations in this fabrication step are monitored by five floating or fitting parameters in the OCD model, including WFin, fin height (HFIN), buried oxide thickness (TBOX), oxide recess height (HREC), and hardmask thickness (THM). Cross-sectional TEM micrograph in Figure 4(b) shows the periodic OCD test structure of the Ge fin structure. The OCD model output was found out by Normal incidence SR and SE spectra with angle of incidence (AOI) of 65°, as indicated in Figure 4(b). Excellent static precision, with 3 lower than 0.2 nm, was achieved in all parameters by all three technologies, as shown in Figure 4(c). With additional information, the combined SR-SE technology demonstrates the best static precision in all five fitting parameters, as compared to SR-only and SE-only technologies.

References:
3D shape measurements of fast moving rough surfaces by two tilted interference fringe systems

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Shape measurement of moving, especially rotating objects is an important task in the field of process control. Rising automation, decreasing tolerances and production of small batches demand for precise and reliable process monitoring. A wide range of measurement techniques is available to determine the surface profile exist. Mechanical probes usually require unclamping the work piece in order to determine the shape. The measurements are slow and if the work piece has to be processed again problems can occur due to misalignment when reclamping it into the lathe. In contrast, optical techniques such as chromatic confocal sensing, triangulation, multiple wavelength interferometry, low coherence interferometry or digital holographic interferometry operate contactless and enable in-situ measurements in principle. They offer low distance measurement uncertainties down to the sub micrometer range, can measure lines or whole areas on the surface at a time employing cameras or offer measurement rates of several kHz. Stand-alone however, none of these techniques is able to measure the 2-dimensional shape i.e. angle resolved radius of the work piece, since exact knowledge of the distance to the rotational axis is necessary additionally to the measured distance between sensor and surface. Otherwise tumbling, vibrations, eccentricity and drifts of the rotational axis lead to measurement errors.

The laser Doppler distance sensor technique overcomes these limitations by measuring the lateral surface velocity simultaneously to the surface distance. The measurement principle has been introduced by the TU Dresden several years ago and can be realized by two tilted interference fringe systems [1]. While the lateral velocity is determined from the Doppler frequencies of the two scattered light signals, the distance is coded in the phase offset between both signals. However, due to the speckle effect, the envelopes and phase jumps of the scattered light signals depend on the illumination angles. With increasing tilting angle between the fringe systems, necessary for a steep calibration function, the signal correlation decreases and high uncertainties of the phase difference as well as the distance result. By a novel matching of the illumination and receiving optic the distance uncertainty has been improved of about one magnitude [2]. At high surface velocities of over 3 m/s a distance uncertainty of about 800 nm was achieved.

A fibre optical setup including a robust sensor head with great potential for miniaturization is presented. The determination of the diameter, ellipticity, eccentricity and generally the three-dimensional shape of rotating objects with a single sensor will be discussed as well as the possibility to detect misalignment of the sensor.

8788-66, Session 15

Characterization and demonstration of a 12-channel Laser-Doppler vibrometer

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Scanning Laser-Doppler Vibrometry is the standard optical, non-contact technology for vibration measurement applications in all areas of mechanical engineering. The vibration information is obtained from the modulation of a measurement laser beam which is scanned point-wise over the test surface to acquire operational deflection shapes of the specimen at any frequencies. Thus, the vibration signals from the different measurement points are measured at different time points. This requires a synchronization signal and the technology is limited to repeatable or periodic events. Therefore, several research groups have realized multichannel vibrometers during the last 10 years to enable laminar measurements of transient and chaotic vibrations [1], [2], [3]. However, all solutions had drawbacks which have prevented the acceptance of the multichannel technique by the technical community in mechanical engineering. Such drawbacks are a static measurement grid which limits the flexibility, low vibration measurement bandwidth, low maximum measurable velocity amplitude, high noise, and parasitic disturbance signals. Our first approach in the BMBF cooperation project Holovib (ref. numb. 13N9338) was a new 14-channel setup with a spatial light modulator SLM to position and focus the single measurement beams. Although our solution did work in principle we have not been able to realize a system which would meet the needs of an acoustics analysis engineer. The sensitivity and resolution of this solution was to low because the pixel number of the available SLM limits the product of possible beam deflection angle and numerical aperture. A description of this system and an analysis of its performance can be found in [4] and [5].

Therefore, we have explored a new solution for the optical setup of the sensing system. The approach for the demodulation scheme and the software solution for the evaluation of the measurement data have been maintained compared to the solution presented earlier [4], [5]. The software component to arrange the measurement grid has been changed slightly. Our new optical system is a 12-channel vibrometer and consists of a 12-channel interferometer unit which is connected with 12 optical fibers to a sensor head with 12 fiber-coupled objective lenses. Every objective lens can be focused manually and every sensor head with objective lens is fit in the bore of a sphere. The sensor heads can be tilted by hand and the spheres can be fixed by locking screws. Thus, it is possible to adjust the angle of every sensor separately and to align a user-defined measurement grid. A digital camera is placed in the middle of the objective array and the operator can define the geometry of the measurement grid in the software by just clicking on the laser foci in the image. Our system has synchronous analog-digital-conversion for the 12 heterodyne detector signals and a digital 12-channel-demodulator which is connected via USB to a computer. We can realize large deflection angles (15°), proper velocity resolution (in the μm/s range), sufficient vibration bandwidth (currently 10 kHz), and high maximum vibration amplitudes (> 1 m/s²). This solution fulfills the needs of the users in Holovib and has been applied intensively during the last months to study transient vibration events in automotive applications which could not be measured before. In this paper, we demonstrate the new optical and the improved electrical setup of the manually adjustable 12-channel vibrometer. In addition, we present the experimentally evaluated performance of our device and first measurements from real automotive applications that prove the utilizability of our measurement system.

References


8788-67, Session 15

Quantitative video-rate holographic imaging of nanoscale surface waves

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We report quantitative video-rate optical imaging of nanometric out-of-plane surface vibrations with a parallel laser Doppler measurement scheme on a sensor array. Our approach is based on time-averaged heterodyne holography in off-axis and frequency-shifting conditions. Small sinusoidal optical phase modulations are recorded and imaged with a frame exposure time much longer than the modulation period by time-averaged holography. In practice, sinusoidal out-of-plane surface motion creates side bands at the harmonics of the modulation frequency in the radiofrequency spectrum of the reflected laser beam. The heterodyne detection variant of time-averaged holography benefits from a frequency-shifted optical local oscillator to shift the first optical modulation sideband within the temporal bandwidth of the sensor which increases the detection sensitivity - a requirement for screening surface waves of nanometer magnitudes at radiofrequencies. We further increased the measurement sensitivity in practical experimental conditions by measuring the amplitude ratio of the first modulation sideband and the non-shifted band. This method requires mapping of optical path length modulation depth. For that purpose, we used a coherent frequency-division multiplexing technique with a dual local oscillator to measure both sidebands simultaneously. Experimental images of out-of-plane mechanical vibration amplitudes versus excitation at audio frequencies will be presented. The proposed imaging technique is single-frequency but tunable throughout the available range of local oscillator frequency shifts. Our latest developments in transient vibration sensing with a high-speed camera will also be reported.

8788-68, Session 16

Diagnostic of structures in heat and power generating industries with utilization of 3D digital image correlation

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The heat and power generating industries are one of the most important branches of the economy. The lack of adequate maintenance procedures can lead to failures of pipelines, heat exchangers, and other parts of installations. This in consequence can be a threat for employees and local population and also can lead to huge financial losses for industries. Despite of development of standard, point-wise techniques, which are used for monitoring of some parts of heating and power generating installations, there are still many unsolved problems. This fact justifies a search for alternative techniques for both monitoring and measurement/diagnostic tasks, which could be more accurate, relatively cheaper and could provide more useful data. These requirements may be fulfilled by optical, vision-based measurement methods. Displacement maps, strain maps or 3D point clouds, which are the most common outputs can be easily post-processed in order to provide the most informative data in particular applications. In the paper we present applications of 3D Digital Image Correlation aided with a thermovision technique for diagnostic of structures in heat and power generating industries. In-situ measurements with 3D Digital Image Correlation, which is widely used in laboratory conditions, provided huge amount of useful data for our partners from industry. The obtained data have been used to expand knowledge about the ongoing processes and to draw conclusions how to avoid possible failures in the future.

In this paper we report on two interesting applications of 3D DIC
for displacements and strains measurements: measurements of displacements of expansion bellows in a heating chamber and measurements of pipeline suspensions in a power plant. In both applications 3D DIC was aided with an infrared camera in order to correlate features of a measured object with thermal loads. Expansion bellows in heating pipelines are mounted in order to compensate thermal expansion of pipelines, caused by temperature variations of water inside pipelines. The length and the complexity of a heating network as well as difficulties with regular modernizations (which are connected with expansive ground works) influence on failure frequency of expansion bellows. Failures connected with displacements of extension bellows concern two aspects:

- too high in-axis displacements,
- out-of-axis displacements.

An occurrence of either of these conditions can lead to damage of a compensator itself, damage of steel directional support, displacements of fixed point (made of concrete), or even displacements of heating chamber’s walls. The application of 3D DIC aided with IR camera provided possibility to detect both mentioned alarm conditions simultaneously and in consequence to minimize a risk of a failure. Measurements were carried out in two sessions: late October (at the beginning of a heating season) and in February (winter), when the biggest displacements of expansion bellows occur. Both sessions lasted for 24 hours and were used to evaluate the health of the structure.

The second example presented in the paper concerns measurements of displacements of pipeline suspensions in the Jaworzno III power plant in Poland. Break-downs in power plants are often connected with sudden production shutdowns, which can be caused by alerts (true and false) or by decrease of power requirements (for example at night). The biggest displacements of pipelines are during shutdowns and during start-ups of installations and lead to changes of whole geometry of pipelines. We applied two 3D DIC systems to observe suspensions of the pipeline in the Jaworzno III power plant during whole cycle: sudden shutdown at night and start-up early morning. We extracted the data from crucial object points and compared them with the installation’s design assumptions.

8788-69, Session 16
Integrated digital image correlation for residual stress measurement
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Residual stress measuring by optical methods has been proposed by several authors in the past years; nevertheless the technique is far from mature and the various applications are still confined to optical laboratories. Most of the proposed approaches are variations of the standard hole drilling technique, where the strain gauge rosette is replaced by an optical—usually interferometric—measuring technique. Indeed the large sensitivity of these experimental methods allows measuring very low stress values; moreover the huge number of data points ensures reliable results; however all these advantages are completely obscured by the high sensitivity to vibrations, which makes the use of optical techniques very difficult outside of optical laboratories.

Digital Image Correlation is a non-interferometric technique able to measure bi- and three-dimensional displacement fields. It works by numerically correlating two images acquired before and after the material removal using the assumption that the optical flow remains constant during the acquisition. Since this approach results in an under-constrained set of equations, the solution is usually obtained in the least square framework, thus each data point corresponds to a local fit over of a small area of the reference image on the target one. The most frequently used error functions are the Correlation and the Least Square Difference; both depend on the coordinates of the pixel where the measurement is performed, the displacement components to be measured u and v, and finally on Ir and It, the intensities of the reference and target images. These last are expanded using Taylor series truncated to the first or second order, thus the non-linear fit has to identify 6 (12 in case of second order expansion) parameters. The problem is clearly non-linear and a Newton-like algorithm (e.g. Levenberg-Marquardt) has to be used. This class of algorithms require a starting point, which should be near enough to the sought one; thus a simpler, less accurate, pre-processing step is executed using a matching-block algorithm (without taking into account deformations) or by the digital equivalent of speckle photography (FFT algorithm) or by a pyramidal approach.

Digital Image Correlation is intrinsically not well suited to measure large gradients in space: indeed its accuracy depends on the square root of the number of points used to estimate the error function; in presence of gradients the block must be small to enable following the fast variation of the signal and the total number of points involved in the fit is consequently small. Thus the “standard” accuracy of DIC in these regions is about 500 μm/m (or worse) making it difficult to reliably measure elastic strains in metals. It is clearly possible to use a sampling step smaller than block size, but the improvement is only fictitious since neighbors blocks share part of the data and their results are correlated.

On the basis of the above discussion, it is apparent that Digital Image Correlation is also not well suited for replacing either strain-gauge rosettes or the interferometric techniques in the hole drilling (and similar) techniques. Indeed the gradients near the border of the hole constitute almost all the significant data; moreover the overall strains are relatively small. In fact the few examples of application of this technique to the residual stress field use large holes (to have large strains), low Young modulus materials (for the same motivation) and significant simulated residual stress (of the order of hundred of MPa).

The difficulties of Digital Image Correlation to model large gradients areas are mainly related to the shape functions used to model the local behavior during the estimation of the error function. A general polynomial code assumes univariant or paraboloid function, then a local block is only a rough approximation of the real behavior of displacements and several sampling points are required to correctly follow the data in presence of gradients (thus imposing the use of small blocks). However this constraint can be removed by making the shape functions able to correctly model the displacement field. This approach (known as IDIC, i.e. “integrated” DIC) cannot be followed in a general code, but it has already used for specific applications, e.g. to model the displacement field near the crack in fracture mechanics.

In this work we propose using IDIC for residual stress measurement. Indeed the hole-drilling related displacement field is well known, thus it is possible to replace the standard shape functions of the hole-drilling block with specific functions, obviously augmented by rigid translation to account for rigid body motion during drilling. The sampling of multiple points to follow the data is no more required and the full image constitutes a single patch whose deformation is controlled by 5 parameters: the 3 residual stress components and the two in-plane rigid translations. Since the accuracy of the method directly depends on the number of pixel involved in the evaluation of the error function, this approach results very effective allowing replacing interferometric techniques with Digital Image Correlation. The advantages are significant with respect to the interferometric techniques: DIC does not require recent illumination and is much more robust against vibrations thus making possible using optical methods in industrial environments.

8788-70, Session 16
Infrared differential interference contrast microscopy for overlay metrology on 3D-interconnect bonded wafers
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Semiconductor device packaging technology is rapidly advancing, in response to the demand for thinner and smaller electronic devices. Three-dimensional chip/stacker stacking that uses through-silicon vias (TSV) is a key technical focus area, and it has been shown to deliver reduced inductance compared to traditional wire bonding. However, many metrology challenges are new to the industry due to the relatively large variety of via sizes and density, and new processes such as wafer thinning and stacked wafer bonding.

Typically these TSVs are filled with copper (Cu). The temperature coefficient of linear expansion (TCE) mismatch between Cu and Si is relatively large (Si: 2.5x10-6/°C and Cu 17.5 x10-6/°C) and therefore the TCE induced stress is expected. The undesired stress generation can have an impact on the device performance in the thin silicon device layers which might be located near the TSV. Thus a detailed study of local stress introduced by the TSV process is critical not only for device reliability and yield, but also for purposes of optimizing the appropriate
Three-dimensional chip/wafer stacking that uses through-silicon vias (TSV) is a key technical focus area, and it has been shown to deliver reduced inductance compared to traditional wire bond. Typically these TSVs are filled with copper (Cu). The temperature coefficient of linear expansion (TCE) mismatch between Cu and Si is rather large and therefore TCE induced stress is expected. The undesired stress generation can have an impact on the device performance in the thin silicon device layers which might be located near the TSV. Thus a detailed study of local stress introduced by the TSV processing is critical not only for device reliability and yield, but also for purposes of optimizing the appropriate materials and layout.

In this paper, we have studied 3D stress distributions in Si surrounded by Cu filled TSVs, with various dimensions sizes, depths and pitches. The stress measurement was done using a semi-automated, NIR 976 nm excitation laser, micro-Raman spectroscopy system designed specifically for deep Si penetration depth and 3D confocal stress analysis applications. The system is designed to sequentially measure Raman signals along TSV depth axis with PZT vertical translations. Stress free silicon exhibits a sharp and strong Raman peak at 520.3 cm⁻¹, corresponding to the optical phonon energy of Si regardless of excitation wavelength. The magnitude of the shift of Raman peak position is proportional to the stress in the Si. The Raman signal shift of 1.0 cm⁻¹ from Si towards the higher and lower wavenumber side is equivalent to a compressive and a tensile stress of 434 MPa respectively. The unique features of a very long wavelength allowed the achievement of real 3D confocal NIR-Raman spectroscopy to map the spatial distribution of stress in the TSV surrounding structures as a function of TSV depths, sizes and spacing.
Assessment of the scatterometry capability to detect an etch process deviation (Invited Paper)
Nicolas Troscotomp, Maxime Besacier, LTM CNRS (France); Mohamed Salb, Aselta Nanographics (France)

Deviations of tool conditions during an etching process is one of the main reasons leading to fabrication failure and drop of throughput. As a consequence, being able to detect and reset, in real time, this possible deviation of the tools parameters during a dynamic process is one of the important challenges in semiconductor industry as reducing the defect rate (a less flow, source power or a stuck temperature) is a fundamental point.

This topic is addressed in this article with the application for the etch process during a resist trimming.

To follow in real time this dynamic process, one of the most common in-line metrology techniques is used: the spectroscopic scatterometry. This method, based on the measurement of the polarisation change of a light ray induced by a reflection on a periodic sample, has several advantages; it is already widely implemented on production chain, accurate, fast (i.e. real time compliant), non destructive and the results (geometric parameters of the measured sample) are in-line available.

The variation of the geometric parameters of the measured sample is known to be very sensitive to the value of the etching parameters.

Then, in our applications, we assess that knowing the trends of the geometric parameters of the measured sample is a way to know the evolution of the tool parameters. As a consequence, we consider the scatterometric tool as an external sensor of the etching tool parameters, examining the dimension parameters of pattern. The final goal, for future works, will be to make a real time feedback loop to control the tool parameters during the etch process.

An etch tool has a lot of internal sensors allowing the knowledge of many behaviour parameters and then the evolution of the process. Some of them have a huge influence on the proceeding of the etch step whereas others are less significant. The most relevant parameters, such as pressure, gas flux, ampere power or a stuck temperature, are then determined. A constraint is applied on these parameters leading to strain the initial recipe to be modified. Then the influence on the dimensional parameters of the pattern can be shown.

Scatterometry is an indirect method, and its in-line property is very dependant of the software method used to solve the inverse-problem. In parallel of this work applied to the etch process, a new method of resolution of this inverse problem dedicated to scatterometry is developed, in order to decrease the computation time and the memory storage usually needed by the traditional methods (library methods, etc.).

The work presented in this paper must follow a three-phases scheme: first, we must determine the most important etching parameters, i.e. those whose variation have the most important impact on the etching process, secondly provide a DOE and launch these etching experiments in which we collect both the variations of these tool parameters and the geometrical parameters of the sample measured thanks to the scatterometry technique. Finally, determining the correlation between the different etching speeds (for critical dimension, height, angle,...) of the sample measured by scatterometry) and the value of the tool parameters.

Thanks to this new method, we determine the evolution of the geometrical parameters of the measured sample in 20 experiments, each sampling the tool parameters space in a wide range. Finally, we are able to determine the impact of those etching parameters.

Mueller matrix characterization using spectral reflectometry
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The fast evolution of microelectronics fabrication technology demands a parallel development in metrology capabilities. In recent years, Mueller Matrix (MM) scatterometry has been asserted as a useful tool in characterizing critical dimensions (CD) in periodical arrays of nanometer-size structures. Specifically, some symmetry properties of the measured structure can be readily extracted from the MM, allowing effective isolation of abnormal features. One example of importance is measuring deviations of grating structures from perfect mirror symmetry, characteristic of faults in the fabrication process.

The most general form of the Mueller matrix requires 16 independent measurements, and requires the measurement complexity of spectral ellipsometry. However, using some very general conditions on the reflection properties of the measured sample, which are the common case in optical metrology, one can reduce this number considerably. Such conditions are the independence of the reflection properties, and homogeneity of the sample (i.e. - constant reflectivity throughout the measurement spot). We show that under these conditions the Mueller Matrix can be completely measured using spectral reflectometry. Specifically, we analyze the case of asymmetric gratings (an application for which MM was shown to be useful), and show how the grating asymmetry properties can be directly addressed through application of such measurements. The proposed approach is then compared to the existing method of characterizing the Mueller matrix, based on spectral ellipsometry.

Characterizing asymmetry is then further analyzed, and a new approach for such measurement based on spectral reflectometry is presented. This approach is shown to provide better sensitivity to the sample asymmetry properties than allowed by the existing full MM metrology, and also requires only two distinct measurements leading to improved throughput.

Numerical investigations of the influence of different commonly applied approximations in scatterometry
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Scatterometry is an indirect measurement method, where dimensions and geometry of the structures under test are reconstructed from the measured scatterograms applying inverse rigorous calculations either by nonlinear optimisation or by comparison with relatively large previously computed data bases. Since both approaches are numerically very elaborate, for reasons of limited computational time and memory resources so far usually some common approximations are used to analyse the measurement data.

For example the interaction area is generally supposed to be infinite in space. The illumination light is approximated to be a mono-frequent plane wave. However, in real systems a Gaussian beam with a finite spectral bandwidth is used. In addition surface roughness as well as linear and line width roughness are usually neglected, although the diffraction efficiencies are significantly affected by such roughness effects. To achieve traceability in scatterometry the influence of each approximation has to be analysed and quantified thoroughly to develop an exhaustive and reliable uncertainty analysis [1].

We therefore started with investigations of the influence of some of these approximations like a varying spot size on the sample, and the influences of existing line widths (critical dimensions, CDs) non-uniformity and line edge roughness on the scatterometric measurement results.

Based on rigorous modelling we investigated quantitatively the influence of a varying spot size on the measured scatterograms. Additionally the corresponding influence on the sizes and geometries
derived from these measurements is evaluated and for significant influences specific methods for an improved data analysis of the measured data are developed to compensate for these effects. The corresponding limits and consequences will be discussed.

It is well known, that line edge (LER) and line widths roughness (LWR) may have a relatively strong influence on the measurement results, if they are not considered correctly in the data evaluation [2-5]. We have quantified by numerical simulations the impact of LER/LWR on goniometric scatterometry in the DUV spectral range and we extend the currently available data analysis methods, such as the maximum likelihood method, to compensate for and additionally estimate the amount of LER/LWR directly from DUV scatterometry data.

We will present the status of these investigations, comparisons with measurement data obtained with PTBs goniometric DUV scatterometer [6, 7] and first estimations of the size of these effects typically omitted in current industrial scatterometry applications.

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8789-4, Session 1

Scatterometry sensitivity analysis for conical diffraction versus in-plane diffraction geometry with respect to the side wall angle

Victor Soltwisch, Physikalisch-Technische Bundesanstalt (Germany); Sven Burger, JCMwave GmbH (Germany); Frank Scholze, Physikalisch-Technische Bundesanstalt (Germany)

Scatterometry, the analysis of light diffracted from a periodic structure, is a versatile metrology tool for characterizing periodic surface structures with regard to the critical dimension (CD) and other properties of the surface profile. For extreme ultraviolet (EUV) lithography masks, inspection with EUV radiation provides direct information on the mask performance in the operating EUV regime. With respect to the small feature dimensions of EUV masks, the short wavelength of EUV is also advantageous, since it provides a large number of diffraction orders from the periodic structures. In recent years we investigated goniometric EUV scatterometry at line-grating test structures with respect to the determination of the line profile parameters like width, height and side wall angle (SWA). With respect to width and height the attainable uncertainties are well in line with the requirements of the ITRS metrology roadmap. For the SWA, however, the required uncertainty well below 1° is still challenging.

Therefore, we investigated alternative EUV scatterometry approaches. Recent investigation have typically used the in-plane geometry with the light incidence at a plane perpendicular to the grating lines. For the determination of the SWA this might be disadvantageous because due to the oblique incidence of both incoming and diffracted beam the side walls are in the shadowed range in the picture of geometrical optics. For conical diffraction, however, with the light incident in a plane parallel to the grating lines, the side walls are illuminated also in the geometrical optics limit.

In this presentation we compare both scatterometry geometries. We present rigorous, FEM based simulation results of the different experimental set-ups, and we discuss first experimental results obtained at the EUV scatterometer at BESSY.

8789-5, Session 2

Phase unwrapping using geometric constraints for high-speed fringe projection based 3D measurements (Invited Paper)

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Industrial quality inspection and control always requires faster and more accurate methodologies for 3D surface measurement.

Phase-shifting profilometry based on fringe projection is one of the established techniques to realize accurate contactless surface measurements.

Phase unwrapping is a necessary step in the procedure of 3D point calculation in order to achieve both uniqueness and precision of the 3D measurement. However, phase unwrapping requires either limitations to the objects surface or additional code which prolongs the data acquisition and the data processing time.

We present a new methodology which enables real-time measurement and high-speed performance of 3D surface measurements based on fringe projection and stereo camera observation. The essence of the new technique is a drastic reduction of the fringe code which makes the process of pattern projection and image recording faster and real-time applicable. The new algorithm allows the complete omission of the typically used Gray code sequence or other additional code to the phase shifted sinusoidal fringe sequence. Its main concept is a special geometric design of the arrangement of the projection unit in relation to one of the involved cameras.

A typical implementation of a contactless 3D surface measurement system based on fringe projection is given by a sensor consisting of a fringe producing illumination unit (projector) and a stereo camera pair. Depending on the application a certain measurement volume is covered by the illumination and observation defining the maximal size of the measurement object which can be captured with one single shot measurement. In general measurement volume depth is smaller than width, also due to the depth of field.

The approach of the new methodology is the following: Besides the two stereo cameras the third optical component is the typically used Gray code sequence or other additional code to the objects surface or additional code which prolongs the data calculation. This means that it has to be calibrated, too.

Two geometric parameters of the system, namely the triangulation angle between the principle rays of the projector P and one of the cameras, say C1, and the width (or period length) of the projected fringes have to be arranged in such a way that the correspondence between any point in the image of camera C1 and the point in the projector image plane becomes unique. This can be enforced as it will be shown in the paper. Typical triangulation angles are between 3° and 5° for measurement volumes with relative extended depth and even bigger angles are for depth limited measurement volumes (e.g. for flat objects).

In a first step a rough estimation of the coordinates of the 3D point M can be obtained by triangulation between P and C1. However, as it is known, triangulation angles between 3° and 5° lead to weak precision of the 3D measurement data. In order to achieve optimal accuracy, the triangulation is performed again using the correspondences between the points in the images of cameras C1 and C2. The rough estimation of M allows a restriction of the search area of the corresponding point and makes the correspondence finding unique.

First experiments with two different 3D measurement systems show the robustness of the new method. Real time measurements can be performed which is the precondition of the supervision or quality check of several dynamic processes. However, depending on the depth of the measurement volume and the resolution of the cameras used, the minimal possible fringe period length may be longer than by using additional code which may limit the achievable measurement accuracy.
Future work should be addressed to the improvement of the calibration strategies of such systems and to the combination of the introduced methodology with other code reducing algorithms in order to improve the achievable measurement accuracy without loss of processing time.

8789-6, Session 2

Sensitivity analysis of tilted-wave interferometer asphere measurements using virtual experiments

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The tilted-wave interferometer (TWI) is a technique that was recently developed by the University of Stuttgart for the high-accuracy measurement of aspheres and freeform surfaces. The system works in a non-null measurement fashion and simultaneously uses several test beams with different tilts. Reconstruction of the specimen under test from TWI measurements is challenging, and in order to correctly separate the real surface topography from systematic system aberrations, the employed interferometer needs to be small normalized. This characterization as well as the reconstruction of the specimen from TWI measurements requires sophisticated data analysis procedures including ray tracing and the solution of an inverse problem.

A simulation environment was developed at PTB in order to generally investigate accuracy and stability of TWI systems, and to explore possibilities and limits of this promising measurement technique. Virtual experiments were carried out to quantify the sensitivity of the results with respect to the assumed linearity in the reconstruction procedure, positioning errors, and measurement noise. Furthermore, the virtual experiments can be used to (optimally) design the experiments, e.g. select the employed light sources according to the size, shape, and position of the specimen.

Our first results suggest that the mathematical TWI reconstruction technique basically allows for high-accurate measurements down to a few nanometer provided that calibration errors of the optical systems are kept small. The stability of the results and their accuracy can, however, depend significantly on the exact surface of the specimen and on the choice of experimental settings. The proposed simulation environment turns out to be a useful tool for (optimally) selecting the latter.

8789-7, Session 2

A method to measure sub nanometric amplitude displacements based on optical feedback interferometry

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Optical feedback interferometry is a well known technique which has been extensively studied during the past three decades. The OFI effect appears when a part of the light emitted by a laser diode (LD) is back-reflected in a small amount from a moving target and re-enters the laser cavity. This introduces sinusoidal beats in the emission of the laser which can be monitored as a modulation of the optical output power. The target displacement information can be directly extracted with a basic resolution of \( \frac{1}{2} \), equivalent to a fringe in a classical interferogram. It is important to remark that several regimes of modulation can be obtained depending on the strength of the feedback. Nevertheless, most of the studies agree that for displacement measurements it is better to stay within the moderate regime (C<1) where the LD output optical power acquires a sawtooth-like form, and in which each transition represents the minimum resolution while, in addition, information of the direction of movement of the sample may be extracted.

The resolution of OFI techniques is thus acceptable for displacement measurements in the micrometric range. However, when the displacement is within the range of \( \frac{1}{16} \), the quantification of it becomes a hard, or even an impossible task. To overcome this issue, two techniques have already been proposed by different groups. The phase unwrapping technique proposes the use of a special processing algorithm that increases resolution to a level of \( \frac{1}{16} \). A second technique uses an electro-optic modulator to increase the resolution to \( \frac{1}{12} \). Still, both of these techniques lack the capability of measuring true sub- \( \frac{1}{2} \) displacements since they rely in the appearance of at least one fringe to enable the measurement.

From our point of view, it is quite unlikely that standard OFI sensors can reach by themselves true nanometre amplitude resolution. However, as it will be shown, it is possible to reach such limits by comparing the signals obtained from two OFI sensors. The proposed method is valid for amplitudes within \( \frac{1}{2} \).

In the proposed method, the first LD is used to measure a reference displacement while the second LD measures the same reference as well as the target displacements. After acquisition, both signals are spatially compared. From this comparison it is possible to reconstruct the displacement information with a new time scale proportional to the rate appearance of the transitions on the reference waveform. Theory suggests that with typical signal acquiring devices it would be possible to reach resolutions within the sub-nanometre scale with low-cost, simple and compact setups.

To prove the proposed concept, several simulations have been performed to quantify as many factors as possible prior to the experimental testing. Best results of the simulation show that it is possible to reach displacement resolutions of around 0.1nm for low frequency measurements, while at higher frequencies resolutions within 2 and 3nm are still achievable. Some experimental issues which need to be managed, such as the effects of wavelength difference on both lasers, the effects of feedback regime and of the noise on the measurement have also been studied by simulation showing resolutions which stay well within the sub-nanometre scale.

Further work on this matter will focus on implementing a test bench for the technique as well as on solving environmental noise issues to satisfy that the measurement are not coupled with environmental displacements. Main applications for the technique being explored include fields such as material characterization, sonar type equipment, biomedical research and micro-magnetic field sensing.

8789-8, Session 2

Influence of surface structure on shape and roughness measurement using two-wavelength speckle interferometry

Thomas Bodendorfer, Philipp Mayinger, Alexander W. Koch, Technische Univ. München (Germany)

Surface shape and surface roughness are parameters of technical surfaces with major importance in e.g. production processes or quality control. The standard measurement system in industry is still based on stylus measurement techniques although optical measurement systems feature advantages like non-contact, non-destructive and fast measurement time.

In speckle interferometry the two-wavelength technique offers the possibility of both shape and roughness measurement. An object under test arranged in an interferometer is illuminated with laser light having two different wavelengths. In the most simplified case the two acquired interferograms are intensity-subtracted. The resulting possibility of both shape and roughness measurement. An object under test arranged in an interferometer is illuminated with laser light having two different wavelengths. In the most simplified case the two acquired interferograms are intensity-subtracted. The resolution of OFI techniques is thus acceptable for displacement measurements in the micrometric range. However, when the displacement is within the range of \( \frac{1}{16} \), the quantification of it becomes a hard, or even an impossible task. To overcome this issue, two techniques have already been proposed by different groups. The phase unwrapping technique proposes the use of a special processing algorithm that increases resolution to a level of \( \frac{1}{16} \). A second technique uses an electro-optic modulator to increase the resolution to \( \frac{1}{12} \). Still, both of these techniques lack the capability of measuring true sub- \( \frac{1}{2} \) displacements since they rely in the appearance of at least one fringe to enable the measurement.

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regarding their influence on speckle interferometry. Next to classical statistical distributed surfaces, different fractal approaches are used to create close to reality surfaces to perform numerical simulations of speckle patterns. Here three different algorithms are described and implemented in the diamond square algorithm, the Perlin-noise algorithm and a fragmentation algorithm. The used optical simulation method is a combination of geometric optics and wave optics, which offers good agreement between theory, simulation and measurement results. The underlying optical setup can be represented by a Michelson interferometer, where the surface model (which also includes parameters like reflectivity) consists of a 2D matrix of height values z(x,y). In all presented simulations the surface is chosen to be a tilted plane with respect to the reference mirror with constant angle to get comparable data. The simulation results are used to calculate fringe pattern and phase images of the simulated surfaces. Next to the actual shape, different parameters, known from speckle interferometry, like speckle contrast C or fringe visibility V are extracted and correlated with surface related roughness parameters (R_a, R_q, R_z, ...) in combination with the surface model types.

As a result we provide an answer to the question whether, and under which circumstances, the assumption of normal distributed surface structures in shape measurement using two-wavelength speckle interferometry is reasonable. Furthermore we compare different roughness parameters regarding their influence on speckle interferometry and shape measurements. As an outlook we shortly discuss a method which can be used together with the presented results to estimate roughness parameters using acquired interferograms from surface shape measurements together with algorithms related to the field of multivariate statistics.

References:

Design rules for a compact and low-cost optical position sensing of MOEMS tilt mirrors based on a Gaussian-shaped light source

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Systems containing Micro-Electro-Mechanical components (MEMS) are increasingly used for industrial applications. One subcategory of increasing interest is constituted by MEMS based optical elements (MOEMS). Well-known components in this area, based on very mature technologies, are electrostatically driven scanner mirrors which can be produced using CMOS compatible processes. Those mirrors, either designed as tiltable quasistatic mirrors or fast oscillating surfaces is available. It uses the Doppler Effect caused by

approximations. The use of an LED, small laser diode or VCSEL as a lightsource is appropriate due to their small size and inexpensive price. Those light sources typically emit light with a gaussian intensity distribution, which makes an analytical prediction of the expected detector signal quite complicated.

In this publication we want to present a numerical simulation model and derived design rules for best SNR and linearity for this optical mirror tilt-sensor design. The optical setup is modeled for one tilt-axis with two detectors in the simulation software ZEMAX® and the simultaneous influence of the parameters was evaluated afterwards via MatLab®. The divergence angle (sigma) of the Gaussian intensity distribution as well as the mirror radius (r), the height between light source and mirror backside (h), the active detector length (l) and the position (d) of the detectors away from the light source were identified as main parameters influencing signal SNR and linearity. The source is modeled as a point source with a given divergence angle and a Gaussian distribution for the irradiance. This complies with the far field approximation of the Gaussian beam description. The software uses a Monte-Carlo algorithm for ray tracing and thus does not support full electromagnetic Gaussian beam description and propagation. The mirror acts as a 100% reflector and the detectors track the intensity of the reflected light.

It is convenient to define the intensity difference between both detectors (1 and 2) as tilt-angle detection parameter. Normalization of the difference with respect to the overall intensity gives the “relative differential intensity” (RDI = (I1 - I2) / (I1 + I2)). This value is calculated for every tilt-angle in the range of alpha = ±20° for all influencing parameters (sigma, r, h, l and d). A linear relationship between the tilt-angle and the corresponding RDI value is desired. Thus, it is suitable to make a Taylor series expansion of the RDI curve for a full angle range (20° - alpha < ±20°) at expansion position alpha = 0. Due to symmetry only the uneven taylor terms are non-zero. Taylor coefficient T1 describes the desired linear behavior of the RDI curve and coefficient T3 is the first approximation for nonlinear contributions to the error. Higher Taylor terms were not evaluated.

The linearity of the RDI curve is very sensitive to the height h parameter. A good linear behavior can be found for positions very close or further away to the mirror. The divergence sigma of the Gaussian beam source and the radius r of the tilt radius are linked to each other for a good linear behavior. The detector should cover a large active area l for good linearity. However the SNR drops for larger areas. Thus, a compromise has to be found. The detector should be placed a certain distance away from the center. In this case also a tradeoff between good linearity (further away) and low overall signal has to be found.

Further and more detailed results will be presented in the final paper and at the conference.

REFERENCES

Extremum seeking control to avoid speckle-droppouts in a vibrometer

Robert Dehnert, Sascha Mayer, Bernd Tibken, Bergische Univ. Wuppertal (Germany)

To gather information about physical parameters from electric or electronic methods, the signal to noise ratio (SNR) plays a decisive role. It can be used as a measure of goodness for the current data acquisition.

With a laser Doppler vibrometer a contactless measurement of oscillating surfaces is available. It uses the Doppler Effect caused by
the local deviation of an oscillating surface, which can be analyzed interferometrically. Depending on the roughness of the surface, interference phenomena can occur and are usually known as speckle effects. The coherence behavior of the light in a laser Doppler vibrometer can lead to destructive interference, with the result that the signal to noise ratio is too low to perform a sufficient measurement. This interference related phenomenon is also called speckle-dropout.

To counteract this effect, the vibrometer was equipped with an adaptive optics, which can modify specifically the phase front of the coherent wave. In a first approach, the potential of signal optimization was investigated. Based on superposed Zernike polynomials, special phase pattern were calculated and written into that adaptive optics. Such polynomials are the common method to describe wave fronts in optical systems and, accordingly, are sufficiently precisely analyzed. Each Zernike polynomial has a related coefficient to weight it individually in a superposition.

These coefficients are the decision variables in an optimization algorithm. Correlated with a loop-back control, the coefficients can be interpreted as regulating variables. With the assumption that the system states are close enough to the optimal states, an extremum seeking control was developed to track and hold the system at that optimum. The algorithm depends on the successive parabolic interpolation, which was developed by Heath for one-dimensional problems. It was extended for solving a multi-dimensional problem definition and, furthermore, embedded into a loop-back control.

This talk presents the current design of the extremum seeking control and discusses the benefits with some results of the improved measurements.

8789-11, Session 3
Characterisation and comparison of ophthalmic instrument quality using a model eye with reverse ray-tracing
Conor Sheil, Alexander V. Goncharov, National Univ. of Ireland, Galway (Ireland)

A physical model eye was constructed to test the quality of ophthalmic instruments. The accuracy and precision of several commercially available instruments were analyzed. For these instruments, a particular model eye was constructed to mimic the physical properties that would be usually measured e.g. corneal topography or optical path within the human eye. The model eye was designed using relatively simple optical components (i.e. plano-convex lenses) separated by appropriate intraocular distances taken from the literature. The dimensions of the model eye were known a priori: The lenses used in the construction of the model eye were characterized according to values given in the manufacturers’ data sheets and also through measurement using an interferometer. The distances between the lenses were calculated using the interferometric data with reverse ray-tracing. Optical paths were calculated as the product of refractive index and axial distance. The errors inherent in measuring these ocular parameters by different ophthalmic instruments can be considered as producing an erroneous value for the overall refractive power of the eye. The latter is a useful metric for comparing various ophthalmic devices where the direct comparison of quality is not possible or is not practical. For example, a 1% error in corneal anterior radius of curvature will have a more detrimental effect than the same error in crystalline lenticular anterior radius, due to the relative differences in refractive indices at those surface boundaries. To quantify the error in ocular refractive power, a generic eye model was created in ZEMAX optical design software. The parametric errors were then used to compute the overall error in predicting ocular refractive power, thus highlighting the relative importance of individual errors. This work will help in future determination of acceptable levels of metrological errors in ocular instrumentation.

8789-13, Session 3
Modelling PTB’s spatial angle autocollimator calibrator
Oliver Kranz, Ralf D. Geckeler, Andreas Just, Michael Krause, Physikalisch-Technische Bundesanstalt (Germany)

The accurate and traceable form measurement of optical surfaces has been greatly advanced by the development of a new generation of surface profilometers which are based on the reflection of light at the surface and measurement of the reflection angle. As these devices are optimally suited to measure very large optical surfaces and topographies with high dynamic ranges and gradients, they have been successfully applied to the measurement of flatness standards at National Metrology Institutes (NMI) and of aspherical beam-shaping optical surfaces for applications in synchrotron beamlines and Free Electron Lasers.

For this application, high-resolution electronic autocollimators have proven to be capable of providing accurate and traceable angle metrology. Their precise calibration is central to making full use of their potential by correcting residual angle errors. In the recent years, great progress has been made at the Physikalisch-Technische Bundesanstalt (PTB) in this field. However, several important challenges remain, such as (1) the extension of traceable angle calibration from the plane to the solid angle and (2) the calibration of the effects of optical path length changes of the autocollimator beam. For an advanced autocollimator characterisation, innovative strategies and novel equipment have been developed.

At PTB, a novel calibration device has been established: the Spatial Angle Autocollimator Calibrator (SAAC). A 3 m long granite base plate which is mounted on six vibration isolators acts as the basis for the whole system. The mechanical parts of the Spatial Angle Autocollimator Calibrator (granite base plate and bridge, linear stage, two-axes tilting system) were manufactured by Q-Sys, Helmond, Netherlands. The SAAC is located in the PTB’s clean-room facility which provides excellent environmental conditions regarding vibration isolation and temperature stability.

The system makes use of an innovative Cartesian arrangement of three autocollimators (two reference autocollimators and the autocollimator to be calibrated). The Cartesian arrangement of the three autocollimators is achieved by mounting the two reference autocollimators (manufactured by Müller-Wedel Optical, Wedel, Germany) to a granite bridge whereas the autocollimator to be calibrated is placed onto a movable linear stage. The autocollimator’s optical axes are arranged orthogonally and the autocollimators are facing a reflector cube (made by Zeiss, Jena, Germany). The reflector cube’s tilt and yaw angles (as seen from the autocollimator to be calibrated) are manipulated by a high perforated two-sphere tilting system. Due to the Cartesian arrangement each of the reference autocollimator is sensitive primarily to changes in one of the two relevant tilt angles and can thus be calibrated and traced back to our national primary angle standard for the plane angle in a conventional manner. The autocollimator to be calibrated is sensitive to both angles. The optical path length between the reflector cube and the autocollimator to be calibrated can be varied flexibly by use of the linear stage. Thus, the SAAC meets the two above mentioned challenges to autocollimator calibration which are of special interest to profilometry.

Alignment errors of all components as well as non-orthogonalities of, e.g., the reflector cube’s surfaces and the tilting axes, affect the autocollimator beam reflection angles. As the reference autocollimators are extensively calibrated, the deviations can be used in an optimisation algorithm to determine the alignment errors and to correct the measurements of the reflector cube’s angular orientation. The corrected angles are used for the calibration of the third autocollimator. In the future, the installation of an angle interferometer is planned to measure the differential angle between the reflector cube and the linear stage on which the autocollimator to be calibrated is placed on. This will enable measurements with dynamically varying optical path lengths.

These efforts will allow advancing the form measurement with autocollimator-based profilometers substantially and to approach fundamental measurement limits. Additionally, they will help manufacturers of autocollimators to improve their instruments and will provide improved angle measurement methods for precision engineering.
Transmission functions of optical choppers for Gaussian beam distributions: modeling and simulations

Octavian Cira, Virgil-Florin Duma, Aurel Vialcu Univ. of Arad (Romania)

The paper presents a mathematical modeling of the transmission / modulation functions of the classical optical chopper wheels - with windows with linear edges. Based on our previous theoretical analysis on constant intensity distributions (top-hat) laser beams, in the present paper the complete modeling and simulation of the chopping process of light beams sections with Gaussian beams is proposed. The different possible cases of the relationships between the geometry of the chopper blades and of the beam section in the plane of the wheel are considered. The three relevant situations that can be met are approached: (i) large blades in front of the beam section (that can be thus completely covered by each blade); (ii) narrow single blade in front of the (larger) beam section; (iii) multiple narrow blades placed simultaneously in front of the beam section. The experimental chopper module we have built with different blades we have designed and fabricated as prototypes is also reviewed. Perspectives and future work on other types of optical chopper configurations conclude the study.

Selected References:
Virgil-Florin Duma, Prototypes and modulation functions of classical and novel configurations of optical chopper wheels, Latin American J of Solids and Structures, 10, 2013 - in print

Deconvolution microscopy of living cells for phase-contrast imaging (Invited Paper)

Guansiao Cheng, Ping Xu, Zhilong Sun, ChunQuan Hong, Zelin Li, Shenzhen Univ. (China)

Deconvolution is a key computerized inversion method for restoring an image distorted during the image formation process. In deconvolution microscopy for phase-contrast imaging, the goal is to reassign the optical blur to its original position and to reduce statistical noise, thus visualizing the cellular structures of living cells in three dimensions and at subresolution scale.

This paper aims to describe the major features of this technology for a phase-contrast microscopy that we presented based on a type of compound diffractive lenses “Zernike apodized photon sieves” [Opt. Lett. 35(21), 3610, 2010], from theoretical aspects to practical solutions. Use of the ZAPS to generate phase-contrast is an attractive method of implementing phase-sensitive imaging due to the simplicity and ease in alignment. The ZAPS is a single optic that integrates the appropriate ±π/2 radians phase shift through selective zone placement shifts in a region of an apodized photon sieve pattern rather than by material transmission from a separate filter. The shifted portion of the photon sieve corresponds to the region of zeroth order light determined by the illuminating geometry of the system. It presents the theoretical and experimental description of image generation through a phase-contrast microscope. The degradations process of a microscope can be modeled as an point spread function PSF, which, together with the noise N, operates on an input image to produce a distorted image Id. Deconvolution microscopy is a mathematical process that computes an object’s approximation I0, given the acquired image Id, knowledge of the degradation model PSF, and the noise N. Although deconvolution is able to deblur the cell image to a great extent, the artifacts of ringing around the sharp intensity contrast areas in the restored image is unsatisfactory. However, appropriate specimen preparation, image acquisition, eliminating high-contrast areas from the processing or specifying a better PSF will usually eliminate these artifacts. Methods are detailed for the determination of point spread function, as a crucial step for the characterization of a phase-contrast microscope and a key preliminary step for image deconvolution. A few possible sources of aberrations and image degradation processes are discussed. In the last part of this paper, some restoration algorithms used in the field of phase-contrast microscopy are described in theoretical terms and a few of results obtained with simulations are also provided. The theoretical and experimental results have shown that deconvolution microscopy can enhance resolution and contrast by either subtracting or reassigning out-of-focus blur.

Measurement based simulation of microscope deviations for evaluation of stitching algorithms for the extension of Fourier-based alignment

Florian Engikel, Markus Kästner, Eduard Reithmeier, Leibniz Univ. Hannover (Germany)

Image stitching is a technique used to measure large surface areas with high resolution while maintaining a large field of view. We work on improving data fusion by stitching in the field of microscopic analysis of technical surfaces for structures and roughness. Guidance errors and imaging errors such as noise cause great problems in seamless image fusion of technical surfaces. The optical imaging errors of three 3D Microscopes, such as confocal microscopes and white light interferometers, as well as the guidance errors of their automated positioning systems have been measured to create a software to simulate automated measurements of known surfaces with specific deviations to test new stitching algorithms. To emulate the imaging process of the microscopes, their noise behavior was analyzed by statistical evaluation of a large number of measurements of a mirror standard. The mean image of the mirror is always superimposed on the images acquired with the microscope, like a watermark and is independent of the measured area of the mirror (Figure 1). This effect needs to be compensated to achieve seamless image fusion. By means of imaging chessboard structures with known features the radial distortion caused by the objective lens was analyzed using the model by Brown [1]. The drift behavior of the z-axes of the microscopes, which leads to faulty height measurements, was analyzed by imaging a sphere standard with a limited measuring range. This results in rings of valid height data, with a radius depending on the z-position of the microscope. Using cross correlation the drift behavior of the x- and y- axes was analyzed for a large number of measurements. A structure standard was measured repeatedly over the course of hours and the resulting images where registered in respect to one another to gain relative positional data. The repeatability and the on-axis-accuracy of the x- and y-axes where measured using a structural standard to get a statistical evaluation of their positioning errors. To achieve this, two distinct features of the standard where used as targets while movements of equal length where performed between them. The resulting images where registered using cross correlation to estimate the movement error.

The angle between the translational axes and the axes of the CCD-chip where measured by moving along one of the translational axes and registering the measurements with respect to one another. By statistical evaluation of the translational component perpendicular to the direction of movement the rotational angle can be identified.

The measured parameters, resulting in positional uncertainty and quality reduction of the images where used to create simulation software which rapidly creates image mosaics with distortions and motion errors to test image stitching algorithms.

The software was used to evaluate a method developed to decrease the overlap ratio of fourier-based correlation, which is a computationally cheap and robust method for image registration but which is not applicable for overlap regions smaller than 30% of the image, as the fourier cross correlation becomes inconclusive (Figure 2) [2]. Inspired by histogram based alignment methods presented in [3], our algorithm uses 1D projections of surface features to estimate the overlap region (Figure 3). Following this rough alignment the fourier-based

8789-14, Session 3

8789-16, Session 4
further evaluate the use of integrating supporting reference metrology parameters such as side wall, feature profile and etch depth. We will for the quantitative evaluation of correlation effects due to fitting of the discretized three-dimensional scattered fields and allows below 20 nm in critical dimension. The technique involves parametric and evaluate uncertainties in the measurement of dense features and develop a library for regression based fitting to experimental data, This paper will use rigorous electromagnetic simulation tools to acquire the “optical tool function” which is used to represent the hardware. We will also develop the experimental methods needed to acquire the “optical tool function” which is used to represent the hardware. We will also develop the experimental methods needed to acquire the “optical tool function”. This method allows for the quantitative evaluation of correlation effects due to fitting of the discretized three-dimensional scattered fields and allows for the quantitative evaluation of correlation effects due to fitting.

In this paper, a novel method for the characterization of defects using Fourier normalization to obtain Sub-nanometer parametric uncertainties Richard M. Silver, Bryan M. Barnes, Jing Qin, Hui Zhou, Martin Sohn, National Institute of Standards and Technology (United States)

Recent advances in 3-D optical metrology that use imaging optics for critical dimension measurements have the potential for very small measurement uncertainties. Sensitivity to nanometer scale changes has been widely observed when measuring critical dimensions of sub-wavelength features or when imaging defects below 20 nm using angle-resolved and focus-resolved optical data. However, since these methods inherently involve elaborate imaging optics, developing an accurate analysis of the complex three-dimensional electromagnetic fields has remained elusive. In this presentation we will develop a rigorous analysis of three-dimensional through-focus optical images using quantitative statistical regression algorithms. We will apply Fourier optical normalization methods in combination with statistical methods to evaluate sensitivities and uncertainties in the measurement of targets encountered in 16 nm node critical dimension metrology. Electromagnetic simulation tools are integrated with optical microscope characterization functions to achieve significant improvement in modeling accuracy. In addition to these methods have great potential for enabling in-die metrology applications. A central theme of the presentation will be the quantitative evaluation of high magnification focus-resolved and angle-resolved 3-D optical imaging and the potential for sub-nanometer scale uncertainties due to the increase in optical information content. These very low uncertainties are fundamentally based on the phase and frequency information inherent in optical imaging of the scattered fields. Unlike standard scatterometric methods that use only the reflected intensity from targets that overfill the field of view, an image based method acquires significantly more optical content and information. The significant challenge in accessing this additional information is a complex set of hardware errors that must be properly accounted for in the simulation-based estimation and data fitting. We will develop and present a comprehensive normalization approach applied in the Fourier domain that is capable of correcting for a broad range of amplitude, polarization and phase errors introduced by the hardware. We will also develop the experimental methods needed to acquire the “optical tool function” which is used to represent the complete set of tool errors. We will discuss the complications in quantifying polarization and phase errors with solutions. This paper will use rigorous electromagnetic simulation tools to develop a library for regression based fitting to experimental data, and evaluate uncertainties in the measurement of dense features below 20 nm in critical dimension. The technique involves parametric fitting of the discretized three-dimensional scattered fields and allows for the quantitative evaluation of correlation effects due to fitting parameters such as side wall, feature profile and etch depth. We will further evaluate the use of integrating reference metrology measurements in a Bayesian hybrid metrology.

Reconstruction of SNOM near-field images from rigorous optical simulations by including topography artifacts Markus Ermes, Stephan Lehnen, Karsten Bittkau, Reinhard Carius, Forschungszentrum Jülich GmbH (Germany)

In thin-film photovoltaics, light scattering textured surfaces are used to increase the path length of photons in a wavelength region where the thickness of the absorber layer is (much) thinner than the absorption length of the material. This path length enhancement, photons are more likely to be absorbed. To achieve this efficiently, surface morphologies with steep flanks have proven to be efficient. To investigate the light propagation and light trapping in silicon based thin-film solar cells with rough substrates in detail, scanning near-field optical microscopy (SNOM) is a powerful tool providing the measurement of the near-field intensity which is related to guided optical modes. These measurements can be combined with rigorous solving of Maxwell’s equations - in our case via the Finite-Difference Time-Domain (FDTD) method - to gain more insight into light propagation and absorption inside the layer, which is not accessible via experiment. However, there are major differences between the simulated near-field intensity directly above the surface and the intensity obtained by SNOM measurements. The SNOM measurements are performed in a way that sample and probe have a distance of about 20 nm at their closest point, therefore the finite size of the probe has a severe impact on the measurement. Any steep flank, such as those beneficial for light scattering, present in the topography leads to an increased distance between the aperture of the tip and the sample surface, since the shortest distance between sample and probe occurs at the side of the tip. This behavior modifies the measurement at all points where the geometry does not allow for the aperture to be placed 20 nm over the topography since another part of the probe gets in contact with the surface, leading to so-called topography artifacts. Due to these artifacts, the intensity of evanescent waves, which decreases exponentially with the distance, is reduced in experiment. To account for these topography artifacts in our simulations, we developed an algorithm to calculate the height of the probe above each point of the surface. Using a probe geometry calculated from a set of parameters or given as an arbitrary geometry, we obtain the height at each point of the topography in a way that the shortest distance between any part of the probe and the sample is e.g. 20 nm by varying the distance between probe and sample. This procedure results in a specific distance between sample and probe at each point of measurement. Repeating this process for the whole topography, we obtain a map of tip positions. These tip positions can be combined with simulated data from FDTD to create an intensity distribution at the same positions as the SNOM measurement. This intensity distribution shows a much better agreement to experiment than assuming a constant distance of 20 nm from the surface. Additionally, the influence of the aperture of the probe on intensity distributions is investigated by comparing the intensity at the tip position with an averaged value considering the whole area inside the aperture of the probe. By this, the finite optical resolution of the near-field probe is taken into account. We will present correlations between the local surface morphology and the probe height and investigate the dependency of this correlation on the assumed probe geometry which helps to analyze the probe geometry from experiment.

Defect parameters retrieval based on optical projection images Dongbo Xu, Sikun Li, Shanghai Institute of Optics and Fine Mechanics (China); Xiangzhao Wang, Shanghai Institute of Optics and Fine Mechanics (China) and Graduate School of the Chinese Academy of Science (China); Tim Fühner, Andreas Erdmann, Fraunhofer-Institut für Integrierte Systeme und Bauelemententechnologie IISB (Germany)

In this paper, a novel method for the characterization of defects
in nanostructures by optical projection imaging is proposed. The parameters of defects in nanostructures are retrieved from measured aerial images of high NA projection systems. In this paper, the difference of aerial images of masks with and without defects is used as reference image to reconstruct the parameters of the defect. The defect retrieval procedure can be expressed as an optimization problem with an appropriate merit function. The measurement performance of the method was simulated by the lithography and imaging simulator Dr. LITHO. Both the Kirchhoff-type mask model and the rigorously simulated masks with 3D shapes are employed in this investigation. Dr. LITHO built-in optimization methods are used in the retrieval procedure. To emulate a realistic scenario, a certain noise was applied to the reference image. The dependencies of the retrieval from illumination setup on design of photomask shapes will be discussed in detail in the paper. Moreover, the sensitivity of the defect detection to Zernike aberrations of the optical image projection lens, and the retrieval accuracy for different mask layout types, mask model, defect types will be discussed. Finally, the proposed method is extended to multi-layer photomasks. First results corresponding retrieval procedure will be presented.

8789-20, Session 5

Alternative discretization in the aperiodic Fourier modal method leading to reduction in computational costs (Invited Paper)
Maxim Pisarenco, Irwan D. Setjja, ASML Netherlands B.V. (Netherlands)

The Fourier modal method (FMM), also referred to as Rigorous Coupled-Wave Analysis (RCWA), has quite a long history in the field of rigorous diffraction modeling. It was first proposed by Knop in 1978 [J. Opt. Soc. Am., 68(9):1206-1210, 1978]. Being based on Fourier-mode expansions, the method is inherently built for periodic structures such as diffraction gratings. However, the aperiodic Fourier modal method (AFMM-CFF) has been proposed [J. Opt. Soc. Am. A, 27(11):2423-2431, 2010] which allows modeling of finite structures illuminated under arbitrary angles of incidence. The new method reformulates the governing equations in terms of a contrast field and introduces perfectly matched layers at the boundaries with implicit periodicity. As a result, the same (radiation) condition is imposed on all boundaries of the computational domain and the restriction of using Fourier harmonics in the periodic direction is eliminated. This opens new possibilities for alternative discretizations leading to lower computational costs.

The classical FMM uses a combination of spectral and spatial discretizations. In the vertical direction the domain is divided into layers. In each layer, the horizontal direction is discretized into Fourier harmonics. The complexity of the method scales cubically with the number of harmonics and linearly with the number of layers while the memory space scales quadratically with the number of harmonics and (again) linearly with the number of layers. It appears that the horizontal direction is “more expensive” both in terms of time and memory. For rectangular scatterers/domains that are much longer in the horizontal direction it is reasonable to choose an alternative discretization that makes the longer direction “cheaper” by using spatial discretization into layers and apply spectral discretization in the shorter direction. Moreover, if the scatterer has repeating patterns (local periodicity), swapping the discretization directions facilitates the reuse of previous computations.

Second, we explore influence of the defects in the underlying grating topology on the HCG spectral properties. We show that spectral response of HCGs is robust in the presence of symmetric defects, while asymmetric defects may introduce completely new spectral response. An interesting connection between theory of 1D photonic crystals and periodic HCG structures has been observed in [1]. However, some fundamental differences are present due to different operating regimes between HCGs and photonic crystals. We show examples, for the first time, of modeling of the high-Q resonances in the case of HCGs by using theoretical estimates. Where differences arise the reason is identified numerically in the paper.

Numerical experiments demonstrate a considerable reduction of the computational costs in terms of time and memory. For a specific test case considered in this paper, the new method (based on alternative discretization) is 40 times faster and requires 100 times less memory than the method based on classical discretization. The speed-up and memory use factors obtained with alternative discretization are dependent on the imposed accuracy, number of repeating patterns and the size of jump discontinuities in the background multilayer.

Numerical experiments confirm that the alternative discretization shows significant improvements for geometries with small jumps at the layer interfaces and a large number of periods. Next to practically computed speed-up and memory use factors we derive their theoretical estimates. Where differences arise the reason is identified and explained.

8789-21, Session 5

Modeling and optimization of high index contrast gratings with aperiodic topologies
Milan Maksimovic, Focal 2.0 BV (Netherlands)

Optical gratings are the fundamental and ubiquitous element used for shaping of spatial, temporal and spectral properties of light signals. Recently, a new type of high-contrast gratings (HCG) has been proposed. HCGs are the ultra-thin elements set to operate in near-wavelength regime with the period of the grating in order of the wavelength and with the high-index grating material fully surrounded by low-index material. Owing to these structural characteristics HCGs exhibit great variety of novel features with great importance in integrated optoelectronics such as: ultra-broadband high reflectivity, high-quality-factor resonances, wave front phase control for planar focusing reflectors and lenses in integrated optics, etc. [1].

We concentrate on the HCGs with the defects in the periodic grating structure or with the complex unit cells having an aperiodic topology. These topics are scarcely explored in the literature. Main emphasis of our paper is on the theoretical analysis and exploration of parameter space for designing HCGs with prescribed properties such as broadband reflection or high-Q resonances in transmission or reflection. We use for numerical simulations rigorous coupled wave analysis (RCWA) and coupled mode theory (CMT) in-house Matlab code and finite element method (FEM) in open-source FreeFem++ suite [3].

First, we start with analysis of the periodic HCGs supporting high broad band reflectance or high-Q resonances. We explore conditions and parameter space constraints for extending these spectral regions and resonances expected for periodic HCGs to the obliquely incident excitation. Our results show the boundaries of the parameter space landscape were broad-band reflectance or high-Q resonances are achievable. To test the tolerances of the designed response we simulate influence of random perturbations of the HCGs structural parameters according to expected fabrication limitations. Our results show the boundaries of the parameter space landscape were broad-band reflectance or high-Q resonances are achievable. To test the tolerances of the designed response we simulate influence of random perturbations of the HCGs structural parameters according to expected fabrication limitations. Our results show the boundaries of the parameter space landscape were broad-band reflectance or high-Q resonances are achievable. To test the tolerances of the designed response we simulate influence of random perturbations of the HCGs structural parameters according to expected fabrication limitations.}

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Numerical experiments demonstrate a considerable reduction of the computational costs in terms of time and memory. For a specific test case considered in this paper, the new method (based on alternative discretization) is 40 times faster and requires 100 times less memory than the method based on classical discretization. The speed-up and memory use factors obtained with alternative discretization are dependent on the imposed accuracy, number of repeating patterns and the size of jump discontinuities in the background multilayer.

Numerical experiments confirm that the alternative discretization shows significant improvements for geometries with small jumps at the layer interfaces and a large number of periods. Next to practically computed speed-up and memory use factors we derive their theoretical estimates. Where differences arise the reason is identified and explained.
landscapes. We chose the most suitable parameters and apply local numerical optimization procedure. As a last step, we take a finite approximant structure and use the FEM simulation for local tuning of the parameters.

Owing to importance of HCGs in integrated optics it is useful to understand constraints in the design parameter space, validity and limitations of computational and modeling methods. Depending on the underlying HCG structure we make a comparison of numerical results for selected examples between ROWA, FEM and CMT methods. These results can serve as guidance for selecting proper method and parameters for simulations or design of complex HCGs. The design of aperiodic grating structures through optimization is a computationally expensive task due to the size and complexity of the optimization space. Global optimization and direct search algorithms may become ineffective in finding a meaningful optimum due to presence of numerous local optima. Our methodology and analysis helps with the successful selection of the efficient initial topology.


8789-22, Session 5

Finite element method for computational metrology

Sven Burger, JCMwave GmbH (Germany) and Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany); Jan Pomplun, Lin Zschiedrich, JCMwave GmbH (Germany); Frank Schmidt, JCMwave GmbH (Germany) and Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany); Bernd Bodermann, Physikalisch-Technische Bundesanstalt (Germany)

Computational methods have become an integral part in metrology. For optical metrology of nanostructures accurate simulation of light propagation is an essential component. A challenge consists in reducing computation times for simulation results matching predefined accuracy requirements. This is especially important when real-world structures of complex geometry are considered.

We present a fast, finite-element based method to address such computation challenges. In this contribution we focus on (i) online-offline-approaches for parameterized simulation problems and (ii) finite-element based computation of derivatives of the propagating light fields with respect to geometrical parameters of the geometrical setup.

As application examples we present simulations of the light scattering response of structures on a scattersetor reference standard.

8789-23, Session 5

Effect of imposed boundary conditions on the accuracy of transport of intensity equation based solvers

Juan Martinez-Carranza, Kostantinos Falaggis, Tomasz Kozacki, Małgorzata Kujawinska, Warsaw Univ. of Technology (Poland)

Non-destructive techniques that allow accurate and quantitative measurements of phase objects had a tremendous impact in many fields ranging from biology to physics and engineering, because they allow visualizing an industrial or biological sample that would otherwise not be visible. These techniques are usually divided into interferometric and non-interferometric methods. Although interferometric methods are widely used, they are limited by the coherent illumination or the interferometer stability. One important example of non-interferometer techniques are based on the Transport of Intensity Equation (TIE) that relates the phase of an object to the intensity distribution in the Fresnel region. Although this technique was developed for Transmission Electron Microscopy [1], and X-ray imaging [2], the TIE technique has also found a variety of applications in fields as astronomy, adaptive optics and others. TIE based approaches allow to estimate the phase directly without necessity of phase unwrapping [3], having an resolution close to the diffraction limit, using a single beam with partially coherent illumination, and a series of intensities -that have been recorded for various axial positions. There are two popular approaches, to solve the TIE, the first is based on the Fast Fourier Transform (FFT) [4] that solves the TIE in the frequency domain, and the second on the Multigrid (MG) Poisson Solver Method [5] that solves the TIE in the spatial domain. A well accepted approach to solve the TIE by using the FFT method is to make the assumption that the magnetic vectorial potential can be neglected and the optical field can be described solely by the electric scalar potential, which implies that the full the TIE is not solved. In its basic configuration the FFT method inhibits a periodic boundary condition, as well. The MG technique can acquire a solution of TIE using the finite differences over the whole equation, where any boundary condition can be introduced on the phase (Periodic, Neumann or Robin boundary condition). The effect of the boundary condition is independent of the chosen solver which must be chosen carefully because it affects the numerical stability and could introduce artifacts. In this work, a numerical analysis, which investigates the influence of the boundary conditions in terms of accuracy, is presented. A comparison of the results of both solvers is presented to identify the fundamental problems of these popular approaches. This analysis is carried out using a Full Multigrid Method (FMM) [6] and an extended FFT method (eFFT) that makes use of a mirror padding scheme [7], which allow imposing special cases of the Neumann or Dirichlet boundary conditions. It is shown that the error depends on the spatial frequency range of the object, the maximum phase change, and the presence of noise. The performance of eFFT based TIE solvers (with electric scalar potential approximation) show to be superior in comparison to conventional FMM based Poisson solvers. However, if the scalar potential approximation is adopted in the FMM scheme, the robustness and accuracy are significantly increased and the error is in the same order as for FFT based solution, but allows applying arbitrary instead of special of the Neumann or Dirichlet boundary conditions.

References


8789-24, Session 5

Rigorous Dyson equation and quasi-separable T-scattering operator technique for study of magnetic response from ordered and disordered non-magnetic particles’ ensembles at electromagnetic wave multiple scattering

Yuri N. Barabanenkov, Institute of Radio Engineering and Electronics (Russian Federation); Mikhail Y. Barabanenkov,
Institute of Microelectronics Technology and High Purity Materials (Russian Federation)

Starting with paper [1], where the incident wave electric field is supposed to have the Floquet property, we derived an exact Dyson equation for averaged over electromagnetic crystal unit cell propagating total wave electric field. The mass operator related to periodic structure effective tensor dielectric permittivity via known relation is written as double Fourier transform from T-scattering operator of the structure unit cell. The Lippmann-Swinger equation for the unit cell T-scattering operator, written in terms of the unit cell T-scattering in free space and the electric field lattice tensor Green function interaction part, is resolved by recently presented quasi-separable method [2]. Note that this quasi-separable approach to unit cell T-scattering operator enables one to consider unit cell containing several particles, with coupling between them directly inside the cell as well as through the structure via above lattice Green function interaction part. The obtained quasi-separable unit cell T-scattering operator is applied to study a new magnetic phenomena in microstructured composites as artificial double diamagnetic-paramagnetic narrow peak in metamaterial with unit cell of coupled plasmonic particles. Actually this magnetic phenomenon is appeared as combination result of space-group resonance [3] between two small dielectric spheres and plasmonic resonance inside a single sphere. Side by side with artificial magnetism at wave propagation in spatially periodic ensemble of dielectric and conducting nonmagnetic particles we consider such magnetism in random discrete media. We use Dyson self-consistent exact equation [4] for ensemble averaged wave electric field inside dense discrete random media, with a random mass operator having been put under averaging sign. The random mass operator was written in terms of particles’ correlations functions of all orders and particles’ clusters’ T-scattering operators. We discuss comparison between an unit cell T-scattering operator of periodic discrete structure and a cluster T-scattering operator of random discrete structure and consider the above double diamagnetic-paramagnetic peak also in random discrete structure of coupled small plasmonic dielectric spherical particles.

References

8789-25, Session 5

The influence of nonlinear modal propagation analysis on MMI power splitters for miniaturization
Mehdi Tajaldini, Mohd Zubir MatJafri, Univ. Sains Malaysia (Malaysia)

This study investigates a method to access the power splitting performances of multimode interference waveguides based on analytical nonlinear modal propagation in the presence of the Kerr nonlinear effect for device miniaturization. Polydiacetylene crystalline is chosen as the core layer of waveguide due to the unique nonlinear optical properties. Nonlinear multimode interference waveguide has been reported in a previous work based on beam propagation analysis (BPM) to make it a special path with intense input for switching purposes. BPM method does not seem a capable method for studying the multimode waveguide performance in small length. Therefore, we established the nonlinear modal propagation analysis that is determined based on the propagation of all nonlinear guided modes throughout the medium whereas this shows the amplitude and phase changes of the guided modes. In fact mentioned change lead to induction of nonlinearity on original guided modes and make them nonlinear. In this paper, the nonlinear guided modes which are activated in effect of decomposing of input beam are measured by solving the nonlinear differential equation. The intensity distribution among the multimode waveguide is made as simulation tools for assisting us to show the possibility to access the 1 N power splitters operated in a small lengths in comparison with past reports in linear regimes. In fact the formation of parallel self-images determined the outputs for splitter and the resolution and contrast of image show the uniformity and insertion loss that result demonstrate desirable uniformity and insertion loss so that miniaturization does not decrease the performance. Also the simulation results show the active device is more sensitive to the input intensity. This sensitivity can be made as a foundation of an arbitrary power splitter ratio device.

8789-26, Session 6

Multi resonant platform based on modified metallic nanoparticles for biological tissue characterization
Renato Iovine, Luigi La Spada, Univ. degli Studi di Roma Tre (Italy); Richard Tarparelli, Lucio Vegni, Univ degli Studi di Roma Tre (Italy)

When the electromagnetic field (in the Visible and Near Infrared Region) interacts with small metallic particles, their conduction electrons start oscillating collectively. This phenomenon is known as Localized Surface Plasmon (LSP). The optical properties (such for example the wavelength corresponding to the resonant condition) are highly dependent on the size, shape and material of the particles, as well as the dielectric properties of the background environment. It is well known that at the resonant frequency, such particles allow to concentrate in a small volume the incident electromagnetic field with a great local enhancement. Exploiting these electromagnetic optical properties several application for biomaterials characterization are reported in literature. For example, the possibility to obtain an enhancement of the Raman Scattering signal (Surface Enhanced Raman Scattering - SERS), using gold nanoparticles, to diagnose tumor in an early stage is referred. This approach compared to traditional assay detection technologies (fluorescence and chemiluminescence) includes several advantages such as high sensitivity, robustness and ability to perform detection in blood and other biological matrices.

In this study we propose modified particles by dielectric incisions on their surface that allow to obtain a multi-resonant behavior. In our approach, at the resonant frequencies correspond different electric field localizations (hot spots) on the nanoparticle surface. In this way the simultaneous multi-characterization of different compounds is possible.

In particular we propose a modified bow-tie particle by asymmetric dielectric incisions.

We have assumed all the bowtie particles to be composed of gold, modeled in our simulations with experimental values of the dispersion of dielectric constant reported in literature. The background material is supposed to be vacuum.

The optical properties in terms of absorption, scattering, extinction cross section and near electric field are evaluated through proper full-wave simulations. The structure is excited by a plane-wave, having the electric field E parallel and the propagation vector k perpendicular to the plane containing the particle.

This excitation is employed to analyze the far-field properties in terms of absorption and scattering cross-sections and the near electric field distribution at the resonant wavelengths to evaluate the local field enhancement. In this configuration the structure exhibits two additional resonant frequencies compared to the one obtained with the classical bow-tie particle.

In our simulation we have verified that each resonant frequency is strongly influenced by the local refractive index variation of the dielectric inside the bow-tie particles. This characteristic make this particle a useful tool for multi-sensing approach.

The refractive index (RI) is a unique physical property of tissue. The dielectric constant changes as a result of changes in electron density of the tissue. From a medical point of view, local changes in tissue refractive index value can be related to different pathological conditions. From a medical point of view, local changes in tissue refractive index value can be related to different pathological conditions. In disease states, such as neoplasia or inflammation, color of tissue changes due to the change in RI, which in turn is related to the relative permittivity of the tissue.

The proposed nanostructure could be able to perform simultaneous
Investigation of microstructured fiber geometries by scatterometry

Poul-Erik Hansen, Danish Fundamental Metrology Ltd. (Denmark); Sven Burger, JCMwave GmbH (Germany)

Hollow-core photonic bandgap fibers guide light using diffraction rather than total internal reflection as is the case with normal single-mode communications fibers. The fibers consist of a hollow capillary (~19 micrometers in diameter) arranged in a honeycomb like structure. The honeycomb structure scatters light in the core such that light within the bandgap wavelengths cannot escape from the core. However, the bandgap properties greatly depend on the accuracy with which the microstructures can be controlled during the fabrication process.

For measuring the geometrical properties of hollow core photonic crystal fibers with a honeycomb cladding structure we use an angular scatterometric setup.

For analysing the experimentally obtained data we rigorously compute the scattering signal by solving Maxwell's equations with finite-element methods.

This contribution focuses on the numerical analysis of the problem. A convergence analysis demonstrates that we reach highly accurate solutions.

Our results show very good qualitative agreement between experimental and numerical results.

We furthermore demonstrate concepts for accurately monitoring dimensional parameters in the fiber manufacturing process.

Alternative methods for uncertainty evaluation in EUV scatterometry

Sebastian Heidenreich, Mark-Alexander Henn, Hermann A. Gross, Bernd Bodemann, Markus Bär, Physikalisch-Technische Bundesanstalt (Germany)

The precise and accurate determination of critical dimensions and its uncertainties of photomasks is crucial issue in the lithographic process to ensure operational reliability of electronic compounds. Scatterometry is known as a fast, non-destructive optical method for the indirect determination of geometry parameters from scattered light intensities. In recent years advanced methods for solving the in reverse problem in scatterometry have increased the precision and accuracy of grating parameter estimations. In this presentation we summarize results from the maximum likelihood approach applied to experimental and computationally derived EUV scatterometry data. Uncertainties of parameters are consistently calculated by the Fisher information matrix. The method is applied to three different underlying mathematical models with increasing number of estimated parameters. The best results could be achieved with the third model that includes absorber line and multilayer roughness. Furthermore, uncertainties derived from the Fisher information matrix are compared with uncertainties calculated from surrogate approximations.
8789-33, Session 8

Modelling laser interferometers for the measurement of the Avogadro constant

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No Abstract Available

8789-34, Session 8

Fundamental performance determining factors of the ultrahigh-precision spaceborne optical metrology system for the LISA Pathfinder mission

Gerald Hechenblaikner, Reinhold Flatscher, EADS Astrium GmbH (Germany)

The LISA Pathfinder Mission is a technological precursor to the Laser-Interferometer Space Antenna (LISA) mission which aims to detect gravitational waves with interferometry.

One of the subsystems at its core, the Optical Metrology System (OMS) performs interferometer measurements of position and attitude between two freely floating test-masses to an accuracy of pico-meter and nano-rad, respectively, which make it the most precise metrology system for space as of today.

On one hand, its measurement data allow determining the residual differential acceleration between the two test-masses to an accuracy of better than $3 \times 10^{-4}$ m/s² (2 orders of magnitude better than state-of-the-art accelerometers). On the other hand, the OMS output feeds into the “drag-free attitude and control system” which counteracts external perturbations acting on the spacecraft and allows demonstration of quasi-free floating test-masses.

As an overview we give a detailed account of the working principles of the Optical Metrology System which is essentially based on the digital phase-readout and processing of the signals of four heterodyne interferometers located on an ultra-stable optical bench.

The impact of various noise sources on the overall measurement performance is briefly discussed, among which frequency and power fluctuations of the laser source, parasitic optical sidebands induced by RF-crosstalk in the modulator and phase noise combined with path-length variations induced by signal transmission through optical fibres are the most prominent ones. These limitations can be overcome by the use of digital control loops which suppress laser frequency noise and differences in optical path-length to such a degree that the final performance is fundamentally only limited by the sensor and quantization noise of the digital phase-meter. Furthermore, overall stability and performance is much improved by balancing the interferometer arm-lengths to a good degree, which specifically reduces the effect of laser frequency fluctuations.

Because of the general system design is that the phase of the “reference interferometer” is subtracted from the phase of the test-masses “position interferometer”, thereby greatly suppressing common mode noise fluctuations occurring in volatile optical path sections shared by both interferometers.

Analyses of experimental data recorded during recent test and qualification campaigns point to an as yet unaccounted phenomenon which relates to imperfect common mode noise suppression when the two interferometer phases are subtracted in the digital domain. We find that the efficiency of common mode noise subtraction depends strongly on the relative difference of the interferometer phases: Increasing phase differences lead to decreasing common mode noise rejection. We theoretically investigate the expected level of noise rejection and discuss its dependency on relative phase, on quantization error, and on the amplitude of the phase-noise whilst comparing our findings to those observed in experimental measurements.

8789-35, Session 8

EFPI signal processing method providing picometer-level resolution in cavity length measurement

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In the last two decades industry and academia are drawing an increasing attention to the optical sensors based on the extrinsic Fabry-Perot interferometers (EFPI) [1]. Sensors demonstrating high sensitivity to measurands (temperature, strain [2], pressure, humidity...
and other physical quantities [1] and utilizing a miniature sensing element are designed. Systems based on EFPI generally register an absolute value of cavity length \( L \), unlike the most of the interferometric optical sensors, which suffer from an uncertainty of initial value of the measured quantity. In most cases principles of white-light interferometry with scanning recovery interferometer are used [1].

However, a more promising idea of measuring \( L \) is based on the registration and further processing of the EFPI spectral transfer function \( S(\lambda, L) \). This concept is advantageous regarding the recent progress in capabilities of optical sensor interrogators for fiber Bragg gratings (FBG), which are widely commercially available. Spectral function of Fabry-Perot interferometer is related to its baseline \( L \) with an Airy function [1], which can be replaced by a simpler expression in the case of low Q factor (small reflective indexes of mirrors, close to the case of Fizeau interferometer)

\[
S(L) = C + S'(L) = C + A \cos(2\pi n L/\lambda + \phi),
\]

where \( n \) is the refractive index of the media between the mirrors, values \( A \) and \( C \) are determined by mirrors refractive indexes, numeric aperture of the fibre and the cavity length \( L \). An additional term in the oscillating component \( S'(L) \) argument appears due to nonplanar wave front of light inside the interferometer and phase shifts introduced by mirrors. It is generally dependent of \( A \) and \( L \). In a number of works an approach based on the measured spectra \( S_m(\lambda) \) extreme points counting for estimating \( L \) is suggested. However, such method doesn’t provide high measurement accuracy. Han et al [3] proposed to approximate measured spectra with the analytical expression (1) by means of finding \( L \) reducing the norm of residual \( R(L) = \| S(\lambda, L) - S_m(\lambda) \| \) between analytical and measured oscillating components to its lowest value.

In order to provide high accuracy of such measurements one is demanded to take into account specialties of EFPI-based systems. Such considerations can be related to a wide variety of questions, requiring theoretical and experimental investigation. However, in any case, the measurement accuracy can sufficiently depend on the algorithm obtaining \( L \) from the measured spectra \( S_m(\lambda) \). Also it’s worth mentioning that the search of the global minimum of \( R(L) \) by direct enumeration requires an enormous amount of calculations. On the other hand, classical approximation methods based on regression analysis can’t be applied efficiently in such cases because of the complicated shape of function \( R(L) \) with a great number of local minimums.

We propose an advanced method of \( S_m(\lambda) \) approximation, based on the analysis of the mathematical model of the extrinsic Fabry-Perot interferometer with low-referative mirrors. The method is motivated by both analytical and experimental studies and provides a reduction of amount of required calculations and at the same time an increase in EFPI baseline measurement precision.

In the proposed method several steps are used for the accurate localization of the \( R(L) \) global minimum. A rough estimate \( L_0 \) of the interferometric delay can be found according to the oscillation period of the EFPI measured spectral function \( S_m(\lambda) \). Subsequent search of the global minimum is accelerated by dividing the search domain into a set of narrow intervals \([L_1; L_2]\), determined by initial estimated value \( L_0 \) and characteristic features of \( S'(\lambda, L) \) function.

Another key feature of the proposed method is calculation of the \( R(L) \) function over most informative spectral intervals, which have a greater impact on the residual of measured and theoretical spectral functions of Fabry-Perot interferometer. These arrangements provide a great increase in stability of \( L \) measurements by approximation procedure and elimination of the impact of spectral function noises on the cavity length registration. Also in consequence of data size reduction an amount of calculations is reduced by several times.

Proposed method also includes a preprocessing algorithm, providing sufficient suppression of noises and parastrical distortions of measured spectra. In real-world measurements coefficients \( C \) and \( A \) can demonstrate a nontrivial wavelength dependence, resulting in disturbances of \( S_m(\lambda) \) function. Developed preprocessing procedure efficiently overcomes these effects and demonstrates remarkable improvement in real data processing.

Besides the argumentation based on the model analysis, proposed method was tested experimentally. Measurements were performed using optical sensor interrogator NI PXIe 4844. Examined interferometer was formed by two fibre ends, air gap between them was varied in limits [20; 700] m. Proposed method of signal processing, including preprocessing and advanced spectra approximation was implemented in LabVIEW, providing an ability to perform EFPI baseline measurements in real time mode (spectra acquisition rate was about 1 Hz). The standard deviation of obtained values \( L \) on the temporal intervals more than 10 minutes (more than 600 points) was between 15 and 40 pm depending on cavity length. Reported result was obtained without any preprocessing of measured spectra or calculated values of baseline length.

Developed algorithms, proposed in current signal processing method are expected to be effective and applicable for the development of broader class of EFPI sensors which register and approximate spectra. This can be a sensor with the multipass Fabry-Perot interferometer with highly reflective mirrors, which spectral function \( S(\lambda, L) \) is to be approximated using Airy function. Any other cases when some exclusive features of spectral function have to be taken into account can be also efficiently treated using the proposed method with some changes in the calculated function \( S'(\lambda, L) \).

References


8789-37, Session PS

Comparative analysis of absolute methods to test rotationally asymmetric surface deviation

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We have provided a comparative analysis of methods that involves multi-angle averaging, pseudo multi-angle averaging, single-rotation and variants based on the combinations. All these methods require measurement results being determined at rotational positions, serving for the interferometric measurement of rotationally asymmetric surface deviation of a specimen. Zernike coefficients and power spectral density (PSD) are computed and used for detailed comparison. The experimental results show that single-rotation method gives noticeably smoother result, thus it is limited to applications of measuring low spatial frequency deviations, taking the advantage of quick measurement time with fairly accurate rms results and potentially less influence of environment; in contrast, the result with multi-angle averaging contains more deviations information of mid and high spatial frequency but it’s time consuming. The pseudo multi-averaging method is the concise variant with fewer measurements. Its result contains more noise errors depending on the number of rotational measurements of multi-averaging method.

8789-38, Session PS

A new method for adjusting the lateral transfer hollow retroreflector

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A new method for adjusting the lateral hollow retroreflector is presented. It allows in a simple way to adjust the hollow retroreflectors with a lateral shifting. It enables to make the manufacturing process of adjustable lateral hollow retroreflectors more easy and cheaper. The testing optical bed of this method is displayed. The sources of uncertainties of this method are described. This new approach bases on a well known principle of relative motion, and uses the principle of inverse solving.
8789-39, Session PS

Absolute testing of flats with all terms by using even and odd functions
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High-accuracy interferometric surface metrology is constantly gaining importance, not only in the classical area of optical fabrication, but also for new application such as semiconductor and lithography lens. Requirements for the measurement resolution in the subnanometer range have become quite common. This includes not only the repeatability or reproducibility but also the absolute measurement accuracy, in which both the slowly varying shape error and the medium-to-high spatial frequency waviness of the surface under test, is important. Result of the testing contain the reference surface errors and test surface errors in the high-accuracy Phase shifting interferometric which test the relative phase between the two surface. The test accuracy can be achieved by removing the error of reference surface. In this case, one of body of so-called absolute tests must be used which can test the systematic errors, including the reference surface, of the instrument to be used to improve the test accuracy. We review traditional absolute testing of flats methods and emphasize the method of even and odd functions. The flat can be expressed as the sum of even-odd, odd-even, even-even and odd-odd functions. Through six measurements the profile of the flat can be calculated. In our paper the odd-odd function can be solved by use the Dove prism which can rotate the optical axis. The Dove prism can be inserted in the cavity which formed by the two flats to get the result Ax+Bx. The odd-odd parts are exactly obtained by the using of dove prism. In our arithmetic we only rotate the flat once for 180°. Only five configurations are used to test the flats. There is no arithmetic error in the five measurements. The new method with Dove prism doesn’t have the rotation interpolation errors. We can exactly get the all odd-even, even-odd, even-even and odd-odd parts. The odd-odd function can be solved by use the prism which can rotate the optical axis. The Dove prism can change the optical axis direction then the odd-odd function can calculate exactly. A Dove prism which is shaped from a truncated right-angle prism is a type of reflective prism which is used to invert an image. A beam of light entering one of the sloped faces of the prism undergoes total internal reflection from inside of the longest (bottom) face and emerges from the opposite slope face. Images passing through the prism are flipped, and the image is inverted but not laterally transposed because only one reflection takes place.

8789-41, Session PS

Efficient and stable numerical method for evaluation of Zernike polynomials and their Cartesian derivatives
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Zernike polynomials play an important role in many areas of optics. Due to their properties they are often used for expressing the wave aberration of optical systems with circular pupils or more generally for modeling of a wavefront shape or a shape of optical surface. In optical modelling the individual optical surfaces shapes can be expressed in several ways. One of the possible descriptions of the shape of optical surface is employing an expansion of the surface shape into orthogonal polynomials. The shape of given optical surface than can be expressed as e.g. a conic part plus Zernike polynomials expansion. The decomposition into Zernike modes is also often used in the field of optical measurement methods for wavefront reconstruction. Methods based on the measurement of a wavefront gradient such as e.g. Shack-Hartmann wavefront sensor, pyramidal sensor or shearing interferometry often use a modal wavefront reconstruction based on a decomposition of measured wavefront into Zernike modes. The values of Zernike coefficients for measured wavefront are then obtained by fitting of x and y derivatives of a wavefront (represented as a Zernike polynomials expansion) to the measured wavefront slope data using the linear least squares minimun. Thereit is necessary to evaluate Zernike polynomials and their Cartesian partial derivatives in order to use such a method. Since those measurement methods are often used in adaptive optics systems the evaluation speed is also important. Our work is focused on a problem of numerical evaluation of Zernike polynomials and their partial derivatives in Cartesian coordinate system. Since the direct calculation using explicit relations is relatively slow (due to the summations and repetitive use of factorial functions) and moreover it is numerically unstable for higher orders there is a need for a more effective and stable method. In recent years several recurrent methods were developed for evaluation of Zernike polynomials. These methods use the fact that the radial functions of Zernike polynomials are related to scaled Jacobi polynomials. Based on this idea using the well know recurrence relations for Jacobi polynomials it is possible to derive several recurrence relations for calculation of the radial function of Zernike polynomials. Those recurrent methods are numerically stable up to very high orders and they are much faster than direct calculation. In our work a brief review of the existing methods for calculation of Zernike polynomials will be given and then analogous recurrence method for evaluation of partial derivatives of Zernike polynomials in Cartesian coordinate system will be derived. The numerical stability of this method and the comparison of computation time with respect to the direct method will be presented using computer simulations.

8789-40, Session PS

Modeling of Risley prisms devices for exact scan patterns
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We investigate the scan patterns produced using different pairs of Risley prisms. Combinations of optical wedges with different prism angles (corresponding to different deviations angles of the prisms) are considered to complete the exact modeling of the scanning process using specialized mechanical design programs. While this procedure is somehow elaborate with regard to approximate methods, it has the advantage of providing the exact movement laws of the laser spot at various types of surfaces scanned with this type of refractive device. The study is made with regard to the characteristic parameters of the device, such as 1 and 2 - the prism angles of the two wedges, 1 and 2 – the rotating velocities of the two wedges, and the geometry of the scanner (which includes the distance between the two prisms, their orientation, and the distance to the scanned plane). The scanner is modeled for a row of values of the classical characteristic parameters k= 2/1 and M= 2/1 introduced in Marshall's classical work. The results allow for choosing the most appropriate patterns for specific scanning applications. A discussion made on these applications concludes the study.

8789-42, Session PS

Numerical analysis of a solid state laser system designated for paint layers removal from various substrates
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Numerical simulation results obtained in investigating a solid state laser system designated to paint layers removal from different metal and/or dielectric substrates, mainly aluminum and titanium alloys, are presented. The numerical simulation is performed considering the design cases of cw pumped Nd:YAG or Yb doped fiber lasers operated in passive Q-switching regime devoted to paint single layer or multiple layers removal from metal and/or dielectric substrates. The main purpose of the developed simulation model is to define the laser oscillator output parameters, mainly pulse energy and FWHM time duration and repetition frequency necessary for removal of paint layers with an accurate defined thickness. The developed simulation model permits defining the laser system output parameters which are optimal for non-affecting the substrate on which the paint layer is deposited. This is an important laser application in aeronautical industry and in
art restoration. The developed simulation model considers transverse laser beam intensity distribution and, consequently, the temperature distribution in the processed mechanical component.

8789-43, Session PS
Mathematical model of a galvanometer-based scanner: simulations and experiments
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The paper presents an insight into our current researches on galvanometer-based scanners (GSs). A brief overview is made on the state-of-the-art, as well as on some of our contributions to optimize the scanning and the command functions of this most utilized scanning device. Considerations on the use of GSs in high-end biomedical imaging applications such as Optical Coherence Tomography (OCT) are made, with a focus towards obtaining the best possible duty cycles and artifact-free OCT images when using galvos for lateral scanning. The scope of our work is to obtain the mathematical model of the GS system (motor and controller included) to be able to optimize the command functions of the device and to support the development of some advanced control structures. Our current study is centered on some of the aspects of the mathematical and experimental modeling of galvos. The results of an experimental identification made on a classical multi-parameter mathematical model proposed for such a system are presented. The experiments are carried out in different operating regimes, and the specific characteristic parameters of the GS are determined. Using these parameters obtained experimentally, we carry out simulations in Mathlab Simulink to validate the theoretical model. With the identified model, several types of controlled structures are proposed to optimize the scanning functions. The match between the theory and the results of the simulations and testing for different types of input signals (such as triangular and sawtooth with different duty cycles) is also briefly presented.

Selected references:

8789-44, Session PS
Design of soft x-ray gratings for free electron lasers: from specification to characterization
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The European XFEL is a large facility under construction in Hamburg, Germany. It will provide a transversally fully coherent X-ray radiation with outstanding characteristics: high repetition rate (up to 2700 pulses with a 0.6ms long pulse train at 10Hz), short wavelength (down to 0.05 nm), fast pulse (in the femtoseconds scale) and high average brilliance (1.6×1025 photons / s / mm2 / mrad2/ 0.1% bandwidth). The x-ray beam will be distributed to several different experiments through ultimate and beyond state-of-the-art mirrors. Due to the very short wavelength and very high pulse energy, mirrors have to present high quality surface, to be very long and at the same time to implement an effective cooling system. Matching these tight specifications and carrying out the high precision optical measurements is very challenging. One of the three foreseen beamlines operates in the soft X-ray range and it is equipped with a diffractive monochromator. The monochromator is a Variable Line Spacing Plane Grating Monochromator (VLS-PGM) that covers the wavelength range from 4.6 nm to 0.41 nm, 270eV and 3000eV respectively. The optical design takes into account two gratings with different line spacing. The grating profile is blazeed and the line spacing parameters are very challenging both to realize and to be tested before the final installation. In this contribution we discuss about the needed requirements of the optics involved in the soft X-ray monochromator. We describe mirror and grating specifications and the tests that we plan to carry out during and after the manufacturing phase in order to ensure the specification match.

8789-47, Session PS
Super-resolution imaging based on liquid crystal on silicon displays technology
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Optical systems devised to obtain high resolved images are very interesting for many purposes such as remote sensing applications or for imaging in medical or biological applications. A super resolved image is achieved when the output image obtained by using a given imaging device is exactly the same as the input object used. However, in practice, the resolution of the signal is always degraded to certain extent. Such loss of the image resolution is due to multiple reasons, as for instance, as a consequence of the environmental conditions, or due to the physical limitations in resolution related either to the optical components or to the geometrical components.

When building up optical systems, aperture sizes, imperfections and misalignments of optical components impose a resolution limit related to the Point Spread Function (PSF) of the optical system. In addition, modern imaging systems also include Charge-Coupled Devices (CCD) that lead to a reduction in resolution caused by the geometrical properties of pixel array, e.g. pixels shape, pixel size and separation of the pixels array [pixel pitch].

Therefore, the development of new optical systems able to reduce to certain extent some of the physical limitations in resolution described above becomes a very desirable feature for the applications of numerous researchers. Due to the great capability of Liquid Crystal on Silicon (LCoS) displays, a type of Liquid Crystal Display that works in reflection, to operate as Spatial Light Modulators (SLM), such devices are nowadays used in a large number of optical applications. In this work, we take profit of the LCoS display technology to achieve super-resolution imaging. This target is achieved by using two different LCoS display based set-ups. The first set-up proposed in this work is able to achieve super-resolution imaging by decreasing the diffractive limitations in resolution imposed by the finite size of apertures. In particular, we propose a new technique able to achieve super resolution imaging by using an object illumination based on different tilted beams generated by means of a Parallel Aligned (PA) LCoS display. The novelty of our proposed technique is the simultaneous illumination of the object by these tilted beams.

Limited apertures permit only low spatial frequencies to pass through and block high spatial frequencies of object, thus losing some object information (i.e. they act as a low-pass filter producing a decrease of resolution at the image plane). Here, in order to retrieve some of these high spatial frequencies which have been lost, the simultaneous tilted beams illumination procedure is used. In particular, by using the PA LCoS display, the object is illuminated with different tilted beams and some constant phases are also assigned to each tilted beam generated. When the object is simultaneously illuminated with all the tilted beams, an on-axis interferometry scheme is produced. An interferogram at the image plane is formed for each set of constant
phases added to the tilted beams. Using proper selection of constant phases for each of the interferograms, the synthetic aperture can be calculated. During the post processing, we take the Fourier transforms of the each image and the portions of the spectrum are spatially shifted and combined to obtain a synthesized spectrum whose inverse Fourier transform gives high resolution image.

By using this proposed strategy, the necessity of a reference beam, which is mandatory in other approaches, is avoided. In addition, it allows achieving a higher stability of the system.

Afterwards, we propose a second set-up which is also based on the LCoS display technology. This second set-up is able to increase the final image resolution by reducing the effect of the CCD camera pixel pitch on the final image.

Resolution of the imaging sensor depends on the density of the sampling points (i.e. the number of the pixels per unit area) and on the pixel size and geometry. Higher resolution than the provided by the sensor pixel density can be achieved by reconstructing several sub-pixel displaced images. To generate image sub-pixel displacements, we address different linear phases to a PA LCoS display placed at the Fourier spectrum plane of an object. By doing this, we are able to produce different displacements of the object image sampled by CCD camera. We want to emphasize that this subpixel displacements are generated without using mechanical elements, as mirrors. In this way, mechanical errors related to mechanical controlled displacements are avoided. Afterwards, by means of the proper combination of the different shifted images, a super-resolved image of the object is obtained. Finally, an inverse filtering process is applied to, enabling to decrease, to a certain extent, the blurring effect introduced due to the intensity average performed inside the pixels area. Experimental results and discussion for the two super resolution imaging set-ups given in this work are provided, showing the validity of our proposed approaches.

8789-48, Session PS
S-Genius, a universal software platform with versatile inverse problem resolution for scatterometry

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The scatterometry is a non-destructive optical metrology based on light diffraction by gratings, which provides the critical dimensions of the pattern cross-section. This technique has many advantages leading it towards a solution for the metrology of future nano-scaled patterns. Among the most relevant advantages, non-destructive, non invasive, fast, accurate, in-situ and real time compliant behaviors can be underlined. Nevertheless, the scatterometry is an indirect technique and it is based on a parametric problem. It leads to a good definition of this problem, with a model as close as possible to the real profile, and to an efficient inverse problem solver (in terms of robustness, accuracy, sensitivity). This paper will present the work achieved in setting up a new software platform, called S-Genius, for scatterometric measurements.

In this software, the rigorous electromagnetic calculation, called "direct problem", is computed using 2D- and 3D-MMFE (Modal Method with Fourier Expansion), where the period of the grating is decomposed in several layers. These various types of layers (squares, bowing profiles, trapezes (symmetric or not), roundings, spacers, etc. with or without passivation layer) are implemented and can be piled up to model the expected pattern stack. To find out the real profile of the grating, some critical dimensions of these layers must be optimized by comparison with an ellipsometric measurement of the light scattered by the grating. The grating profile is obtained by inverse problem resolution. This resolution is achieved here by the implementation of several new algorithms which represent very different approaches but which have in common a global optimization scheme to avoid the finding out of secondary minimum solutions: a Levenberg-Marquardt optimization (with the choice of adapted starting and damping parameters), a global interpolation technique based on kriging (close to geostatistical techniques), and a method using the neuronal networks (with learning phases to set up a kind of "direct" method for inverse problem resolution) have been designed for our specific inverse problem resolution. All these approaches and their possible combinations, to improve the inverse problem resolution, will be presented. This paper will also discuss of the advantages and the drawbacks of all these techniques for both absolute critical dimension determination and real time critical dimensions follow up.

Technically, this S-Genius scatterometric software platform is ready for scientific collaboration, is multi-platform (windows/linux/macOS) and multi-core, and accepts all kinds of entry data from any possible ellipsometers (angle or wavelength resolved) or reflectometers. In addition, this S-Genius scatterometric platform is coupled with an innovative material refractive indexes determination by smart minimization and Tikhonov regularization. It combines a set of inverse problem resolution capabilities that improve the reliability and the velocity of the solution determination: Using a standard 12-core computer, a nanometric sized line pattern with a stack combining a ten-parameter problem may be resolved in the order of one minute. The same inverse problem resolution may be achieved in less than one-tenth second during a real-time process. These techniques of inverse problem resolution have already been used for patterns dimensions measurements like nanoimprinted features or microelectronic etched patterns for instance. The correlation matrix provides the correlation level between cross-linked parameters for optimization and allows to define the final optimized values uncertainty. This paper will also show the advantages of the integration of this software tool in a hybrid metrological platform to show the interest of combining several metrological tools (as CD-SEM or CD-AFM) to achieve absolute measurement (with a precision close to the nanometer) of the grating critical dimensions.

8789-49, Session PS
Testing an aspheric lens combining the Ronchi test and interferometric test by transmission

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Comply with the requirements for the quality of a lens; it is important to ensure its performance within an optical system. Also if one of the surfaces is aspherical the lens becomes critical to ensure that the surface form is manufactured according to the design specifications. In this paper we show the technique used to test an aspheric lens meniscus; first testing the concave aspheric surface using Ronchi test, and after the convex spherical transmission interferometry entire lens. To increase the accuracy of the Ronchi test we propose analyze the interference patterns Ronchigrams as lateral shearing interference pattern and this information was used in the analysis of the entire lens interferograms. This lens is part of the project MEGARA which is an integral field unit (IFU) and a multi-object spectrograph (MOS) consists of compact arrays of optical fibers. The outlet end thereof pseudoslit form the spectrograph. The instrument will work in the range of wavelengths: 3700Å - 9800 Å, The f-number (f/#) of the spectrograph should be approximately f/3 and the diameter of the pupil must not be greater than 170mm. Finally it must have a fixed geometry of 68° between the collimator and camera.

8789-50, Session PS
Phase recovery from interferograms under severe vibrations

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A phase reconstruction method from several interferograms obtained in severe vibration environment is proposed. Existing algorithms can recover the phase from interferograms with non-uniform phase shifts and they can be useful when vibrations are moderate and the phase shift is nearly constant. In this work the address the problem of phase recovery under severe vibrations in which the phase...
difference between two or more interferograms is non-constant and may undergo a sign change. This last condition may not be handled correctly with other techniques. It may be observed that the phase difference among the interferograms is composed by tilt, defocus and piston aberrations, being the more dominant the tilt term, even tough it may change depending on the interferometric set up being used. Given that the phase difference is mostly linear it may be recovered calculating its cosine and processing it with a Fourier technique. Once the phase difference has been recovered the phase encoded in the interferograms may be recovered easily. This is demonstrated in simulated and experimental data.

8789-51, Session PS
Optical testing of soft contact lenses with a rigid cornea
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In addition to correcting the main refractive error (defocus) in the eye by means of soft contact lenses (SCLs), compensating for the eye’s imperfections associated with astigmatism and other so called higher-order (HO) aberrations could be beneficial. These aberrations need a customized correction using toric or aspheric lenses, which show greater sensitivity to misalignment in terms of the final image quality. The HO aberrations introduced by misalignment effects of SCLs are not desirable and require special attention. The present paper studies the optical effect of the motion of the SCL on the cornea and the resulting changes in ocular aberrations. A physical model of a rigid cornea was designed for testing wavefront aberrations induced by SCLs. Usually SCLs are optically tested in vitro, however it is known that the initial lens shape will change due to the wrapping of the contact lens on the surface of the cornea and its interaction with the eyelids. The lens flexure is rather difficult to predict theoretically, yet this deformation can potentially introduce new aberrations that cannot be measured in vitro. As a consequence, it is desirable to assess the optical performance of deformed and misaligned SCLs.

In our approach, we put an actual soft contact lens (conveniently moistened with a saline solution) on a rigid cornea made out of a glass hemisphere. A diaphragm is placed on the flat side of the hemisphere to mimic the iris and a larger glass hemisphere plays the role of the anterior and vitreous chambers. We do not take into account the crystalline lens as the study is constrained to the study of contact lens aberrations. Furthermore, in front of our system composed of the rigid cornea and the SCL, we have a wavefront sensor designed to allow measurements of the wavefront aberrations of the SCL along different directions.

The multidirectional feature of the wavefront sensor is important because thanks to the symmetries of the setup, each off-axis direction can be related to a particular misaligned position of the contact lens. Consequently in order to simulate the misalignment of the contact lens without any moving parts, we instead analyse the wavefront coming from different points in the field. And rather than varying the orientation of our point source on the model of the glass retina, we place a set of sources in a ‘cross’ configuration so that each source corresponds to a special amount of misalignment. Moreover thanks to an adequate optical design involving folding mirrors and a segmentation of the pupil of a Hartmann-Shack wavefront analyser, we suggest a method to simultaneously analyse the wavefront for every beam configuration. This simultaneous measurement principle could also be applied to a real eye (supposing an intermediate illumination system to create spots on the retina), which would allow us to get a better understanding of the field aberrations of the human eye at one precise time, as opposed to the current measurements of field aberrations which are sequential and are therefore not a precise mapping of the field aberrations of the human eye at one time.

Overall, this is a new approach for evaluating the effects of deformation and misalignment of SCLs on ocular aberrations. It is interesting in the sense that it is not too complex to implement and it is using the actual physical SCLs and then is an attractive way of better understanding the behaviour of SCLs in vivo. The experimental results are compared to the theoretical predictions of lens misalignments on the cornea and the contribution of the lens flexure has been estimated so that it could be compared to a careful modelling of the lens flexure via e.g. finite element analysis.

8789-52, Session PS
The dispersion of the refractive index visualization in the broadband source interferometry
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Low-coherence interferometry is intensively developed In last years in relation to the investigation of optical structure of scattering objects – full field optical coherence tomography or interference microscopy. The difference between this methods and the traditional OCT is to use a thermal broadband source of white light with spatial-coherent illumination of the object,. Due to small coherence length the chromatic dispersion of optical elements and object are influence on interference pattern. In this work we present the results of numerical simulation of the effects of chromatic dispersion in the manifestation broadband light interferometry. It is shown that the experimental results are correlated with numerical experiment: the bringing in of additional parallel-sided dispersing layer in one arm of a balanced microinterferometer leads to broadening of the interference pulse and decreasing contrast. It is also shown the observed dependence of the contrast on the dispersing layer thickness.
Spin-offs from laser ablation in art conservation (Invited Paper)

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In 1973 The Center for Art Conservation Studies (CASS) was established at the University of California, San Diego (UCSD). This was in response to demonstrations that were conducted during January–March 1972 in Venice for UNESCO, Venice in Peril, International Fund for Monuments and the Italian Petroleum Institute (ENI). The feasibility investigation exploted in-situ pulsed holography, holographic interferometry, and laser ablation divestment for applications in art conservation practice. During subsequent decades scores of UCSD graduate and undergraduate students as well as conservation scientists, academicians, and engineers who resided in CASS as “Visiting Scholars” contributed to advancing the understanding and performance of radiation technologies in the arts. Several technologies in addition to those involving optical wavelengths were also investigated to aid in art conservation and preservation science. Magnetic Resonance Imaging (MRI) and Nuclear Magnetic Resonance (NMR) were employed to detect and map moisture within tostone. Lead isotopic analyses revealed authenticity and provenance of Benin bronzes. Inside-out x-ray radiography facilitated the detection of defects in stone. Ultrasonic imaging was introduced for the mapping of fresco strata. Photoacoustic Spectroscopy (PAS) was used to characterize varnish layers on paintings. Digital image processing was introduced in order to detect and visualize pentimenti within paintings as well as to perform virtual restoration and provide interactive museum displays. Holographic images were employed as imaginary theater sets. In the years that followed the graduation of students and the visits of professional collaborators, numerous other applications of radiation ablation began appearing in a wide variety of other fields such as aircraft maintenance, ship maintenance, toxic chemical remediation, food processing, industrial fabrication, industrial maintenance, nuclear decontamination, dermatology, nuclear weapons effects simulation, and graffiti control. It was readily apparent that the customary diffusion of advanced technologies from science and industry into the art conservation field had been reversed. In this paper we trace the migration and adaptation of radiation divestment developments in art conservation to numerous applications in science, industry, and consumer products. Examples described include the robotized hybrid “Flashjet” aircraft paint application system, the “Novotronic” anthrax remediation installation in the Pentagon Building, the InTa automated graffiti removal system employing a carbon dioxide TEA laser, the Bellalite body hair removal product incorporating flashlamp technology, and the Foodco line of optical radiation products for the sterilization of food products. The Foodco products are also applied to the sterilization and/or pasteurization of beverages and beverage containers. A similar device has been adapted to seafood irradiation in order to increase shelf life, as well as for the ablative removal of skin and scales. The Goodyear Tire and Rubber Company, to etch logos and identification information into the sidewalls of pneumatic tires, also developed a flashlamp-based ablation technology. The founders of the CYMER Corporation applied UV irradiation technology to the manufacture of high-performance integrated circuits (viz., memory chips, etc.) In several instances former CASS students and Visiting Fellows consciously adapted the above-learned art conservation methodologies to still other purposes. Thus, these examples of technology transfer may be termed: “Art in the service of Science.” Alternatively, it is evident that many associated innovations developed from independent activities, unconnected serendipity, or through the normal diffusion of information and knowledge across disciplines.
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For the society it is of great interest to make cultural heritage accessible to the general public. The subsequent increase of museum loan services can be related to artwork degeneration. Hence, in addition to the age related deterioration transportation is another source of damage. Despite modern packaging technologies, smallest vibrations and environmental change can add up and damage the transported object. In order to preserve and restore our cultural heritage it is necessary to detect damages at an early stage before they reach a critical extend. Optical methods for damage assessment provide the necessary sensitivity and flexibility to investigate changes on a micro scale [1], [2]. The properties of fringe projection and speckle photography can be combined to investigate and detect topographical and structural changes and damages. Besides obvious mechanical influencing quantities, a main concern is the detection of climate induced damages. Smallest changes in the relative humidity can add up and cause inner strain, which can lead to defects. White light fringe projection was successfully applied to detect object changes due to variations of the relative humidity down to 8 % as well as transport related damages on artwork like changes in the object dimensions and surface defects, respectively. Recently, the Stuppach Madonna, a painting by Matthias Grünewald (magnum opus, painted 1514 - 1516), was investigated with speckle photography after the return from the exhibition "Himmelscher Glanz. Raffael, Dürer und Grünewald malen die Madonna" in Dresden, Germany. In addition to the necessary process of restoration the condition of the wooden panel painting was evaluated and recorded where the speckle photography was applied to assist the conservators. Due to the size of the large painting (186 cm x 150 cm) it was segmented into 16 subareas. For each subarea a separate speckleographic measurement was conducted. Therefore, a segment was illuminated by an expanded laser beam with a wavelength of 532 nm. Images captured with a shearing camera before and after thermal loading were processed to obtain shearograms. Those shearograms revealed a variety of defects like bubbles, delaminations and tunnels caused by wood worms. Even the planking of the wooden panel and cementsations could be observed. Due to the nature of art, every artwork is unique. Hence, there is no universally valid model. Nevertheless, for example paintings can be categorized to consist out of different layers of material, which roughly can be image carrier, primer, different layers of paint and varnish. The transparency of those materials and therefore the penetration depth for the incident radiation depends on the wavelength. To investigate defects and features in the different layers of material, the spectrum of the illuminating beam can be extended from visible (VIS) to ultraviolet (UV) and infrared (IR). For example, the painting layers usually show good transparency for IR between 1500 nm and 2000 nm, whereas the primer reflects electromagnetic radiation in this wavelength range. Therefore, it should be possible to detect damages and features on the primer. Damage classification by analysing obtained results could lead to novel methods of damage detection and damage prevention of cultural heritage. Furthermore, from an insurance point of view it is of great interest to evaluate the condition of moveable artwork. Our aim is the development of a system for transportation damage monitoring in museum loan services.

References

8790-4, Session 1
Use of the LIBS method in oil paintings examination, based on examples of analyses conducted at the Wilanow Palace Museum
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This paper describes the preliminary results of a study of the paint layers in 17th-century paintings belonging to the collection of the Wilanow Palace Museum. The works chosen for examination are of great importance to the Museum, as they might have been painted by artists in the court of King John III Sobieski. The portrait of Krasinski is attributed to M. Palloni, a Florentine painter who worked in the Polish-Lithuanian Commonwealth from 1676, and left behind an impressive collection of works, particularly murals, in the Wilanow Palace galleries among other places. We do not yet have full knowledge about the technique of the artist, who also painted on canvass. Currently, comprehensive research is being conducted in order to determine the techniques and materials the painter used. New technologies greatly increase the effectiveness of these activities. Other pieces with the image of King John III himself were probably painted during his life, but they have not yet been attributed to any author. The aim of the study was therefore to determine the technological structure of the paintings, to confirm their authenticity, to determine the scope of conservation interventions and, above all, to gather comparative material that would serve to conduct further multidisciplinary attributive research.

The presentation relates to studies in which laser-induced breakdown spectroscopy (LIBS) and optical microscopy were used as diagnostic tools.

LIBS is based on the evaporation of a small amount of the material under investigation, and the generation of plasma which emits continuum and line radiation. The analysis of line radiation allows us to identify the elements appearing in the sample being investigated. In LIBS experiments, high-power pulse-laser radiation is used for plasma generation. Radiation intensity should exceed 0.1 GW/cm² on the sample. Experiments with power density of the order of 0.1 GW/cm² are used for studies of very sensitive and valuable objects such as the paint layers of historic artworks, and we used this power density in our experiment. An ESA 4000 echelle spectrometer of about 200000 ( / ) resolving power was used in the measurements. The plasma radiation was measured in the 200–700 nm wavelength range. For plasma generation, a Quantel/BigSky Brio laser was used, and the laser pulse applied was of 10.2 mJ energy, 4 ns duration and 266 nm wavelength.

The laser radiation was focused using a 100mm focal length quartz lens, and the lens-to-surface layer-distance was set to 97 mm, to avoid incidental laser sparking in front of the paint layer under investigation. Plasma radiation was acquired every 5 µs, 500 ns after the laser pulse. The microscope pictures were taken using a Bresser Digital Hand Micro 1.3Mpx microscope at 5x and 200x magnifications. During the stratigraphy measurements, sometimes up to 200 laser shots were applied in the same spot for thick paint layers; typically 30 shots were applied. The final interpretation of the results was also based on already known information about the painting techniques of the epoch. As a result, it was possible to identify pigments used by the old masters. The stratigraphy of the paint layers in the measurement spots examined was also determined. At the same time, the sensitivity of the research method made it possible to learn new information about historical techniques and technologies, as well as about conservation interventions which had been difficult to recognise.

The results obtained have confirmed the utility of the LIBS method in the study of artworks. They have also proven that it can be used as a method to complement microchemical analysis, as well as an method to identify and examine artworks from which samples cannot be taken, as it is micro-destructive and the analysis can be conducted directly on the object, without the need to take samples. The paper presents the traces of a laser beam - paint layer surface interaction, and demonstrates the micro-scale damage.

The research has been conducted by the Wilanow Palace Museum and the Military University of Technology (project PBN/03-189/2012/WAT).

8790-5, Session 2
Unwrapping layers in historic artwork: virtual cross-sections with pump-probe microscopy (Invited Paper)
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Development and application of portable hyperspectral imaging cameras for the identification and mapping of organic artist's materials such as paint binders and textile fibers

John K. Delaney, National Gallery of Art (United States); Paola Ricciardi, The Fitzwilliam Museum (United Kingdom); Kathryn Dooley, Suzanne Lomax, National Gallery of Art (United States); Murray H. Loew, The George Washington Univ. (United States)

Near-infrared (750 to 2500 nm) reflection imaging spectroscopy has been recently shown to be a useful tool to map and identify various artists’ pigments. This approach has utilized both electronic transitions (color) and vibrational overtones from hydroxyl (-OH) and carbonate groups (-CO3[1]). Here we present results on effect (ii) have developed this methodology to map and identify non-pigment artist materials such as paint binders and textile fibers in situ. Imaging spectroscopy, the collection of hundreds of contiguous narrow-band images, offers an improvement over site-specific fiber optic reflectance measurements by combining both spatial and spectral information. Currently new portable high sensitivity hyperspectral cameras are being developed that will operate under the low light levels conditions necessary to examine paintings, drawings, illuminated manuscripts as well as textiles. These cameras will have both high spectral (2.4 to 4 nm) and high spatial resolution (<0.1 mm per pixel) capabilities. Identification and mapping of these organic materials will be done using the higher harmonics of the vibrational features found in the mid-IR which are routinely used to identify these materials using FTIR spectrometers. These chemical signatures include overtone and combination vibrational features associated with amide bonds, -CH2-OH, and -CO3 groups. The cameras utilize transmission-grating spectrometers and state-of-the-art infrared detectors, such as InGaAs and InSb arrays of 640×512 pixels and 1024x1280 pixels, to obtain the required sensitivity. The instrument’s performance is being verified using test panels and paintings in the National Gallery’s collection whose composition is known by GC-MS and FTIR analysis. To date we have demonstrated (i) the ability to separate and map test panels painted using drying oils versus whole egg tempera, (ii) have mapped an egg yolk binder in a 15th century illuminated manuscript (i), and (iii) have separated this methodology and silk fibers within a c. 1500 tapestry. The knowledge gleaned from these instruments will help art historians better understand, and conservators better preserve, important works of art.


Deterioration estimation of paintings by means of combined 3D and hyperspectral data analysis

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Deterioration of artwork, in particular paintings, can be produced by environmental factors such as temperature oscillations, relative humidity variations, ultraviolet radiation and biological affection among others. The effects of these parameters produce changes in the painting structure and chemical composition. While well established analytical methodologies, such as those based in Raman Spectroscopy and FTIR Spectroscopy require the extraction of a sample for its inspection, other approaches such as hyperspectral imaging and 3D scanning present advantages for in-situ, non-invasive analysis of artwork. The combination of the aforementioned non-contact techniques can be used to develop analytical tools which extract rich 3D and hyperspectral maps of the objects, which in turn can be process to obtain accurate quantitative estimations of the deterioration and degradation present in the piece of art. In particular, the construction of four dimensional maps allow the identification of risk maps on the painting representation, which can allow the curators and restorers in the task of painting state evaluation and prioritise intervention actions.

The methodology propose in this work consists of two defined parts. Firstly, the production of 3D-HS (Hyper Spectral) point clouds obtained in the visible spectrum with spectral resolution of 20 nm—given by Gaussian-shaped filtering windows. Secondly, the development of processing algorithms for the combined 3D-HS data maps for classification and quantification of deterioration from both structural and a chemical points of view.

The generation of the tridimensional point clouds is carried out by means of structured light patterns projected over the painting and recorded at different spectral bands, from 400nm to 700nm. Firstly, band fusion techniques are used to generate a single-band, gray-scale image collection of the two fringe projection, from which the depth information can be derived. Different 3D reconstruction approached, such as frequency and phase shifting techniques are assessed for implementation to generate the 3D point cloud.

The analysis of the resulting data sets is therefore processed by means of morphological algorithms which can identify points of structural modification of the due to support, ground and paint and varnish damage. Using supervised non-linear classifiers, such as support vector machines and neural networks, the surface of the painting may be inspected to identify discontinuities and alterations in the pigment and binder application, giving an indication of loss or change in material. Deterioration quantification is given for the following conditions:

- Physical deterioration
- Support damage (crease, dent, tear, bulges, cuts, buckling)
- Ground damage (blister, aging cracks, cleavage)
- Paint damage (abrasion, alligating, crackle, drying cracks, loose, paint, lacunas)
- Varnish physical damage (particle deposition form combustion smoke, craquelure, superficial grim)
- Chemical deterioration
- Pigment alterations (due to light radiation, due to chemical interaction with other elements, due to heat damage)
- Varnish alterations (oxidation, blooming, heat damage)

The described methodology is implemented in a device capable of recording and processing four dimensional data from art paintings (canvas and wooden panels). The system integrates a structured light projector based on DLP® technology and an electronically tunable spectral separator, optically coupled to a CCD.

The main results achieved in this contribution are in the following areas:

- Digitisation and characterisation of the different physical damage occurrences described above.
- Digitisation and characterisation of the chemical damage types described above.
- A novel method for generating 4 dimensional maps of the painting by means of combined hyperspectral and 3D data recording.
- Morphological and spectral feature extraction from the 4D data
- Development training and validation a model for physical damage detection and quantification
- Development, training and validation of a model for chemical detection and quantification (based on dimensionality reduction techniques and nonlinear supervised modeling).

Additionally, secondary data processing techniques, such as principal component analysis for dimensionality reduction, and discrete wavelet transform for compression and de-noising, are evaluated and considered.

This work is part of the ongoing development being currently carried out in SYDDARTA project (www.syddarta.eu), funded by the European Commission under the 7th Framework Programme (project number 265151).

8790-8. Session 3

Extending hyperspectral imaging from Vis to NIR spectral regions: a novel scanner for the in-depth analysis of polychrome surfaces (Invited Paper)

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Over the last decade Hyper-Spectral Imaging (HSI) techniques have been increasingly applied to investigation and documentation of 2D artworks, as it is documented by a flourishing research and the recent literature focused on this topic [1-6]. HSI is based on the capture of a series of images (2D data) of a given surface at different optical wavelengths across an extended spectral region (typically the Vis-NIR range). HSI systems are designed for acquiring hundreds of images on almost contiguous narrow spectral bands (with a bandwidth of few nanometres), thus providing highly resolved spectra for each pixel of the image captured. The high-spectral resolution may be decisive for attaining reliable materials identification and discrimination, and this fact makes this cutting-edge technology highly attractive for applications in Cultural Heritage. The acquired data set (file-cube) contains the spectral information for each cell (pixel) composing the full imaged area. The reflectance spectrum may be exploited for a non-invasive identification of materials (pigments, dyes, fillers, preparation materials and alteration products), as well as for colorimetric analysis. The file-cube may also be processed to extract high-resolution colour (RGB) images, as well as elaborated images in the different spectral bands so as to highlight the desired information (e.g. images at different wavelength, false colour maps, etc.). Nevertheless, the type of information which may be extracted from the file-cube is strictly related to the extent of the spectral range investigated, which in turns depends on the technical features of the detectors employed. For example, high-quality colour images may be obtained starting from 2D data in the Vis range (400-700nm), whereas a good discrimination of the materials may be attained only extending the inspection to the SWIR range (900-1700nm).

This paper reports the latest developments of the on-going research carried out at IFAC-CNR, within a new prototype of a high-performance hyper-spectral scanner, operating in the NIR spectral region (900-1700nm range), has been designed, assembled and tested. This system is based on a commercial prism-grating-prism line-spectrograph (Specim® - mod. ImSpector N17E) coupled with a 6812-pixels camera (Onyx 9 mod. Xedipix 1.7-640), specifically designed for professional applications in the SWIR range (thermo-electrically cooled InGaAs detector). Since the applications of interest concern the image capture of large size paintings, problems related to the mosaicing process and full image reconstruction were carefully considered in the choice of the optical objective. This new NIR scan-head has been designed to be mounted on the same mechanical structure already used for the earlier IFAC-CNR scanner prototype which operates in the 400-900nm [7,8]. As ultimate goal the whole system is intended to extend the spectral information attainable up to 1700nm, so as to strongly improve the capability of pigment discrimination, and the possibility of visualising the underlying features of the polychrome surfaces (such as under-drawings, pentimenti, etc.). In the present version, this NIR scan-head operates with a spectral sampling rate of about 2 nm, and a spatial sampling rate of about 9 detail per millimetre.

The results of testing and characterisation of the new high resolution NIR IFAC-CNR scanner are presented, with a focus on the main technical problems tackled in customising the new system for the investigation and documentation of artworks.

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Automatic registration and mosaicing of conservation images

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As high-resolution conservation images, acquired using various imaging modalities, become more widely available, it is increasingly important to achieve accurate registration between the images. Accurate registration allows information unavailable in any one image to be compiled from several images and then used to provide a better understanding of how a painting was constructed. The algorithm that we will describe has been configured to solve several important conservation problems: 1) registration and mosaicing of multiple X-ray films, ultraviolet images, and infrared reflectograms to a color reference image at high spatial-resolution (200 to 500 dpi) of paintings (both panel and canvas) and works on paper, 2) registration of the images within visible and infrared multispectral reflectance and luminescence image cubes, and 3) mosaicing of hyperspectral image cubes (400 to 2500 nm), including those acquired with a scan mirror and thus having sub-pixel registration than can be achieved by manual registration.

The algorithm has been used to register and produce mosaiced infrared reflectograms of over 50 paintings and works on paper, as well as create over 10 large mosaics of large paintings, wherein each consisting of 10 to 40 image cube captures (each 640-by-640 pixels by 256 spectral bands). While computationally-intensive, the process has reasonable run times. For example registering/mosaicing of 150 infrared reflectograms (each 512-by-640 pixels) to a true color image of a panel painting took approximately 90 minutes on an 8-core computer, containing a graphics processing unit, and produced a final infrared reflectogram of 4700-by-6000 pixels.

Micromorphology of gold jewels: a novel algorithm for 3D reconstruction and its quality assessment

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There is a significant gap between the development of new computer vision algorithms for surface reconstruction and their effective application in the field of material science. The efficiency of the novel algorithms is typically tested on synthetic images, while, up to now, it has not been applied to the real-world objects, where each real-world images are processed in order to produce three-dimensional (3D) reconstruction of an object from a collection of pictures. The surfaces, which can be encountered in practical are usually rough at some low-level scales. Generally, at a given level, each surface exhibits random high frequency spatial variations. Therefore, in real world images, the surface exhibits random in a manner between adjacent pixels. For this reason the efforts in computer vision are still needed in order to develop novel mathematical procedures which take into account not only such features of the real world images.

Another important issue to be considered whenever dealing with computer vision algorithms for surface reconstruction of real world objects is the image quality. The image degradation can be ascribed mostly to the electronic noise and to the blurring. These two factors affect the resulting 3D reconstruction and the extraction of useful information from the surface under examination. The electronic noise can never be avoided, whereas blurring can be exploited for 3D reconstruction. This technique is referred as “Shape from focus” (SFS). It relies on the estimation of the depth and 3D shape of an object from a sequence of images achieved at different focus settings [1]. The implementation of this technique allows computing the best-focus map by maximizing the cross-correlation between the images’ phase information, and 3) it filters the matched pairs of points to obtain the most accurate set of pairs that will be used to compute the spatial transformation coefficients. Because the algorithm automatically detects control points, a larger number of them are used than would be practicable if they were selected manually, yielding more accurate (sub-pixel) registration than can be achieved by manual registration.

This automatic algorithm for registering/mosaicing multimodal conservation images is expected to be a valuable tool for conservators attempting to answer questions regarding the creation and preservation history of paintings. For example, an analysis of the reflectance spectra obtained from the sub-pixel registered multispectral image cubes can be used to separate, map, and identify artist materials in situ. And, by comparing the corresponding images in the X-ray, visible, and infrared regions, conservators can obtain a deeper understanding of compositional changes. To date, the algorithm has been used to register and produce mosaiced infrared reflectograms of over 50 paintings and works on paper, as well as create over 10 large mosaics of large paintings, wherein each consisting of 10 to 40 image cube captures (each 640-by-640 pixels by 256 spectral bands). While computationally-intensive, the process has reasonable run times. For example registering/mosaicing of 150 infrared reflectograms (each 512-by-640 pixels) to a true color image of a panel painting took approximately 90 minutes on an 8-core computer, containing a graphics processing unit, and produced a final infrared reflectogram of 4700-by-6000 pixels.

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can represent a smart approach in order to address a variety of characterization problems. The micro-morphological 3D reconstruction of different surfaces, such as those of jewels, paintings, stone and metal sculptures and other, can reveal information on the state of conservation, the manufacturing processes, and hence on the authenticity of the artifact under examination.

The development of a reliable algorithm, valid for non synthetic surface, and its efficiency evaluation are the main issues of this paper. We present for the first time a novel algorithm for sharpness evaluation especially designed for metal surfaces, which is based on a modification of the Energy of Laplacian operator (MEOL). The images processed using MEOL have been captured with a novel homemade microscope prototype [2, 3]. Microscopes and in general magnifying imaging systems present limited depth of focus (DOF), which does not allow the inspection of an entire image of a 3D surface in a single frame, as only those portions of the surface which are within the DOF of the system are in focus, while the others are blurred. DOF is responsible of the SFS effectiveness: the shorter the former, the better the latter, and similarly for spatial resolution. Such a requirement is in conflict with the requirement of large field of view (low magnification). A trade-off has to be determined, depending on the object to be inspected. Different examples of 3D reconstructions of metal artifacts have been considered in the present work. Preliminary tests on objects with known geometry and different textures have been used in order to demonstrate the better performances of the algorithm when processing pixels with high intensity, as compared to other operators. This commonly occurs in images from metallic surfaces, where the specular reflection, which can give rise to saturated portions in the images, is partially responsible of the image degradation. The novel algorithm has been therefore applied to study micro-morphological features of an original and two fakes of Etruscan gold jewels.

Finally, the assessment of the 3D reconstruction quality has been carried out by considering the structural similarity index (SSIM). The statistical approach commonly used, has been replaced with the SSIM index since the latter has shown to be more effective in measuring the quality of natural images distorted by a large variety of biases. It calculates the quality of a distorted image by comparing the local correlations in contrast and luminance with the correspondent ones of a reference image. In the framework of SFS for 3D surface reconstruction, in which distorted means blurred, the SSIM index has been considered as a quality parameter for reconstruction performance testing.

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8790-11, Session 3

Surface monitoring measurements of materials on environmental change conditions

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Climate Change is one of the most critical global challenges of our time and the burdensome cultural heritage of Europe is particularly vulnerable to be left unprotected. Climate for Culture2 project exploits the real damage impact of climate change on cultural heritage at regional scale. In this paper is described the development of the study with in situ measurements and investigations at cultural heritage sites throughout Europe combined with laboratory simulations. The first results from climate simulation of South East Europe (Crete) are presented. A full study in regards to the four climate regions of Europe is foreseen to provide values for development of a precise and integrated model of thermographic building simulations for evaluation of impact of climate change. Cultural works of art are susceptible to deterioration with environmental changes causing imperceptibly slow but steady accumulation of damaging effects directly impacted on structural integrity. Laser holographic interference method is employed to provide remote non destructive field-wise detection of the structural differences occurred as climate responses.

Development of a third generation user interface software optimised portable metrology system (DHSPy II) is designed to record in custom intervals the surface of materials witnessing reactions under simulated climatic conditions both on-field and in laboratory. The climate conditions reacted to real data-loggers readings representing characteristic historical building in selected climate zones. New generation impact sensors termed Glass Sensors and Free water sensors are employed in the monitoring procedure to cross-correlate climate data with deformation data. In this paper results from the combined methodology are additionally presented.

8790-12, Session 4

Systematic noninvasive optical investigation of wall paintings at a UNESCO world heritage site

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The Mogao caves near Dunhuang at the edge of the Gobi desert is a Buddhist temple site with a history that extends over 1000 years from the 4th C to the 15th C. There are 735 caves (409 with wall paintings) and 45,000 square metres of wall paintings at the site, which is an immense resource for the study of the history of art and architecture, religion, science and technology, politics and cultural exchange along the Silk Road. The wall paintings are vulnerable and therefore any examinations conducted for art conservation or historical and archaeological studies should preferably be non-invasive and non-contact.

In this paper, we show an example of a systematic in situ study of the wall paintings using a range of non-invasive optical imaging and spectroscopic instruments. PRISMS, the remote spectral imaging system developed in our group, has the capability of high resolution remote multispectral/hyperspectral imaging at distances of tens of metres making it convenient to examine ceiling paintings at a height of 11-12m. Since these paintings have been in caves with very low natural lighting over the centuries, it is important to ascertain the stability of the paint to light before using strong illumination. While imaging is generally considered non-invasive, all imaging techniques need some sort of illumination which can potentially cause photochemical changes in the artefacts being examined. A microfading spectrometer developed in the group monitors the change in spectral reflectance of a material while subjected to accelerated light ageing using a focused beam of light of high intensity at a tiny sub-mm sized spot, was used to examine the light stability of various paints in a cave before imaging. Spectral imaging revealed faded writings, preparatory sketches and allowed pigment identification. An OCT was brought to this remote site for the first time. It was initially thought that unlike European paintings, East Asian paintings have very thin paint layers and larger pigment to binding medium ratios and therefore not suitable for OCT examinations. However, our results showed that OCT was very effective in separating the layers on which the preparatory sketches and the final sketches were drawn. This paper demonstrates through examples how a combination of these non-invasive imaging
and spectroscopic methods can yield a wealth of information for conservation and art history.

8790-13, Session 4

Close range photogrammetry applied to the documentation of an archaeological site in the Gaza Strip, Palestine

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In a geopolitical very complex context as the Gaza Strip it has to be dealt with an enhancement of an archaeological site. This site is the monastery of St. Hilarion. To enable a cultural appropriation of a place with several identified phases of occupation must undertake extensive archaeological excavation. Excavate in this geographical area is to implement emergency excavations, so the aim of such a project can be questioned for each mission. Real estate pressure is also a motivating setting the documentation because the large population density does not allow systematic studies of soil before construction projects. This is also during the construction of a road that the site was discovered. The implications of this development heritage is important, that is why it was decided to give the possibility to a palestinian team to be formed photogrammetric documentation techniques. This is a Franco-Palestinian whic has been implemented to allow the transfer of know-how. The objective is to eventually let the palestinian team manage self-preservation of their heritage. First of all, control of survey tools is essential. Then comes the practice in the case of the survey of the monastery under the supervision of the French team to control images and 3D data calculations. And finally, management survey must be made totally by local scientists.

Site dimensions are 150m by 80m. It is located on a sand dune, 300m from the sea. To implement the survey, four different levels of detail have been defined for terrestrial photogrammetry.

The first level elements are similar to objects, capitals, fragment of columns, tiles for example. Modeling of small objects requires the acquisition of very dense point clouds (density: 1 point / 1 mm on average). The object must then be a maximum area of the sensor of the camera, while retaining in the field of view a reference pattern for the scaling of the point cloud generated. The pictures are taken at a short distance from the object, using the images at full resolution.

The main obstacle to the modeling of objects is the presence of noise partly due to the studied materials (sand, smooth rock) which do not favor the detection of points of interest quality. Pretreatments of the acquisition of very dense point clouds (density: 1 point / 1 mm on average). The object must then be a maximum area of the sensor of the camera, while retaining in the field of view a reference pattern for the scaling of the point cloud generated. The pictures are taken at a short distance from the object, using the images at full resolution. The main obstacle to the modeling of objects is the presence of noise partly due to the studied materials (sand, smooth rock) which do not favor the detection of points of interest quality. Pretreatments of the cloud will be achieved meticulously since the outer of points on a surface of a small object results in the formation of a hole with a lack of information, useful to resulting mesh.

Level 2 focuses on the stratigraphic units such as mosaics. The monastery of St. Hilariam identifies thirteen floors of which has been documented years ago by silver photographs, scanned later. Modeling of pavements is to obtain a three-dimensional model of the mosaic in particular to analyze the subsidence which it may be subjected. The dense point cloud can go beyond by including the geometric shapes of the pavement. The calculation mesh using high density point cloud colorization allows cloud sufficient to final rendering.

Levels 3 and 4 will allow the survey and representation of loci and sectors. Their modeling can be done by colored mesh or textured by a generic pattern but also by geometric primitives. This method requires the segmentation simple geometrical elements and creates a surface geometry by analysis of the sample points. Statistical tools allow the extraction plans meet the requirements of the operator can monitor quantitatively the quality of the final rendering.

Each level has constraints on the accuracy of survey and types of representation especially from the point clouds which are detailed in the complete article.

8790-14, Session 4

Evaluation of historical museum interior lighting system using fully immersive virtual luminous environment

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The interior luminous environment of Saint Rocco Museum, a historical building located in Venice, Italy is used as a case study to explore the performance of its’ lighting system and visible light impact on viewing the large size art works. Museum curators often use actual materials or paintings to evaluate the changes in color appearance of their surfaces under different lighting conditions. The virtual reality (VR) mock-up is designed to have a high degree of interactivity to study the performance of the museum lighting system design within the public areas.

The transition from three-dimensional architectural rendering to the three-dimensional virtual luminance mapping, visualization and color perception within a virtual environment is described as an integrated optical method for its application in design evaluation toward preservation of the cultural heritage of the space. Lighting simulation programs represent color as RGB triplets in a device-dependent color space such as ITU-R BT709. Prerequisite for this is a 3D-model which can be created within this computer aided virtual environment.

The onsite measured surface luminance, chromaticity and spectral data were used as input to an established algorithm to produce the best approximation for RGB to be used as an input to generate the image of the objects. Conversion of RGB to and from spectra has been a major undertaking in order to match the infinite number of spectra to create the same colors that were defined by RGB in the program. The ability to simulate light intensity, color and spectral power distribution provide opportunity to examine the impact of color inter-reflections on historical paintings. Different lighting systems need to meet cultural heritage standards while providing visual environments that are acceptable to the ardent viewers. VR offers an effective technique to quantify the visible light impact on human visual performance under precisely controlled representation of light spectrum that could be experienced in 3D format in a virtual environment as well as historical visual archives. The system can easily be expanded to include other measurements and stimuli.

8790-15, Session 4

Defects detection and non-destructive testing (NDT) techniques in paintings: an unified approach through measurements of deformation

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In the last thirty years, a great attention was reserved to preservation of canvas paintings. Many progresses in understanding how a canvas painting is constructed and how it responds to its environment and strain’s actions have been made. Conservators began to understand that not only the canvas and sizing but also the paint could respond to moisture very significantly, and that the moisture content influences the mechanical properties of the paint, making it more susceptible to the effects of heat and pressure.

Degradation processes in art objects are usually slow and gradual. Although this situation is preferable from a curator’s point of view, it presents a problem for conservation scientists who would like to clarify the mechanism responsible for these degradation processes. In the absence of direct information on the behaviour over time, local spatial differences in the condition of a material within a single object can provide important clues to factors that enhance or reduce degradation. These local differences are therefore of special interest in the conservation science. In the field of the conservation of canvases paintings, an example of such local difference is the variation in the condition of the paint layer and that of the canvas in the regions directly over the stretcher, strainer or cross bars and the condition of the painting in the other regions behind which no wood is present. The term stretcher is used to indicate any part of the wooden support of the canvas, and refers to the local, sharp transition in the condition of the painted canvas. It is known as “stretcher effect”. Although this effect is well-known to paintings conservators, the explanations
of why it happens is a matter of current research. The most popular explanation for this effect is that the presence of the stretcher induces a local deviation of the relative humidity behind the canvas, which controls the moisture content of the canvas, ground, and paint layers. This local deviation of the moisture content will lead to a localized swelling of the layers in the painting at the stretcher area in comparison to the area where no stretcher is present. Over time this might lead to the "stretcher effect".

Paintings constructed with acrylic artist paints seem indestructible even to the latter effect, compared to many more delicate painting mediums such as gouache, watercolor, encaustics and tempera, or drawing mediums such as pastels or charcoal. Under most environmental conditions, acrylic paintings are very flexible, and this dramatically reduces the potential for cracking in most situations. The price paid for this flexibility is a softer film; one that can be scratched, scuffed and marred easily. Another property of this flexible paint surface is the relative permeable nature of the waterborne acrylic. This property allows for dirt or pollutants to become embedded (especially in a fresher film). Finally, the most significant property of the acrylic film (again especially representative of fresh films) is the potential tackiness of the surface.

With this information it is possible to say that canvas is the core of a painting. Since it is strictly linked to mechanical stress induced by environmental local variations. Therefore, the deformation studies of canvas mounted on wooden frames are key points in order to understand the defects' temporal evolution. In the present study, this was realized using tensioning devices, adjustable and micrometrically controlled via a pin supported in a hollow cylinder. Strains were analyzed by holographic interferometry (HI) using an appropriate frame. A mathematical model of the canvas deformation and a discussion of the HI results with a comparison between theoretical and experimental graphs are reported.

The second topic discussed in the manuscript concerns the need to improve the conservator's knowledge about the defect's detection and defect's propagation in acrylic painting characterized of underdrawings and pentimenti. To fulfill this task, a sample was fabricated in order to clarify the several doubts inherent the influence of external factors on their conservation. Underdrawings and pentimenti were retrieved by near-infrared (NIR) reflectography technique, using LED lamps working on different wavelength narrow bands.

The sample painting represents a detail of “La crocefissione di San Sepolcro” (beginning of XVI century), by Luca Signorelli, i.e. the part where an author's pentimento was detected. In addition, three mylar defects were inserted at different depths and an ancient double canvas was used. The canvas affected by biological attack, was also repaired in several parts in order to simulate previous restorations. A sponge was glued on the rear side of the canvas and impregnated with precise amounts of water by means of a syringe in order to verify the "stretcher effect" by digital speckle photography (DSP) technique. The same effect also affects the sharp transition of the canvas at the stretcher’s edge, probably due to a mechanical contact between stretcher and canvas. In the present case study, this assumption was investigated by holographic interferometry technique. It reflects the real behaviour of paintings where the stretcher is in close contact with the canvas, and where the latter provides direct mechanical support. Finally, the advanced algorithms applied to the square heating thermography (SHT) technique were very useful to detect the mylar inserts simulating detachments between the canvas and the paint layers, and/or inclusions of foreign materials inside the double layer. In addition, these fabricated defects were also confirmed by the optical techniques, while digital speckle photography method was the only one capable of retrieving the positions of fungal attack affecting the canvas rear side.

Nondestructive inspection and characterization of the surface of wood artworks and artifacts and structures is fundamental for a proper preservation and in defining the suitability of a certain kind of material for a specific application or in studying its reaction to environmental constraints. Non-destructive rugometric and microtopographic inspection on wood surfaces should be performed. Active optical triangulation based microtopographers, like the MICROTOP systems developed at the University of Minho, can be successfully employed on the rugometric characterization and microtopographic inspection of different types of wood surfaces. In this communication we will describe the employed system and inspection procedure and present a set of representative results of applications to the inspection of different wood artworks.
Apart from wide spectral range optical spectroscopy, the novelty lies in the utilisation of model KH 8700 digital optical 3D microscope from Hirox Co. (Japan). The microscope allows for observations and three-dimensional quantitative measurements of surface topography as well as the interior of transparent objects in reflected and transmitted light, with illumination varying from cylindrical to point, with an adjustable incidence angle. Based on digital image record, a direct analysis of almost all elementary geometrical data (e.g. measure of straight line, curve, angle, envelope, surface, volume) and basic roughness parameters is possible. A rotary microscope head allows for filtering, and the software enables image and film recording with varying depth of field. Standard analyses of L*, a* and b* colorimetric coordinate changes in the so-called CIELab three-dimensional colorimetric space have been used in colorimetric examinations of amber samples. These analyses will be supplemented by the results of analyses run within the colorimetric cylindrical coordinates of CIELCh space, using more perceptive coordinates of colour saturation (chrominance) C = sqrt(a^2 + (b^2)/2) and hue (hue angle) h = arctan(b/a^2).

The description and discussion of the analyses' results have been divided into three chapters in regard to the kind of amber specimens transferred to different environmental conditions. The collection is regularly examined and documented in the world [1]. The collection is regularly examined and documented annually by over 26 thousand inventory numbers of Museum of the Earth in Warsaw, its collections, aims and publications. Moreover, many years of observations of the collection belonging to Museum of the Earth of Polish Academy of Sciences in Warsaw allowed to notice considerable differences in preservation of various owned succinite specimens from Russian, Ukrainian and German deposits. It indicates the purposefulness of correlation between material properties of this amber's variants with preparation of its exposition and conservation. Those tests have not been finished by the time of the abstract's preparation and the discussion of their results will be presented at the Optical Metrology symposium and in the paper's full version.

8790-39, Session PS
Optical characterization of amber specimens from the unique collection of the Museum of the Earth of the Polish Academy of Sciences in Warsaw
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Museum of the Earth of the Polish Academy of Sciences in Warsaw owns a collection documented by over 26 thousand inventory numbers of amber and other fossil woods, belonging to some of the largest ones in the world [1]. The collection is regularly examined and documented using various analytical methods [2]. Part of the Museum's collection features an extremely poor preservation, and its fast, frequently varying degradation affects the archaeological objects, having been transferred to different environmental conditions.

The paper presents examination methodology and results for selected amber specimens and prepared amber samples, with particular emphasis put on the use of noninvasive methods of topographic and material analyses. Digital optical microscopy, UV-VIS-NIR-FTIR spectrometry as well as colorimetry have been used in primary research. Apart from wide spectral range optical spectroscopy, the novelty lies in the utilisation of model KH 8700 digital optical 3D microscope from Hirox Co. (Japan). The microscope allows for observations and three-dimensional quantitative measurements of surface topography as well as the interior of transparent objects in reflected and transmitted light, with illumination varying from cylindrical to point, with an adjustable incidence angle. Based on digital image record, a direct analysis of almost all elementary geometrical data (e.g. measure of straight line, curve, angle, envelope, surface, volume) and basic roughness parameters is possible. A rotary microscope head allows for filtering, and the software enables image and film recording with varying depth of field. Standard analyses of L*, a* and b* colorimetric coordinate changes in the so-called CIELab three-dimensional colorimetric space have been used in colorimetric examinations of amber samples. These analyses will be supplemented by the results of analyses run within the colorimetric cylindrical coordinates of CIELCh space, using more perceptive coordinates of colour saturation (chrominance) C = sqrt(a^2 + (b^2)/2) and hue (hue angle) h = arctan(b/a^2).

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Bibliography
Studies on watercolour deacidification by means of the Bookkeeper preparation.

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The aim of the first stage of presented studies was to check the possibility of Bookkeeper method application for deacidification of watercolors and other works of art made with use of moisture or solvents sensitive techniques.

The Bookkeeper method is the mass conservation method mainly used for deacidification of 19th and 20th century prints, based on poor quality papers and it has been known since 30 years. During this time the influence of deacidification on physical and chemical properties of paper has been thoroughly examined. Therefore this study concentrates on the influence of this procedure on color durability of watercolors and other paper works made with use of moisture or other solvents sensitive techniques.

A preliminary stage of this research consisted of accelerated aging test of model samples prepared with the use of selected watercolors and thin films of paper treated and non-treated reference samples were aged with light in Xenotest 150S apparatus. The color change evaluation was conducted on Elrepho SF450 spectrophotometer in CIE L*a*b* color space. Positive test results obtained during this experiment allow us to begin second phase of the research, which are studies with the original art objects.

Application of spectroscopic techniques for the study of the surface changes in poplar wood and possible implications in conservation of wooden artefacts

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Introduction

The aim of this work is to study the surface modifications of poplar (Populus spp.) wood by reflectance spectrophotometry and Fourier Transform Infrared (FT-IR) spectroscopy in order to understand the mechanisms that cause the changes and to suggest possible solutions to avoid the degradation phenomena. The choice of poplar was due to its widespread use in Italy for the creation of statues, ceilings, furniture, doors, painted panels, etc.

In cultural heritage the monitoring of wood surfaces during light exposure should be performed though non-destructive methods to avoid the paradox of damaging a work of art while monitoring its preservation state. For this reason colour measurements were chosen as possible method to evaluate wood surface changes. Since colour changes on wood surfaces are due to photo degradation of its chemical constituents, the study of the relationship between CIELAB colour changes and changes in chemical composition due to irradiation is of practical importance both in cultural heritage and in contemporary artefacts and objects.

This work starts from the yet published results obtained by the same authors of this abstract regarding the colour measurements on poplar and chestnut wood1. The novelty, in comparison to those papers, is that in the present work the colorimetric data are correlated to the chemical information derived from the FT-IR spectroscopic analysis.

Concerning the surface protection of wood, starting from the results obtained by testing different commercial products3, the attention has been focused on Linfoil®, a novel organic preservative/consolidant product that seems to attract a great interest in the field of conservation of wooden artefacts. Also in this case, starting from the previous results, Linfoil® was chosen and analysed in order to understand its composition and its time stability.

Materials and methods

Wood samples were obtained by a single board of poplar. The wood samples were treated with Linfoil®, a mixture of vegetable oils, resins and waxes in an aliphatic solvent. Linfoil® was diluted with Linfosolv® (1:1 volume ratio), a solvent system made of a mixture of refined paraffinic aliphatic derivatives and extracts from citrus.

To perform the FT-IR analysis directly on wood surface, slices with a size of 10 (diameter) x 2 (thickness) mm2 were obtained from the specimen of poplar.

Linfoil® samples were prepared by applying the product on glass slides and allowing it to dry.

The accelerated ageing of the samples was performed in a Model 1500E Solar Box (Enrichsen Instruments). The system is equipped with a 3 kW xenon-arc lamp and an UV filter that cuts off the spectrum at 280 nm. The samples were exposed in the Solar Box chamber from 1 to 504 h at 550 W/m2, 55°C and the UV filter at 280 nm. After exposure for a given length of time the samples were removed from the Solar Box chamber and the colour was measured using an X-Rite CA22 reflectance spectrophotometer according to the CIELAB colour system.

FTIR spectra were obtained using a Nicolet Avatar 360 Fourier transform spectrometer in diffuse reflectance (DRIFT) modality. Spectral data were collected and elaborated with OMNIC 8.0 (Thermo Electron Corporation) software.

Linfoil® samples exposed in the Solar Box chamber were investigated by analytical pyrolysis at 600°C using a microfurnace pyrolyser (Pyrojector II, SGE) coupled to a gas chromatographic-mass spectrometric system (HP 5971 MSD). The pyrolysis products were identified comparing their mass spectra with those in the NIST and Wiley libraries in order to determine the nature of polymeric components presents in the protective product.

Main results

Wood surface colour undergoes an important variation due to photo-irradiation. The greatest changes occur within the first 24 hours and they are mainly due to L* decrease and b* increase. Linfoil® treatment modified wood colour. Nevertheless, wood samples treated with Linfoil® exhibited colour changes much lower than those of untreated samples. This product seems to protect wood surface by reducing the yellowish.

FT-IR spectrometry allowed to investigate the rate of photo-degradation of wood surface due to lignin oxidation. The most important result is that a correlation of the colour changes may be derived with the photo-degradation of lignin obtained by FT-IR analysis. This finding demonstrates that non-invasive colour measurements can be used to evaluate the photo-degradation of untreated and surface treated wood.

References


u-XRPD studies of blue pigments in Gdansk paintings of the 17th century

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The analysis of the blue pigments from 17th century Gdansk paintings is described in this paper. Three world famous panel paintings, ‘Alms Table’ (1607; St. Mary’s Church in Gdansk, Poland) by Anton Möller (1563/65 – 1611), ‘ServiliusAppius’ (1608; the Gdansk History Museum).
With respect to fixed points, and a communication module to transfer all the electronics to handle the sensor signals and the firmware to a multispectral camera, a module to interface the sensor, that contains sensitivity range from uV to IR corresponding to the sensitivity range of the above fields.

In this paper we describe a Multispectral Light Metering System for diagnosis and conservation. The system is based on a multispectral sensor with an extended wavelength range, are even more demanding and require to pay further attention to a number of parameters characterizing the lighting system. A critical issue for lighting systems, even in the visible light, is the color we perceive from a surface is our eyes’ interpretation of the linear spectral combination of the illuminant spectrum and the spectral reflectance. If there is a lack of energy in a portion of the visible spectrum, that portion will turn into black to our eyes (and to whatever instrument) regardless the actual reflectance of the surface. In other words a lack in the exciting energy hides part of the spectral reflectance of the observed subject. Furthermore, the wider is the investigated spectrum, the fewer are the sources of light able to cover such a range. A viable solution could be the use of compound sources made of more individual components, each one of which covers a specific portion of the spectrum. This is a very common solution to achieve wide range spectra out of an optical fiber powered by more sources mixed all together through a diffusive mean. Unfortunately, the amount of energy reachable in this way is quite poor and not enough to provide lighting for large surfaces such as paintings and frescoes. Very well known wide range sources of light are them based on Xenon, both impulsive lights (flashes) and continuous lights (plasma arc), ranging from UV-A ~300 nm to NIR ~1000 nm. Xenon flashes are widely available due to extremely large use of them in traditional photography, without practical restriction about the achievable power. Flash lights should be preferred even to the so called “cold lights”, the reason to prefer photography, without practical restriction about the achievable power. Flash lights should be preferred even to the so called “cold lights”, the reason to prefer xenon flashes resides in the much more homogeneous spectrum of the xenon compared the spiked one of the discharge sources. A spectrum made of high spikes and a low continuous land offers a Color Rendering Index that is really poor to observe a painting with all its degrees of colors.
Even if flash lights offer all these advantages, there are conditions and operations that require continuous illumination and homogeneous light over a surface. One very common activity with these characteristics is the restoration. Very rarely (especially in a laboratory) a restorer is so lucky to work at natural light, and most of the time they use artificial light, and it is redundant to underline the importance of the quality of this light when they have to match original colors with an available palette. The same issue arise when a museum wants to offer to visitors a quite high level of fruition and reading of the masterpieces.

Another field of strong interest is the multispectral imaging. One quality parameter for an imaging system is the sharpness of the images it is able to produce. Multispectral Imaging Systems need to produce sharp images in a wide range of wavelengths. Due to a refraction index that significantly changes with the wavelength, each multispectral band requires then a separate focus settings.

The autofocus system of a reflex camera, when the optical viewfinder is used, is based on prisms and on the "equal path" assumption between the direct to sensor and the through the mirror distances. This stands for true only in the visible spectrum, for which the autofocus system is trimmed and calibrated. As soon as other wavelengths show up, because the refraction index is a function of the wavelength, all calibrations are not valid anymore. In this case it is of great help the live-view function by now offered by all the reflex cameras. Live-view means that you get what you see, included the degree of focus, but this means also that to focus it is needed a continuous light, with a wide wavelength range, and with an homogeneous distribution. This quality rare to find together in a single practical and portable equipment.

In this paper we propose a modular approach to the wide spectrum continuous lighting that is suitable to be used both for restoration and for multispectral imaging.

The base module consist of a medium power continuous xenon light as a source of light, a two axes light steering mechanism, an electronic driver of the arc lamp, a control unit, a communication module, a battery and a power supply. Each module is autonomous and doesn’t require any other equipment. Through the buttons and display on the control unit it is possible to turn light on and off, and to steer the light head to the desired direction without touching the lamp.

While a single module is already a solution, more modules can be combined to form a lighting system as complex and rich as it is needed. Each module can be positioned individually exactly where it is needed, and all the module can be remotely controlled by a wi-fi remote control (or with a computer).

This allows design the lighting following specific rule, as the "45/0 degree" to optimally measure the reflectance, or to use raking light from different position activating one of them at time without changing the setup or moving anything.

The steering heads allow to distribute the beams over the surface of interest in the best way, controlling everything from a remote control or from a computer, to achieve an even illumination or to concentrate more energy to a specific area.

One of the goal of the project is to keep the cost of each module affordable and to achieve a system tailorable and optimized for each specific activity.

8790-46, Session PS

A systematic study of historic writing and drawing inks using THz-TDS spectroscopy and imaging

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With the development of ultra-short pulse lasers in the last decade, terahertz time-domain spectroscopic (THz-TDS or pulsed) imaging has emerged. As THz radiation induces changes of amplitude in inter-molecular vibrations between neighbouring molecules, materials with a different chemical composition or crystalline structure have different absorption and dispersion responses in the THz region. THz spectroscopy can therefore be used for material characterization and, combined with THz imaging technology, can produce a contrasted image of a sample based on differences in composition. Additionally, the low-energy radiation allows for non-invasive analysis to a depth of a few cm, depending on the material and the conditions of the experiment. This could be particularly useful for the analysis of historical objects where restricted handling is required.

In this context, the present study examines the potential of THz-TDS imaging as a diagnostic and imaging tool for studies of archival documents, such as manuscripts, maps and drawings.

Pulsed terahertz spectroscopy in transmission was performed between 0.2 and 3 THz on historically informed model writing and drawing inks: sepia, ivory black, lamp black, bistre and iron gall inks, as well as vermilion, minium, verdigris, malachite and lapis lazuli, often used in manuscripts.

As the nature, purity and proportion of the compounds used for the preparation of iron gall inks varied greatly from ink to ink, different mixtures were prepared by changing the ratio of the acid (gallic or tannic acid), and by varying mass and molar ratios of iron(II) sulfate to acid, or adding copper sulfate to the preparation. These inks were left to dry before analysis, and some were additionally subjected to accelerated degradation.

Black and coloured pigments, dried iron gall inks and individual constituents of iron gall inks were ground into fine powder, mixed with a material transparent to THz (polyethylene powder) and pressed into pellets with the same mass and thickness. All spectroscopic analyses were done in triplicates. Each pellet was then placed in a purged nitrogen chamber before spectral acquisition. In the case of iron gall ink samples, the spectra were analysed using multivariate data analysis to enable the comparison of the behaviour of different spectral features during degradation experiments. These spectra complement the terahertz online spectral library of art materials (http://thzdb.org), in which most of the inks and pigments are not analysed with TDS but rather with FTIR systems, showing good signal to noise ratio only above 3 THz.

In THz-TDS, both the amplitude and the phase of the THz electric field are transmitted through a sample. This provides (i) the absorbance spectrum informing on the chemical nature of an ink, such as its crystalline or amorphous structure, and (ii) the frequency dependence of the refractive index and the absorption coefficient of the material. This allows for the interpretation of THz image of layered structures such as ink on support, and allows for the understanding of the combined influence of the nature of the individual layers and the THz pulse on the image contrast. To support spectroscopic evidence, THz imaging was performed on the above mentioned model inks on historic rag paper and parchment, and the image contrast of the different ink dots on supports were compared. The inks were applied on the different supports with a pipette in droplets of 2 μL, to avoid any indentation on paper, which could otherwise contribute to the THz image contrast. The roughness of the different supports was also measured and taken into account in the interpretation of the differently contrasted THz images.

This first systematic comparative study enabled the analysis of historic documents with inaccessible information such as unopened letters or parchment maps used as book covers, by obtaining well-contrasted images of the content without altering the document.

8790-47, Session PS

Multiscale modelling of surfaces by profilometry based on conoscopic holography

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Optical profilometry enables non-destructive and non-contact surface metrology, and is therefore suitable for the measurement of surface topography of artworks. By examining the artwork surfaces with different techniques, e.g. laser triangulation or white light interference methods, it is possible to obtain surface maps at various scales and resolution in order to construct a suitable 3D model, according to the specific case study. However, if guidelines and standard parameters are well
defined in surface metrology for engineering applications, the problem of surface analysis and characterization, at a microscopic level, is still open when dealing with an artwork. The lack of rules in defining the measurement and the characterization of main surface features, such as roughness and waviness, is a crucial point. Despite this, qualitative analysis of surface in works of art is an interesting challenge that has many potential applications, ranging from the documentation of the surface morphology, e.g. canvas or support deformation in paintings, varnish and painting layers, to the monitoring of the surface decay and the effects of treatments, etc.

This work deals with optical micro-profilometry based on conoscopic holography, a technique that has recently being applied to the investigation of artworks. Conoscopic holography (introduced by Sirat & Psaltis and then patented by Optimet) is an incoherent-light interferometric technique based on light propagation on anisotropic crystals, which allows to perform reliable and stable profilometric measurements down to the scale of micron (or sub-micron, according to the type of sensor).

In this work, surface data are collected and analyzed with a multi-scale approach. Surface texture is modelled in terms of roughness and waviness features on different scales.

In order to perform surface measurements at multiple scales, a modular device has been assembled in laboratory and a custom software implemented. The punctual conoscopic probe was mounted on two motorized high-precision linear stages (micron step) for raster scanning at different spatial grids, and different objective lenses (16mm, 50mm, 75mm) were used. Surface data sets be collected at different quota resolution (2μm, 6μm, 10μm), transversal resolution (5μm, 15μm, 25μm) and dynamic range (0.6mm, 8mm, 18mm).

Analysis of surface features at micrometric scales was carried out on the 3D datasets, after removing the main shape. The surface texture was then analyzed for separating the spatial features at short wavelengths (roughness) from the components at longer wavelengths (waviness). A Gaussian filter was used to separate the two surface components. Roughness is related to the microstructure of the surface material whereas waviness is mainly related to the local surface deformation. The filtering of roughness texture at different spatial lengths is discussed. The spatial length at which roughness becomes waviness depends on different factors.

Artwork surfaces exhibit specific properties at different scales, related to the object structure and material, and a 3D model based on a multi-scale topography enables a more effective analysis.

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8790-48, Session PS

NavOScan: hassle-free handheld 3D scanning with automatic multi-view registration based on combined optical and inertial pose estimation

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Portable 3D scanners with low measurement uncertainty are ideally suited for capturing the 3D shape of objects right in their natural environment. Battery powered, compact scanning devices without the need for other stationary equipment provide scanning opportunities in museums or directly at excavation sites. To fully measure an entire object, usually multiple views are required. However, elaborate manual post processing was typically necessary to build a complete 3D model from several overlapping scans (multiple views). Alternatively, expensive or complex additional hardware (like infrared or magnetic trackers etc.) was needed. On the contrary, the NavOScan project aims at fully automatic multi view 3D scan assembly through an add-on unit (Navigation Unit) attached to arbitrary 3D scanners.

The light weight Navigation Unit combines an optical tracking system with an inertial measurement unit (IMU) for robust relative scanner position estimation. The IMU provides robustness against swift scanner movements during view changes. Also, extra stability during challenging situations for optical tracking systems (like moving background, illumination changes) is provided. The IMU position estimation is enhanced by a wide angle, high dynamic range (HDR) optical tracker focused on the measurement object and its background. This ensures accurate sensor position estimations. The underlying software framework, partly implemented in hardware (FPGA) for performance and energy efficiency reasons, fusions both data streams in real time and estimates the navigation unit’s current pose.

Using this pose to calculate the starting solution of the Iterative Closest Point (ICP) registration approach allows for automatic registration of multiple 3D scans. After finishing the individual scans required to fully acquire the object in question, the operator is readily presented with its finalized complete 3D model!

The paper presents an overview over the NavOScan architecture, where a Navigation Unit provides robust sensor pose estimations for an arbitrary 3D scanner. Several key aspects of the registration and navigation pipeline are highlighted, like adaption of the ICP algorithm for real time purposes and HDR sensor usage for outdoor usability.

Several measurement examples obtained with a prototype of the Navigation Unit attached to a hand held structured-light 3D scanner are presented and performance and measurement uncertainty figures are given.

8790-49, Session PS

Multispectral noninvasive techniques for investigations of Gothic mural paintings: case study of chapel in Chwarszczany (Poland, West Pomerania)

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The village of Chwarszczany is located in West-Pomeranian province, My?lib?rz county, commune of Boleszkowice. The former chapel of the Knights Templar/ Knights Hospitaller in Chwarszczany is presently the succursal church of the parish of Sarbinowo. In 1232 the Prince of Wielkopolska, W?dy’s/Custodeic granted to the Poor Fellow-Soldiers of Christ and of the Temple of Solomon (the Knights Templar) 1000 acres of land between the rivers Odra, Warta and My?la. The centre and the seat of the landlords became the village of Chwarszczany.

After cassation of the Order of Knights Templar in 1312 their property, including Chwarszczany with eleven other villages was taken over initially by the margraves of Brandenburgia (1318) and then by the Sovereign Military and Hospitalier Order of St. John of Jerusalem, Rhodes, and Malta, the members of which were being called the Knights Hospitaller or Knights of St. John. In 1540, due to the efforts of the margrave Jan of Kostrzy? (Johann/ Hans von Küstrin) Knights of St. John exchange Chwarszczany with the belonging villages for Twidwin.

The present chapel in Chwarszczany is a brick-built edifice, with lower parts of the walls built of granite.

The perfect composition of mural painting in the space of the church, their iconographic type as well as the making allow to attribute them to the painter aware of the best European art of the period, the artist perfectly educated and well experienced. The forms and execution of the murals brings up the association with the monumental murals on the pillars of churches in Hanza towns. The origin of the artist as well the iconographic sources of the types of representations are impossible to establish without preliminary research in the field of art history. The investigation of mural paintings included the analyses of architecture and painted decoration, the technology and technique of the making.

The materials and structure of the murals were determined with the use of such non-destructive techniques as the UV-reflectography, UV-induced fluorescence, coloured infrared, IR-reflectography.
thermovision, ground-penetrating radar (bipolar aerial 2 GHz and 900 MHz). The thermovision and radar examination of some fragments of the walls revealed irregularities in the wall structure. The detailed multielemental physical and chemical microanalysis allowed for determination of possible composition of pigments, mortars and bricks, as well as the presence of micro-organisms. The research made use of microscopic analysis in UV, in visible range, in polarised light, coloured infrared, IR-spectroscopy (FTIR), X-ray fluorescence (XRF) and gas chromatography (GC). In UV reflectography thin layer of the 19th century repaintings are clearly visible. UV light is strongly absorbed by amber and copper pigments. Strong fluorescence of the paintings which contain the zinc oxide (ZnO). ZnO has been widely used since 1845. In the other parts of the 19th century re-paints the suppressed fluorescence is observed.

In IR false color image the light blue color of background indicates the usage of painting containing azurite, malachite and small amount of red lead, and various shades of green come from iron oxides. The emerald green gives pink color in the IR false color images. The strongest absorption of the IR light is observed in parts of composition drawn up with pigments containing carbon blacks.

In thermography images weak gradients of temperature is seen. Highest temperatures (20.6 °C, 20.7 °C and 20.8 °C) occur in the area of delamination of plaster. In areas of good plaster adhesion, lower temperatures are recorded in IRT images. The size of delaminations was estimated to 1-2 mm on the base of analyses of GPR profiles (not presented here).

Basing on the results of examination the visualisation of the range of 19th-century overpaintings was developed, pigments were identified and the condition of support was determined. Results were used for the protective conservation consisting on re-attaching delaminating plasters and the removal of the secondary glue-based paint from the surface of Gothic murals.

8790-50, Session PS

Original or fake? Investigation of authenticity of three artworks attributed to Lyonel Feininger, George Grosz and Paul Klee

Elzbieta Basiul, Jaroslaw Rogoz, Jolanta Czuczek, Pawel Szroeder, Adam Cupa, Malgorzata Geron, Nikolaus Copernicus univ. (Poland)

The twilight of 19th century and early 20th century were the period of significant changes in arts both in the aspect of ideology, style and technology. It was the period of creative activities of many outstanding individuals, marking out new trends and ways of development of the arts. On the other hand – works of art from that period, especially by well known artists enjoy constant attention of the collectors and reach enormous prices on the art market. Thus it is not surprising, that those works are being extensively copied and forged, and the resulting counterfeits are often signed by the names of the artists and pretend to be original artworks. They display diverse level of performance, but in many cases confirmation of authenticity – or forgery – requires broad spectrum of research.

Three artworks have been subject to analysis, ale from the same collection, signed and attributed to famous artists, like Lyonel Feininger (1871 – 1956), Georg Grosz (1893 – 1959) and Paul Klee (1879 – 1940). Historic and artistic evaluation was performed together with identification of technique of the making and of the materials used. Due to the character of research only non-destructive methods were employed and those involving the analysis of microsamples. Employed were among others: the techniques of recording macro and microphotographic images in VIS, IR-reflectography, coloured infrared (the so called technique of false colours), UV-reflectography, UV-induced fluorescence, IR-spectroscopy FTIR/ATR, IR-microspectroscopy and X-ray fluorescence analysis XRF.

In the same time a comparative research was carried out based on original works of the artists available in Polish and foreign collections. Not a single element was found that would certainly decide on the authenticity of each artwork. In such a situation only complex, interdisciplinary analyses bringing together researchers specialised in particular issues allowed for a joined evaluation and interpretation of the results and the following defining of questionable elements that would discredit authenticity of all three investigated artefacts.

8790-51, Session PS

The use of multispectral nondestructive techniques in conservation diagnostics

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The first stage of research is documenting the condition of paint layer and non-destructive investigation in the range of optical techniques of image recording, that is UV-reflectography, UV-fluorescence, VIS, coloured infrared and reflectography in near-infrared IR.

UV-reflectography is based on recording the UV-rays reflected from the paint layer within the range of 300–400 nm. Using that technique one can easily register old overpaintings and retouching hard to reveal in other bands of electromagnetic radiation.

UV-fluorescence technique consists on the registration of fluorescence images of the artefact lit with a lamp equipped with the Wood’s filter (maximum excitation in 365 nm). The intensity and colour of fluorescence can be helpful in identification of certain pigments and dyes as well as binding media. Recorded contrasts between strong fluorescence of the original paint layer and the retouching, displaying low intensity of luminescence, allow for easy and quick localisation of conservators’ interventions.

The images recorded in visible light within the range of 500 – 700 nm serve for registration of the present state of preservation of the artefact in diffused and raking light and are used as a reference in comparative analyses of images recorded in other non-destructive techniques.

Coloured infrared is based on recording the images in the range of 500 – 1000 nm. The methodology of investigation allows for identification of pigments and better visibility of details appearing beneath the glazes, layer of dirt or tarnished varnish. Different pigments, having the same colour in visible light appear different, which allows for their preliminary identification. Technique of coloured infrared complements and broadens the information obtained in the range of ultraviolet, visible light and near-infrared.

The infrared reflectography images are recorded in bands of 730 – 1000 nm, 780 – 1000 nm, 840 – 1000 nm, 900 – 1000 nm. The investigation allows to reveal old retouches (especially in light areas painted with lead-white). This technique differentiates the areas, where the priming-losses had been filled-in (fillings). The research methodology and software tools allow for good visualization of possible earlier versions of composition of the investigated work or the pentimenti.

The obtained results shall allow for preliminary identification of pigments present in the paint layer as well as for drawing conclusions as to the state of preservation of the whole structural volume of the investigated artefact, that is the paint layer and partially the support. Visualisation of the range of appearance of particular materials and structural anomalies and their interpretation shall allow for determining the causes of degradation of the work.

Basing on the outcomes of the analyses the areas on the surface of historic objects are being selected, where further, more detailed, instrumental analyses are to be carried out aiming for more precise determination of the chemical composition of historic structures. Conscious analysis of the most representative areas will eliminate the coincidental effects that hinder the right interpretation of the results.
Material investigation on three special paper molds from Magnani's museum collections

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Before introduction of the industrial machines in the XIXth century, paper was handmade from wood pulp, cotton, hemp, linen and old rags. The basic procedure of manual production, which still survives for some special luxurious writing paper, includes the use of a mold. The latter is constituted by a rectangular wire screen (a sieve) in a wooden frame (“deckle”), which allows fibers to settle and water to drain. Chopped organic fibers are formerly suspended in water in a vat thus forming slurry then some of such a mixture is scooped up using the mentioned mold, which has to be suitably handled in order to form a uniform web of damp fibers on the metal screen. When the fibers have stabilized in place they are turned out onto a felt sheet and subjected to the subsequent processes including drying, pressing, and other, while the screen mold is immediately reused.

Papermakers usually add watermarks to their products since the Late Middle Ages, when wire watermarking was introduced in Fabriano (1283-4), one of the first European paper mills center. The lines of a wire mark appear more transparent under back illumination and darker than the surrounding paper when placed on a flat surface. Traditionally, this effect is achieved by attaching a wire pattern to the mesh of the paper mold, which produces a corresponding line-thinning effect in the web of paper pulp. Watermarks can reproduce hallmarks, numbering, workman, different grades or batches of paper, as well as coat of arms, figures, or names of the customers. They represent markers of authenticity, which reinforce other discrimination features, such as in particular decked edges and marks left by narrow–meshed lengthwise (laid lines) and widely-meshed transversal wires (chain lines) of the mold.

Within this picture the material and morphological characterization of the paper molds, which are strictly related with specific features of the final product, appears of fundamental importance in order to reconstruct the historical development of papermaking and to derive useful information for authenticating paper artifacts of the past. In the present work a non-invasive technological study on three molds from Magnani’s mills in Pescia (Pistoia, Italy) was carried out. Magnani is a well-known high quality papermaking hallmark, which is manufacturing paper since 1404 and worked for many illustrious customers such as for examples Napoleon, Picasso, De Chirico, Annigoni etc...

The three molds investigated have been those for making: 1) the “Villa dei Quintili” excavation in Rome, are reported. The set of tesserae was retrieved in the thermal analysis of historic glass windows. Laconia V Proceedings 2003, Springer Verlag, Germany (2003), 123.


The preliminary results on the investigation of historic stained glass panels from Grodziec collection, Poland.

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The so called “Grodziec collection” of stained glass panels consists of fourteen objects depicting figures of saints. While their history is not known, probably all belong to one, uniform set from the one of Lower Silesia churches. Recently eight of them are exhibited in Jagiellonian University Museum of Collegium Maius in Krakow, while remaining six are stored in the National Museum in Wroclaw. The Krakow’s panels are already after treatment, and the Wroclaw ones will be restored in nearest future.

The recent paper presents the results of the investigation of composition and corrosion products of glass from two panels of Wroclaw group. Since comparative analysis of historic glass composition is vital for its dating, to obtain the possibly full set of composition data with particular stress on light elements identification, the multi technique approach was necessary. The physicochemical analysis was carried out by micro-Raman spectroscopy at excitation wavelength of 532 and 633 nm, laser induced breakdown spectroscopy (LIBS), X-ray fluorescence (XRF) and scanning electron microscopy (SEM) with energy dispersive X-ray spectrometer (SEM/EDX). The study revealed that some of stained glasses have composition characteristic of northern medieval glass (potash-lime-silicate) while other pieces could be dated on 17th or 19th century due to.

This confirms the suggestion from the former historic and scientific investigation of Krakow’s set that the Wroclaw panels may be of the same medieval origin as the Krakow’s ones and that they were already restored, at least in 19th c.

The possibility of working on the whole set of panels from the Grodziec collection opens up the opportunity for conducting exceptional scientific study which will lead to the definitive designation of the provenance of this important collection, its history and age.

As our research is aimed also at the practical restoration issues, we experimented on using lasers for removal of unsightly and possibly harmful alterations of glass surface. The preliminary results of the possibility of use of ns Nd:YAG laser (1064 nm) for this purpose are presented in this paper.

References


Remote photonic technologies for artwork inspection
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Photonic technologies have introduced an important research field in the examination of artworks including fields of application from materials characterisation to deformation measurements on a variety of items and problems. Thus the last two decades photonic technologies have emerged as unique answer or most competitive alternative into many long-term standing disputes in conservation and restoration of Cultural Heritage (CH). Despite the impressive advances on the state-of-the-art ranging from custom-made system development to new methodologies and practices, photonic research and technological developments remain incoherently scattered and fragmented with a significant amount of duplication of work and misuse of resources. In this context, further progress should aim to capitalise on the so far achieved milestones in any of the diverse applications flourished in the field of CH. Embedding of experimental facilities and conclusions seems the only way to secure the progress beyond the existing state of the art and its false use.

The solution to this embedment seems possible now through the new computing environments. Cloud computing environment and remote laboratory access allows to bring the leading research together and integrate the achievements. The cloud environment would allow experts from museums, galleries, historical sites, art historians, conservators, scientists and technologists, conservation and technical laboratories and SMEs to interact their research, communicate their achievements and share data and resources. The main instrument of this integration is the creation of a common research platform termed here Virtual Laboratory allowing not only remote research, inspection and evaluation, but also providing the results to the members and the public with instant and simultaneous access to necessary information, knowledge and technologies.

In this paper we describe the concept and present first results confirming the potential of implementing metrology techniques as remote digital laboratory facilities in artwork structural assessment. The method paves the way for the introduction of remote photonic technologies in the sensitive field of Cultural Heritage.

Laser investigation to remove microorganisms on Machu Picchu quarry stone
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Laser cleaning of stone is a well established technique in the field of cultural heritage because it provides a fine and selective removal of superficial deposits and encrustations [1]. In a number of laboratory and on-site conservation projects, the laser-based cleaning procedure has yielded very satisfactory results overcoming some of the disadvantages of traditional techniques. In particular it has been shown that irradiation at 1064 nm using nanosecond (ns) pulses efficiently removes the black encrustation. When biodeterioration films constitute part of the stone crust to be removed, the laser approach has different peculiarities, and in fact, removal of biological crust on stone using lasers has received less attention. The integration of information obtained by scanning electron microscopy with backscattered electron (SEM-BSE), micro-Raman spectroscopy and chromatic stone properties is an effective strategy for determining the optimal laser parameters for removal of microorganisms that cause biodeterioration without damaging the stone substrate underneath. In this sense, we recently demonstrated that ns laser irradiation at 1064 nm can be applied to remove lichen and microorganisms, both epilithic and endolithic, from lithic substrates, and thus constitutes an environmentally friendly and efficient method to control stone biodeterioration [2].

Machu Picchu is a pre-Columbian 15th-century Inca site located 2213 metres above sea level in the Cusco Region of Peru, which was declared a UNESCO World Heritage Site and selected as one of the New Seven Wonders of the World. In order to design the best strategy for the preservation of the monument, a previous correct diagnosis of the biodeterioration processes must be accomplished. In fact, lichens colonize extensively many of its walls and currently our group has shown that lithobiontic microorganisms are involved in the deterioration of the monument [3].

In this work, we performed laboratory laser irradiations assays in order to remove cyanobacterial biofilms present on stone surfaces from granite quarries of Machu Picchu located within the same monumental site while ensuring preservation of the lithic substrate. Infrared ns laser pulses from a Q-switched Nd:YAG laser system (1064 nm, pulse duration 5 ns, repetition rate 1-10 Hz) with fluences ranging from 2 to 4
J/cm² were used. Stereomicroscopy, micro-Raman spectroscopy and colour measurements were employed to detect possible structural and chemical changes on the irradiated areas and to assess the efficiency of the stone laser cleaning method. Environmental SEM and SEM-BSE served to evaluate the irradiation effects on the cyano-bacterial biofilm. It was observed that removal of the cyano-bacterial biofilm located on the surface of the stone could be efficiently removed by applying 100 laser pulses at 10 Hz and at 3 J/cm², a fluence which is below the stone ablation threshold of 4 J/cm². Micro-Raman spectroscopy and substrate colour change measurements indicate that, under these laser irradiation conditions, the granite substrate remains unaffected. However, it is especially important to note that SEM-BSE observations evidence the presence of fungi localized in fissures inside and between sheets of mica, which, probably due to the fungal walls thermal resistance, had not been affected by the laser environmental heating.

References


8790-58, Session PS

Laser ablation cleaning of an underwater archaeological bronze spectacle plate from the H.M.S. DeBraak shipwreck

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Laser ablation was successfully used to sequentially remove layers of concretion and corrosion from the surface of a copper alloy spectacle plate from the shipwreck of His Majesty’s Sloop of War DeBraak. The H.M.S. DeBraak was a single-masted cutter that was originally a Royal Navy ship in 1786. The ship sank in the Delaware Bay in 1798 and artifacts were recovered from the wreck site in 1984. This spectacle plate is an important part of the ships rudder and it is part of the collection of the Delaware Division of Historical and Cultural Affairs. The object was brought to The Winterthur/University of Delaware Program in Art Conservation for treatment. The object was examined with cross section microscopy, Raman spectroscopy, X-ray fluorescence spectroscopy (XRF), and Energy Dispersive Spectroscopy (EDS) as well as Back Scattered Electron (BSE) analysis with a Scanning Electron Microscope (SEM). Interestingly, layers of both copper and iron corrosion products were identified within the concretion. A 1064nm Long Q-Switch (LQS) laser with 100ns pulses was tested along with a Short Free Running (SFR) with 60 - 130 microseconds pulses, at various fluences and frequencies, to determine optimal cleaning parameters for removing the concretion. Laser cleaning also revealed fragments of wood from the original rudder, which were previously trapped within the concretion. After laser cleaning, the spectacle plate was treated with 3% Benzotriazole in ethanol and then given a protective microcrystalline wax coating.

8790-59, Session PS

Modern technology in originality and authentication dispute on movable and detached artworks

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Precious artworks are in constant loan due to the increase demand for tour exhibitions around the globe. Archeological findings and historical parts of wallpaintings are detached and get into the route of a fraud market. Most of these detached art pieces are lost, destroyed or hidden by public view by anonymous collectors. The damage to the historical, cultural and aesthetic values is most of the times irreversible.

Originality and authentication are essential properties in the identification of movable artworks provoking dispute and fraud actions endangering the long-lasting public approach to the precious but disputed works of art. Scientific community and technology developments are implemented in the battle against fraud and misinterpretation of origin through systematic and material classified studies. European projects have influenced and provoked intense research in this fragile field of modern technology applications and recent results are presented.

Investigation protocols and classification needed for the standardization of valuation of these critical properties comprise an intense field of research embraced with international interest.

In this paper it is presented long-lasting research effort with photonic technologies to bridge the results with the conventional means and the conservation expert opinion aiding to the identification and ensuring the origin of a masterpiece. Results from laboratory investigation and characteristic examples of paintings faced with the dispute of their authentication are given.

8790-60, Session PS

Surface Skeleton Generation Based on 360-degree Profile Scan

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Rapid prototyping technologies, such as 3D printing and laser cutting, have been rapidly developed for years. New applications and cross-disciplinary research ideas emerge along with the maturity of the technology. In this trend, the interaction between engineering and architecture plays a distinctively important role. Such interactions are especially nurtured and cherished at Singapore University of Technology and Design (SUTD), a recently established government institution with the support of Massachusetts Institute of Technology (MIT).

The conventional notion of rapid prototyping is a non-scalable method of physical design production. Designers are limited to model manufacturing as small, desktop artifacts reduced in size by factors. A typical maximum model size when using common rapid prototyping machines is less than 25 centimeters square. This is due to the physical limitation of the machine’s building method. Software generates data assuming that production is of a single model limited to the build volume of the machine. Research exploration in the field has yet to produce a reliable, cost effective method of prototyping or mass manufacturing of very large objects.

In this paper, we introduce a project funded by the International Design Center (IDC) of SUTD. Our objective is to explore a “very large scale prototyping” technique to extend the physical limit of a laser cutter. This technique takes the optically measured surface profile of an object as the input and automatically generates a very large scale surface skeleton structure as the output. The structure is composed of many “rib” that can be manufactured by a commercial laser cutter. Each rib has a number of slots to enable assembly with adjacent ribs by simple interlocking mechanism. At the end of the processing pipeline, a reverse engineered prototype of the original object can be produced efficiently.
The optical metrology method applied to obtain the surface profile is 360-degree profile scan. The scanning method, by default, is applicable to objects with a single radial axis. We explore this special condition and develop an algorithm that generates surface skeleton (ribs) around the radial axis. Ribs of two orthogonal directions are generated, serving two primary functions. The vertical ribs, in the same direction as the axis, provide the standing structure of the scaled prototype; the horizontal ribs, orthogonal to the axis, provide the linkage to fix the relative position of the vertical ribs. In a broader view, the supporting and linking functionalities are shared by ribs of both directions. The fore-mentioned interlocking mechanism relies on the so-called cross-plane slots – those between horizontal and vertical ribs. In order to prototype an object at a large scale, the algorithm also creates in-plane slots – those joining one horizontal or one vertical alone. Ribs exceeding the physical limit of a laser cutter cannot be cut as a whole; hence, the in-plane slots break a rib into several sections to enable production.

Several large-scale prototypes have been created in this project. Although we have only developed one rib generation algorithm applicable to a specific surface geometry format, this approach can be extended to a variety of surface structures.

8790-16, Session 5
Terahertz analysis of stratified wall plaster at buildings of cultural importance across Europe (Invited Paper)
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Terahertz (THz) radiation is being developed as a tool for the analysis of cultural heritage [1], and due to recent advances in technology it is now available commercially in systems producing broadband (0.1 - 2 THz) beams which can be deployed for field analysis. The radiation is capable of penetrating up to one centimetre of common construction materials, including wall plaster, wood and clay, and is delivered in ultrafast pulses of picosecond duration which are reflected from internal layers within the stratified sample. Post-processing techniques which deconvolve the incident pulse from the sample causing a reflection, access a surface resolution of below 70 μm [2], although this resolution limit decreases, through dispersion, as it penetrates the surface of the wall. The reflectometry technique is non-contact, non-invasive, non-destructive and, unlike x-ray based techniques, provides no long term damage to the regions of wall analysed.

THz radiation fills a gap in current techniques used, non-invasively, to analyse the internal stratified structure of walls in buildings of cultural interest. While ground penetrating or sub-surface radar is able to penetrate over a metre and produce details of internal structures, and other techniques, such as infrared and ultraviolet, produce information about the surface layers of such walls, THz radiation is able to provide information about the interim region of up to approximately one centimetre into the wall surface while being able to achieve sufficient lateral spatial resolution and material contrast to identify the presence of sub-surface paint layers.

The internal structure of this first centimetre layer of the wall is of interest, as it is the region which is likely to include sub-surface wall paintings and sinopia underdrawings and to reveal information about the construction of mural paintings. In addition, areas of restoration are also within this depth range. In this paper, studies from churches and cathedrals across Europe are presented, displaying information about the sub-surface layers of wall plaster up to one centimetre in depth using non-destructive pulsed THz reflectometry. Data from Chartres Cathedral, near Paris, France, the Riga Dome Cathedral in Latvia and Chartreuse du Val de Bénédiction in Villeneuve les Avignon, France, form three case studies for the technique, with each site having a specific research question of interest. The presence of sub-surface paint layers was expected from documentary evidence, dating to the 13th Century, and indicated through UV analysis of wall paintings at Chartres Cathedral. In contrast, at the Riga Dome Cathedral surface painting had been obscured as recently as 1941 during the Russian occupation of Latvia using white lead-based composition. In the 17th Century, wall paintings at the Chapel of the Frescos, Chartreuse du Val de Bénédictin in Villeneuve les Avignon were constructed using sinopia underpainting on plaster covering uneven stonework. This paper compares and contrasts the ability of THz-radiation to confirm documentary evidence, and provide information about sub-surface features in churches and cathedrals across Europe by analysing depth based profiles gained from the reflection of ultrafast pulses from changes in refractive index within the wall.

References

8790-17, Session 5
Laser-induced plasma spectroscopy depth profile analysis: a contribution to authentication
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The illegal market of objects of art and historical interest is experiencing a significant increase. Besides the illicit traffic of genuine artefacts, the commercial demand of this sector is also stimulating a massive production of fraudulent imitations. A consequent demand for reliable authentication methodologies comes from law enforcement agencies, conservation institutions, no-profit organisations, involved in the management and legal market of the cultural heritage. Dating, composition, structural, and technological analysis techniques can provide useful objective data for determining the age and the production context of the artefact. With this respect the authentication of objects of cultural interest could be generally achieved through a large set of material markers and the most reliable are those involved in specific aging processes which cannot or have been replicated. Therefore, analysis should be mainly focused on studying long-time interaction effects between the object and the surrounding environment, which can produce peculiar compositional and microstructural fingerprints. This is for example the case of enrichments and depletion phenomena pointed out in archaeological copper alloy artefacts resting in ancient long-time buried earthenware.

The analysis of quantitative elemental composition of archaeological objects is usually achieved by employing different analytical techniques (including, SEM-EDX, XRF, PIXE and ICP-MS.) However, most techniques cannot be extensively used for routine analysis of historical artefacts either because they require a significant amount of sample and complex sample preparation or because non-destructive techniques are associated with instrumentation which cannot be moved on archaeological sites for in situ measurements. Moreover they usually have severe limitation in depth resolved analysis.

On the contrary, Laser Induced Plasma Spectroscopy (LIPS) [1] is increasingly used to obtain both qualitative and quantitative information concerning the chemical composition of ancient works of art because it does not require any sample preparation for analysis, it requires short acquisition times and is a micro-destructive technique. Furthermore LIPS can be used to perform depth profile analysis by applying a series of subsequent laser pulses on the same spot area of the object giving chemical information about both the surface and bulk elemental composition. This makes LIPS one of the most suitable techniques for probing the distribution of elements in archaeological objects such as bronzes and ceramics where traditional sampling would produce unacceptable damages. In this case the in-depth characterization of layers in scales of tens to hundreds of micrometers achieved through LIPS analysis can allow distinguishing natural corrosion and burial-condition induced surface alteration phenomena of archaeological findings from fraudulent aging and patination.
In this work, we report the potential of Laser Induced Plasma Spectroscopy in authentication studies of ancient style manufacuts trough quantitative elemental depth profile analysis. A homemade portable compact LIPS device [2], equipped with a Q-Switched Nd:YAG/1064 nm), six high resolution Czerny-Turner spectrometers (2,400 grooves/mm) with CCD linear array detectors, covering the spectral range between 200-890 nm with resolution of about 0.1 nm, was calibrated for achieving quantitative chemical analyses of copper alloys (Cu, Sn, Zn, Pb) and earthenware (Ca, Si, Al, Fe) using homemade sets of samples and commercial standards. LIPS measured elemental depth profiles have been accurately characterized in terms of ablation rate and depth resolution. The in depth LIPS-based approach to the characterisation and authentication of bronze [3] and glass artefacts was tested and validated through a systematic study involving prepared samples and authentic manufacuts, revealing a significant potential of such an elemental analysis, not only for achieving the chemical composition of the alloys but also for discriminating between natural and artificial (or accelerated) corrosion. Moreover the depth profile LIPS measurements on ancient earthenware [4] exhibited intense, broad, and structured surface Ca enrichments, as a result of underground transport phenomena followed by secondary minerals formation depending on the burial conditions and porosity of the ceramic body. The investigation is putting in evidence the significant discrimination potential associated with the comparative analysis of elemental depth profiles measured using LIPS. Here, this feature and its application perspective in authentication studies are critically discussed.

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References


8790-18, Session 5

A swept source Optical Coherence Tomography system at 2000nm for imaging of painted objects

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Optical Coherence Tomography (OCT) is a fast scanning Michelson interferometer capable of 3D imaging of subsurface microstructure. In recent years, OCT has been successfully applied to the non-invasive imaging of paintings and other cultural artefacts. Apart from the non-invasive examination of the stratigraphy of paint and varnish layers, OCT has also been shown to be the most sensitive technique for revealing preparatory underdrawings beneath paint layers owing to its high dynamic range and depth selection capabilities. OCT has the potential to become a routine non-invasive tool in museums allowing cross-section imaging anywhere on an intact object where there are no other methods of obtaining subsurface information. While contemporary OCTs have shown potential in this field, they are optimised for biomedical applications. One major limitation of OCT imaging is the limited probing depth through highly scattering paint. OCT systems for biomedical applications are generally restricted to wavelengths between 800nm and 1300nm for the best compromise between water absorption and tissue scattering. However, the requirements of art conservation are very different since most paints are highly scattering and the transparency is not limited by water absorption as in the case of biological tissue. A recent survey of the transparency of historical artists' pigments over the spectral range of 400nm – 2400nm has shown that the optimal spectral window for OCT imaging of paint layers is in a spectral window around 2.2 m [1]. Excluding the lake pigments (which are all highly transparent at wavelengths >600nm) in this range of 45 pigments studied, over 30% of pigments were >5 times more transparent at 2.2 m than at 800nm, and ~25% of the paint samples were >2 times more transparent at 2.2 m than at 1.5 m. Off-the-shelf OCT sources are commonly found around 800nm, 1000nm, 1300nm and few OCT systems have been built beyond 1300nm. Therefore, an OCT around 2000nm will give the largest probing depth and push OCT imaging towards matching the information content given by the invasive method currently employed in museums of microscopic examination of sample cross-sections.

OCT imaging at such a long wavelength presents a number of challenges. The greatest challenge is the source. Since OCT depth resolution is determined by the source spectrum (specifically it is proportional to wavelength squared and inversely proportional to the bandwidth), to achieve the same depth resolution a source at 2 m would need to have a bandwidth ~6 times broader than one at 800nm. Off-the-shelf optical components are less readily available at this wavelength. In addition, detectors at this wavelength are very expensive, therefore spectral domain OCT would be too costly. Time domain OCT is less expensive but also less efficient compared with Fourier domain OCT. Swept source OCT is by far the best choice in this wavelength region both in terms of sensitivity and cost. A wavelength swept Tm-doped silica fibre laser source with 330nm swept range between 1750 and 2080nm is built specifically for this purpose. This paper will discuss a prototype swept source OCT system using this source. Examples of paint cross-section images obtained with the 2 m OCT compared with those from a 930nm Thorlabs spectral domain OCT will be presented and future improvements to the system will also be discussed.


8790-19, Session 5

Application of optical coherence microscopy for studying decorative art objects

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It is known that decorative art objects of small forms are significant part of museum collections of different kinds, and such objects are numerous among of exhibits. Selecting of storage conditions of art objects, fulfilling their conservation and attribution are based on investigating a manufacturing technology, a layer study of individual elements of objects, and permanent attention and control of surface condition. There are used different known methods of diagnosis, but prospects in this diverse activities and success depend on introduction of new nondestructive methods. Today new scientific technologies in museum business include the methods of optical coherence tomography (OCT). The use of optical coherence microscopy (OCM), as a kind of high-resolution OCT in combination with spectral methods can extend application of OCM to study of cultural heritage. Features of decorative art consist in variety of materials and pigments, often with only the author's execution, which requires a painstaking study of individual sections of art object at the microscopic level.

Moreover the variety of technological methods in manufacturing of decorative objects are creating conditions with different diagnostic experimental parameters in specific investigation. Undoubtedly the advantage of OCM method is the ability to visualize a region of interest, using both tomograms and reconstructed 3D images. This allows one to carry out a detailed analysis of a micro structure of materials and study the border areas, and to develop methods for identification of objects and their manufacturing technology.

In our studies, we combine two methods of OCM. At the initial stage to identify regions of interest we used the device with a tunable wavelength source of radiation in the near infrared. Surface structure of art objects was studied at a wavelength of 1305 nm using the capabilities of Michelson Diagnostics EX1301 OCM (United Kingdom), which implements the swept-source Fourier-Domain OCM method.
The device design uses the patented multi-beam OCT optics and light source HSL-2000-11-MDL. The laser wavelength sweep range is 150 nm and the peak power is more then 15 mW. The axial optical resolution (in tissue) is about 10 µm and lateral resolution is approximately 7 µm. After scan, the packet of B-scans is obtained that gives possible to restore three-dimensional images of studied areas. 3D-image analysis and segmentation procedures provide the opportunity to investigating in detail particularly painting layers.

For more detailed study a high-resolving time-domain OCM was used. The automatic Linnik micro interferometer performs investigation of object microstructure using the method of wide field optical coherence microscopy. It provides the highest resolution up to 0.9 µm in three dimensions. In this case, it is possible to carry out very detailed studies of the material microstructure, for example, the spatial arrangement of individual fibers and the micropores of the materials.

The experimental study of porcelain, ceramic, natural and artificial origin stone, wood was conducted. The OCT modifications were also used for studying thick multi-layer paint structure and varnish layers and for evaluating properties of natural and imitation skin, canvas and tissues. We shall present these results.

8790-20, Session 6

Multiphoton microscopy, an efficient tool for in situ study of cultural heritage artifacts (Invited Paper)

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Multiphoton microscopy, also called non-linear optical microscopy, is a widely used imaging technique for biomedical studies. This technique performs three-dimensional (3D) imaging with micrometer-scale resolution based on optical sectioning. These properties are also very attractive for the study of cultural heritage artifacts. Many artifacts are coated with transparent (varnishes) or semi-transparent (glazes, paint layers) coatings, which stratigraphy and composition are very difficult to characterize.

Since few years, Optical Coherence Tomography (OCT) is a well-established technique as contactless 3D imaging tool [1,2]. Nevertheless, the discrimination of the various components is strongly limited with OCT. A key advantage of multiphoton microscopy is its multimodal capability with different modes of contrasts that are directly linked to the chemical nature of the materials under study.

Two-Photon Excited Fluorescence (2PEF), based on the non-linear absorption of two photons and subsequent fluorescence emission, is emitted by a wide range of materials in historical artifacts, especially among pigments and binders. We show that by selecting well-suited spectral bands, we can discriminate the 2PEF emission of the cochineal lake pigments from the one of the sandarac. Moreover, 3D mapping of the pigments and binder in the various layers is obtained thanks to the optical sectioning of multiphoton microscopy.

Second Harmonic Generation (SHG) signals are emitted by non-centrosymmetric structures. We show that plaster particles exhibit strong SHG signals when they are composed of bassanite crystals. Indeed, among the three types of plaster particles (anhydrite, bassanite and gypsum), only bassanite is a non-centrosymmetric crystal. Multiphoton microscopy can then be used for the detection of bassanite as confirmed by X-ray diffraction analysis performed on the same sample. SHG signal is also detected from crystalline cellulose within the wood cell walls.

Single layers and stratified layers composed of the previous fillers are studied by multimodal multiphoton microscopy and the different components are specifically detected and located within the stratigraphy. We are able to discriminate gelatin-based film from sandarac film and to perform 3D imaging of cochineal lake pigments. In the case of two stratified layers composed of cochineal lake pigments and plastic, the different fillers are clearly distinguished (2PEF versus SHG). This technique also allows a precise measurement of the thickness of each layer. Moreover, we show that 2PEF signals from lignin and SHG signals from crystalline cellulose are obtained from wood cell walls. These signals are also detected through 60 µm thick varnish layers, opening the way to wood characterization through coatings with a thickness of several tens of micrometers [3]. This is especially the case for the investigation of the varnish and the wood below in the case of music instrument.

Finally, we demonstrate that multiphoton microscopy can be used for in situ investigation of a historical violin without any observed damage for the instrument. Multiphoton images are compared to conventional optical microscopy and fluorescence imaging, leading to the same area for a better understanding of the different features [3].

To conclude, this study demonstrates that multimodal multiphoton microscopy is a powerful technique for 3D in situ investigation of historical artifacts and woods. The excitation wavelength being in the near-infrared (in our case 860 nm), it allows both imaging of quite deep structures (ca. 90 µm) and reduced possible photo-irradiation damages of the sample compared to conventional (one-photon) fluorescence imaging that would use wavelength in the UV-blue region. In practice, no damage was observed in our experimental conditions (laser power below 20 mW at the focal point) in any of the studied model samples and violin.

This study paves the way for numerous promising applications to the fields of ancient materials and conservation science, as well as, more generally, to the fields of coating materials and wood science.


8790-21, Session 6

Ultra-high resolution Fourier domain optical coherence tomography for resolving thin layers in painted works of art

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Optical Coherence Tomography (OCT) is an imaging technique based on the Michelson interferometer. It is non-invasive, non-contact and capable of imaging subsurface structures in 3D, making the technique a very useful diagnostic tool for visualization of internal microstructure. Improvement in OCT resolution can significantly increase our knowledge about the structure and composition of the material. Scientific examination of works of art is essential for conservation, preservation and understanding of material change. In heritage and conservation, OCT technique has found applications in the examination of paintings, jade, ceramics, ancient glass, enamel, parchment, fabric and other historical objects. It has also been used for dynamic monitoring of the wetting and drying of different varnishes, real time monitoring of varnish removal using solvents and laser ablation of varnish layers as well as tracking of canvas deformation due to environmental changes. Besides the visualization of the stratigraphy of paint and varnish layers, application of OCT to paintings has shown to be the most sensitive technique for revealing preparatory drawings beneath paint layers owing to its high dynamic range and depth selection capabilities.

While current OCTs have shown potential in this field, the best resolution commercial OCT at any wavelength is rarely better than 5µm in air. Currently depth resolution of OCTs used in these applications cannot compete with microscopic examination of sampled paint cross-sections. Conventional microscopic examination of paint cross-sections has resolution approaching 1µm. Since the depth resolution of OCT is proportional to the source bandwidth, ultra wide bandwidth light sources allow greater depth resolution to be achieved. It is known that some varnish and paint layers can be as thin as a few microns. By using a supercontinuum source (NKT SuperK Versa), we have developed a spectral domain OCT at 815nm for high depth resolution imaging of varnish and paint layers. The theoretical depth resolution of 2.2µm in air (or ~1.5µm in varnish) is achieved and it is shown to be able to resolve thin varnish layers.
8790-22, Session 6

OCT structural examination of ‘Madonna dei Fusi’ by Leonardo da Vinci

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‘Madonna dei Fusi’ by Leonardo da Vinci (circle?) is a spectacular example of Italian Renaissance painting. The exact history of the painting could be traced down since its purchase by Henry Petty-Fitzmaurice, 3rd Marquess of Lansdowne in 1809. Since then it was twice restored, but also previous attempts cannot be excluded. The aim of this study is to give an account of the knowledge of the restoration procedures from the past. The evidence of two retouching campaigns will be presented on cross-section images obtained non-invasively with Optical Coherence Tomography (OCT). Specifically, the locations of overpaintings with respect to the original paint layer and secondary varnishes will be given. Additionally, the evidence of a former transfer to canvas by detecting of the presence of its structure incised into paint layer will be shown.

8790-23, Session 6

Study of surface optical properties for characterizing the cleaning process of paintings

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Restoration refers to the removal of surface dirt and discoloured varnish layers, the treatment of the support (canvas/wood/paper), the replacement of missing portions imitating the original by the sympathetic use of similar pigments, or building up fragments of sculpted or moulded areas of an artwork. A painting can be built up in transparent or semi-transparent glazes, which can be partially or totally opaque due to adverse conditions such as lighting, heating, fluctuations in temperature, exposure to direct sunlight which can cumulatively create the need for restoration. Over many years the transparency of the varnish will become clouded and discoloured often resulting in a picture being viewed as if through an amber or even brown filter. These effects on the varnish layers aren’t the only results of the ageing process. Cracks which appear in the most extraordinary formations, apparently on the surface, are also caused by a number of complex interactions between the support (canvas, composition board, paper, wood) and the pigments in layers. While the binding agent in the pigment (e.g. linseed oil) may have been used consistently throughout, the different minerals in the pigment itself will expand and contract under different tensions and over longer or shorter periods. These movements will create fissures, not only in the pigment and binder layers, but in the primer and varnish layers too.

“Cleaning” is a process of carefully identifying the cause of any deterioration or discolouration and then removing or treating these layers. The skill of the restorer is not only to understand the techniques and media used by the artist whereas having a breadth of experience in the use of solvents and chemicals of the trade, but also to nurture an appreciation of and ability to recognise what beauty lies beneath the veils of many years of neglect or adverse conditions.

Surface cleaning is then one of the most important and sometimes controversial stages of the conservation process: it is an irreversible process that generally results in substantial physical changes of the object surface, raising thus a series of questions regarding aesthetics, the potential loss of historical information, and the ability to control the cleaning process adequately. Decisions have to be made regarding partial or complete removal of varnish: technical considerations include selection of a method that allows a great deal of control in the cleaning process, so that undesired layers can be removed without damaging the underlying ones by means of traditional cleaning methods, including mechanical or chemical removal.

Up to know Optical Coherence Tomography (OCT) has been successfully applied for measuring the varnish thickness, but no studies concerning the optical effects of cleaning process are found in literature. In this work we present a study of the optical properties of painting surfaces for the characterization of the cleaning process. Analyses were carried out by means of laser micro-profillometry and confocal microscopy. Laser micro-profilometry is a scanning technique that provides topographic maps of the surface. It allows a probing area of 280x280 mm2 with a sampling distance of 20 microns and a depth resolution of about 1 micron. The distance meter is equipped with a diode laser in the VIS@655 nm resulting in an output which images the roughness characteristics of the surface. Confocal microscopy is a well-established technique widely used in many fields, from biomedical to engineering applications, because of both its ability to image subsurface features selectively in depth and the improved lateral and axial resolution over conventional microscopes. A laser-scanning confocal microscope was designed and built, having a depth and lateral resolution of 10 micron and 2.5 micron, respectively, over a 25 mm profile. The microscope operates in the NIR@1550 nm allowing for a good imaging of paint sections. Measurements were carried out on a few paintings which are under repair at the Opificio delle Pietre Dure in Florence. Selected areas were surveyed with the two above mentioned techniques and results were correlated.

8790-24, Session 6

Artwork analysis by optical surface profilometry

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Cultural heritage comprise artworks and buildings made by several classes of materials (wood, paper, pigments, paints, recycled materials, fabrics, natural and artificial stone, plastic, etc.).

The observer looking at an artwork, at first perceives its surface, that is that portion of the object that allows to recognize and identify the artwork through the subject represented, the materials applied, any signatures, stylistic figures of the artist who has produced it, the state of preservation or the traces of degradation, any restoration. These and other “signs” provide a “finger print” of the object that uniquely identify it. From here we can understand how the analysis of the surface is of primary importance for the recognition of the object, for its study and for monitoring of the eventual decay.

Up to now this study is completed through the photographic analysis, which however is not able to return the “materality” of the work being two-dimensional. An alternative approach is based on morphological analysis that returns 3D images of the surface, without preserving any colorimetric information of the surface, because the 3D shape is usually given as a false colour image. More advanced data processing techniques try to reproduce the real object by combining the two techniques, that is “adapting” the true colour image to the 3D image.

In industrial surface analysis, that is for shape or roughness measurements, a high-accuracy optical profilometer is often used. One of the best optical profilometer available is based on the “focus variation” principle: the surface topography is reconstructed by successive acquisition of images taken while the microscope objective is moving along the line-of-sight. This technique is very attractive in artwork analysis since it is inherently non-invasive and passive, requiring only a white light source for artwork illumination, not requiring any laser source as in other optical profilometry approaches. The 3D image obtained inherently contains both the morphological and colour information. The use of different objectives (2.5x, 5x, 10x, 20x) allows the selection of the field of view and therefore the resolution of the scan. Micrometric lateral resolution and sub-micrometric depth resolution are achieved. 3D images taken with a commercial Infinito Focus optical profilometer are analyzed to extract parameters suitable to identify the observed portion of the artwork. The analysis is performed on selected areas of a maximum size of 5x5 mm2, morphologically significant for the study and monitoring of the artwork, for a well-to-trace degradation.

A similar approach can be used for the identification of the original piece to counteract forgery of the artwork. From comparison of 3D images taken before and after an exhibition, or when a stolen piece is found, we can identify the original piece. The developed instrument is portable, allowing in situ measurements, without moving
the artwork from the exhibition hall; this is very important in cultural heritage preservation, since any displacement from the original site could damage the piece or impair it. Several examples of 3D image comparison of the same object, and of apparently similar objects, are shown and discussed.

8790-25, Session 7

Mid-infrared hyperspectral imaging of painting materials (Invited Paper)

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A novel hyperspectral imaging system (HI90, Bruker Optics), working in the mid-infrared range and recently developed for the remote identification and mapping of hazardous compounds, has been here applied for investigating the painting surfaces.

The system, composed of a Michelson interferometer with a focal plane array (FPA) detector and an external infrared radiation source, allows for performing the reflection measurements of paintings in the highly informative range of the IR fingerprint region. The FPA cooled by a Stirling cooler is made of HgCdTe (MCT) with a maximum lateral resolution of 256 x 256 pixels. The achievable spectral range is 1300-900 cm\(^{-1}\) with a spectral resolution of 4 cm\(^{-1}\). The measurements are carried out at a distance of about 1 m. The field of view of each pixel is 0.69 mm, investigating a total area of 8.8 x 8.8 cm\(^2\). The brightness temperature spectra are calculated by an internal calibrating system which automatically performs the radiometric calibration.

The measurements are performed illuminating the sample with an active infrared radiation source with a brightness temperature practically constant in the spectral range regarded. The source is controlled via USB allowing the user to set the intensity of the emitted radiation. To minimize the exposure time of the analysed painting, the source is equipped with an iris shutter which opens only during the data acquisition.

Two paintings by Alberto Burri, namely Bianco 52 (1952) and Sestante 10 (1982), have been investigated through the HI90 system imaging the distribution of both inorganic and organic materials constituting the artworks.

Mid-Infrared hyperspectral imaging measurements carried out on the monochrome white painting Bianco 52 permitted to identify and localized the different white inorganic fillers (CaCO\(_3\), BaSO\(_4\), CaSO\(_4\times\)H\(_2\)O) responsible of the different morphological and optical effects characterizing the painting. The study revealed the distribution of PVA on the smoother and shine areas of the white painting. The polychrome painting Sestante 10 was investigated focusing firstly the attention on the binder identification, the measurements performed by the HI90 system permitted to identify and image both the acrylic and vinyl binders employed with the different pigments. Secondly, the inorganic material distribution was investigated revealing also the presence of different extenders (kaolin, BaSO\(_4\), CaSO\(_4\)) mixed with the various silica-based pigments present in the painting.

The brightness temperature spectra collected by the HI90 system have been also compared with reflection point infrared spectra acquired by a the conventional portable FTIR spectrophotometer R-Alpha (Bruker Optics) highlighting the good spectral quality of the new imaging system.

This comparison permitted also to evaluate the spectral response and assignments from the reduced spectra range available by the HI90 imaging (1300-900 cm\(^{-1}\)), validating the reliability of the obtained chemical images.

This study clearly highlights the high potential of the new hyperspectral imaging system and opens up new perspectives in the current scientific interest devoted to the application of mapping and imaging methods for the study of painting surfaces.

8790-26, Session 7

High spatial acuity multi- and hyperspectral infrared reflectography from 960 to 2500 nm: applications to paintings and drawings

John K. Delaney, Paola Ricciardi, Marie Didier, National Gallery of Art (United States); Damon M. Conover, The George Washington Univ. (United States); Kim Schenck, Mervin Richard, National Gallery of Art (United States)

Traditional infrared reflectography (IRR) was developed in the 1970’s as a powerful tool for painting conservators and art historians. The technique employs near infrared cameras to visualize preparatory sketches and compositional changes in single broad spectral band. Research by several groups has resulted in improved visualization, achieved by using low noise detectors, interference filters to isolate the spectral region of maximum content, and computational tools to address the challenge of mosaic-killing the resulting images. While significant progress has been made, there remains an interest in extending IRR to works of art on paper, and on paintings to determine the type of drawing materials used in preparatory sketches (e.g. dry versus liquid), and for separating out features in complex over-painted compositions.

Here we present results obtained with two novel portable camera systems, wherein the acquired images were enhanced and analyzed using various image processing applications. The first system is a multispectral low light framing camera which operates from 1000 to 2500 nm and has spatial sampling of 290 or 580 dpi at the artwork depending on which InSb focal plane array is used (840 by 512 or 1280 by 1024 pixels). The camera system utilizes a custom F/D 2.3, 55 mm infrared lens optimized for the 1000 to 2600 nm spectral range. The artwork is placed on a manual 2-D easel, illuminated with light at 50 lux, and moved in the step-stare collection mode. Typically 300 image frames per hour can be acquired using this method. The multispectral images (currently collected in 3 spectral bands) are automatically registered to a high-resolution color image using a novel algorithm on a multi-core computer in a few hours. Using this system, high acuity, multispectral infrared images have been acquired of several works, including Raphael’s cartoon “The Madonna and Child with Saint John the Baptist,” which is thought to have been used for Raphael’s painting “La belle jardinière” in the collection of the Louvre Museum, and Jan van Eyck’s “The Annunciation”.

The second camera systems consists of whiskbroom hyperspectral scanners, also having two different detectors: a high gain InGaAs array operating from 960 to 1680 nm with 2.4 nm sampling and an InSb array operating from 1000 to 2500 nm with 2.4 nm sampling. The cameras collect 640 by 640 and 1024 by 1024 pixel image frames spatially and require less than 2 minutes to acquire each image cube. Typically, 20 to 40 image cubes are collected, mosaic-ed together, and then registered to a reference color image. Using these systems, several paintings have been examined including Picasso’s “Old Woman Ironing” at the Guggenheim, NYC, as well as Leonardo da Vinci’s “Ginevra de’ Benci”.

Image processing techniques utilizing principal component images, difference images, and a new set of paint modeling tools offer ways to visualize the spectrally rich data sets to optimize the appearance of features important to conservators. The ability to obtain spectra in the infrared region not only allows for distinguishing among artist materials that only appear as ‘varying gray levels’ in broadband IRR images, but also provides a basis for determining requirements of imaging systems. This has closed the loop in system design, by establishing the spectral radiance differences associated with various combinations of grounds, drawing materials, and paints.

8790-27, Session 7

Thermal quasi reflectography (TQR): current research and potential applications

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Thermal quasi reflectography (TQR), e.g. imaging in the thermal band 3-5 μm (mid-IR) is discussed as a novel tool for the noninvasive analysis of pictorial surface layers in artworks, and its potential is demonstrated in some applications to genuine artworks.

Optical imaging in the infrared range is widely applied to investigation of artworks, allowing the noninvasive and wide field analysis of many surface and sub-surface painting features. Wide-field major techniques concern the use of Near-IR region 0.75-2.5 μm (reflectography), and the use of Far-IR region 7-14 μm (thermography). Near-IR reflectography is effective for revealing features underneath the pictorial layer, e.g. underdrawings and retouches, thanks to the optical transparency of the pictorial matter in this band. Differences in the diffusion behaviour allow a differentiated detection of painting materials. Thermography enables the inspection of structural defects in paintings, e.g. support anomalies and layer detaches, by exploiting the different emissive behaviour of materials in the Far-IR.

This presentation discusses the current research and some application potentials of a novel tool for artwork imaging, which has been recently applied by the authors. The basic idea is to extract information from the Mid-IR energy reflected by the object, which is strongly related to the surface material properties. Effectively, it is a Thermal Quasi-Reflectography, in which the emitted radiation is minimized in order to properly record the reflected quote. Following the Planck theory of black body, and taking into account that emitted radiation depends on object temperature and object emissivity, it is shown that by properly using the Mid-IR imaging (suitable source and detector) at room temperature, i.e. safe for artworks, the acquired radiation is largely dominated by reflected energy.

Set up to perform Mid-IR reflectography is based on a 3-5 μm camera device (PSti Schottky-Barrier IRCCD) and a set of IR lamps controlled in power to obtain the measurement in reflectance mode, i.e. by avoiding the heating of the surface.

The technique is applied to target models and to genuine artworks in situ. It provides very interesting results, which demonstrate its effectiveness in the characterization of pictorial superfluous layers, such as a selective mapping of some painting materials, and a clear detection of organic painting integrations. It is demonstrated to be very effective in the analysis of rural paintings (tempera and fresco), whereas Near-IR reflectography is less effective. Mid-IR information is related to the superficial thin color layer (through the diffuse reflectivity), and the variegate reflectance response allows the discrimination of materials such as organic painting integration and high reflective pigments.

For such kind of complex artworks the use of Mid-IR region reveals to be crucial, making thermal reflectography a promising tool for the investigation of artworks materials and artistic technique.

The results underscore further development in this field. The novel experimental technique is reviewed here giving focus to the current research and the potential applications.

Short ref.

8790-28, Session 7
Recent developments in microreflectance spectroscopy for photodegradation studies
Tomasz Lojewski, Jacob L. Thomas, Joanna Lojewska, Jagiellonian Univ. in Krakow (Poland)

Microfading testing (MFT) was developed by Paul Whitmore in the mid 1990s as a means to directly evaluate the lightfastness of objects by in situ micro-destructive photodegradation followed by real-time fibre optic reflectance spectroscopy (FORS) and colorimetry. His design and those developed by T. Tame in Japan 0° - 45° confocal geometry which is a standard for colorimetry. These designs suffer from several problems, but particularly probe alignment and displacement. The Paper Degradation Laboratory (PDL) has developed several improved MFT and FORS instruments based on a retro-reflective (RR) configuration. In RR-FORS, a beam splitter and a pair of achromatic doublet lenses are used for both illumination and observation. The angle of incidence is adjustable with a rotation stage and a focusing is via a micrometer translation stage along the optical axis. This design is simpler and more robust than the confocal design and does not suffer from alignment problems.

Additionally, the fore-lens can be easily exchanged while the aft-lens, which couples to the optical fibres, remains fixed. Thereby the illuminated area on the object can be varied with the conjugate ratio of the lens pair without altering fibre coupling efficiency.

Several RR-FORS instruments have been built by the PDL for both heritage and operando catalyst studies. Most recently, the RR-MFT has been adapted to a compact and portable open-beam construction with an integrated light-stabilised Xe source and concave grating spectrometer, a motorised stage with auto-focusing and custom report generation software. This instrument is approaching market readiness. Three operation modes are envisaged: a ‘plug and play’ mode with a ‘traffic light output’ calibrated back to Blue Wool standards for collection surveys, a colorimetric details mode and a spectrometric details mode for different applications.

A RR-FORS instrument has been used in the PDL for operando spectroscopy studies of the photodegradation of historic samples of arylmethane dyes on paper. The samples used in the study have been excised from trade catalogues and sample books from the early to mid 20th century. These materials were distributed by dye manufacturers to paper manufacturers, and because these books are now established provenance, the accompanying information regarding colourant identification, paper type and dye loading can be used with confidence.

A sample matrix including 15 arylmethane dyes on 2 paper substrates (bleached and unbleached sulphite pulp) was evaluated for colour change in 2 atmospheres (nitrogen and air) at 3 relative humidity levels (25% RH, 50% RH and 75% RH). Both acidic and basic dyes are represented, and the sample set was selected to have peak absorption bands distributed across the visible spectrum.

Experiments were conducted using a light-stabilised 150 W Xe source and an Avantes AvaSpec ULS 3648 spectrometer with a RR-FORS instrument. All measurements were conducted at 10° off normal to exclude specular reflection. For photodegradation studies the samples were placed in a Linkam catalyst reactor stage fitted with a fused silica window. The Linkam reactor stage allows for control of temperature, atmosphere composition and humidity levels during spectroscopic measurements.

Using RR-MFT and the Linkam catalyst reactor stage we were able to evaluate the effect of each environmental variable on the rate of colour change of each dye on each substrate in real time, and thereby we were able to translate operando spectroscopy methods from catalyst science to cultural heritage studies.

The designs of the RR-FORS and RR-MFT instruments developed by the PDL as well as data from the operando photodegradation studies conducted with a RR-FORS instrument and a Linkam catalyst reactor cell will be presented.

8790-29, Session 7
μ-MFT : a simplified microfading instrument intended for widespread application
Andrew J. Lerwill, Christel Pesme, Vincent Beltran, James Druzik, The Getty Conservation Institute (United States)

In response to continuing changes in cultural heritage conservation’s relationship with microfading spectroscopy; a new portable microfading spectrometer (μ-MFT from herein) has been developed and is presently being applied to test museum object light sensitivity at the Getty Center. A new instrument was deemed necessary for maximum simplicity of engineering, reduced cost and minimal necessary user training (requirements echoed in heritage conservation institutions worldwide). The overriding aim being to make microfading spectroscopy applied more broadly by conservators at a greater number of institutions.

A micro-fading spectrometer functions as a metrological instrument which measures real time color change due to photochemical damage arising from light exposure from the instrument’s illumination.
This happens through direct illumination of the sample material on a sub-millimeter scale where color measurements are carried out simultaneously. Within the small illuminated area, fading is continued only to a certain level that is not discernible by the viewer and so valuable cultural heritage is able to be directly tested without harm (Whitmore et al. 1999). The obtained estimate of the light sensitivity of the tested collection item is further used in order to create appropriate lighting policy.

The µ-MFT, has two possible light sources; a high-powered continuous-wave xenon light source with (UV filter) or an alternative Cold White Fiber Coupled LED (the later employed to simulate the increasing adoption of solid state lighting in museums). Both light source options provide the same photometric illumination at the testing surface. These are connected directly to a bifurcated optical fiber with transmission in the visible and near infrared. The conjunct end of the bifurcated fiber is connected to a probe designed for this task. The probe contains a ball lens at a set distance from the fiber face which creates a focus at the opposite surface of the lens. When a measurement is being made the ball lens surface is placed in contact with the sample under test. In other contact areas the sample is protected by Mylar®. Scattered light from the fading area is coupled back into a separate optical fiber at an angle of approximately 8 degrees to the normal. The spectrometer receives this signal and makes an automated calculation of color difference of the fading spot.

Analysis of the µ-MFT including; rate of fading, the temperature increase associated with fading, accuracy and precision of color measurement and a comparison of relative degree of fading the two light source create are discussed with corresponding data. A focus is placed on the impact errors have on measurements and the resulting impact on conclusions from measurement uncertainty.

The application of the µ-MFT at the Getty Center is also discussed and conclusions about light sensitivity are made and compared to the most common micro-fading spectrometer design for the same object.

8790-30, Session 8
Multianalytical investigation semi-conductor pigments in 19th century paintings: time-resolved fluorescence spectroscopy and imaging (Invited Paper)

Austin Nevin, Consiglio Nazionale delle Ricerche (Italy); Anna Cesaratto, Cosimo D’Andrea, Gianluca Valentini, Daniela Comelli, Politecnico di Milano (Italy)

We present the non-invasive study of historical and modern Zn- and Cd-based pigments with time-resolved fluorescence spectroscopy, fluorescence multispectral imaging and fluorescence lifetime imaging (FLIM). Zinc Oxide and Zinc Sulphide are semiconductors which have been used as white pigments in paintings, and the luminescence of these pigments from trapped states is strongly dependent on the presence of impurities and crystal defects. Cadmium sulphoselenide pigments vary in hue from yellow to deep red based on their presence of impurities and crystal defects. Cadmium sulphoselenide pigments have also employed Fluorescence Lifetime Imaging (FLIM) to the analysis of the painting by Vincent Van Gogh “Les Bretonnes et le pardon de Pont-Aven” (1888) is studied. It is found that this approach enables LIBS detection in water both in emission and in absorption. It appears that underwater LIBS may be especially useful in underwater archaeology.

8790-33, Session 8
Multispectral hypercolorimetry and automatic guided pigment identification: some masterpieces case studies

Matteo Miccoli, Marcello Melis, Donato Quarta, Profilocolore Srl (Italy)

A couple of years ago (SPIE Optical Metrology 2011) we proposed an extension to the standard colorimetry (CIE’31) that we called Hypercolorimetry. It was based on an even sampling of the 300-1000nm wavelength range, with the definition of 7 hypercolor matching functions optimally shaped to minimize the methamerism.

Since then we consolidated the approach through a large number of multispectral analysis and specialized the system to the non invasive diagnosis for paintings and frescos.

In this paper we describe the whole process, from the multispectral image acquisition to the final 7 bands computation and we show the results on paintings of masters like Pietro di Cristoforo Vannucci called Il Perugino, Francesco Mazzola called Il Parmigianino, Domenico Theotokopulos called El Greco, Guido Reni, and other Masters. Along with the Hypercolorimetry and its consolidation in the field of non invasive diagnosis, we developed also a standard spectral reflectance database. This database has the unique characteristic that includes, for every pigment and its variations, not only the straight spectral reflectance, but also the potential reflection of quasi-monochromatic excitation and corresponding emitted full spectrum. This defines all the kind of fluorescences eventually presented by a pigment, a binder, a substrate or a protective film. In other words, each element is enriched by a bidimensional matrix recording any
input-output wavelength relation showed by the element itself when stimulated by a sweeping monochromatic signal/light.

We describe and propose in this paper a systematic approach to the non invasive diagnosis that is able to change subjective analysis into repeatable measures, independent from the specific lighting conditions and from the specific acquisition system. We highlight also a number of raccomendations and minimum requirements needed to achieve optimal results, along with a sort of best practice.

Along the case studies we produce a number of "side-effect" results, in terms of reliability, precision and potential source of error.

The acquisition system we used is based on a lighting subsystem that is able to provide continuous light with a full wavelength range without spikes in the recorded spectrum. The system is modular and allowed us to tailor it to the specific piece of art under analysis. The continuous light source allowed fast focusing operation. To furthermore speed up the whole acquisition process we used a custom multispectral exposimeter. This allowed us to set-up all exposimetric parameters in a precise yet fast way even outside the visible spectrum.

We used a 36megapixel modified reflex camera and the large amount of data allowed us to perform clustering and classification of pixels, based on their spectral reflectance. It turned out that each masterpiece has a sort of its own signature in terms of number, type and quality of used pigments and binders.

The metric, standard and repeatable approach to the identification of pixels and elements in the painting opens a brand new line of research where comparison among authors can better explain reciprocal cultural contamination. Furthermore, the availability of an enhanced database, on one side, and of a standard measurement method, on the other, is able to better open international cooperation and to remotely investigate paintings based on their pigments.

All the original pigments and their binding have been provided by the Opificio delle Pietre Dure, while the mentioned masterpieces belongs to the Pinacoteca Nazionale of Bologna.

8790-34, Session 8

Automated full-3D digitization system for documentation of paintings

Maciej Karaszewski, Marcin Adamczyk, Robert Sitnik, Jakub Michonski, Wojciech Zaluski, Warsaw Univ. of Technology (Poland); Eryk Bunsch, Wilanow Palace Museum (Poland); Pawel Bolewicki, Warsaw Univ. of Technology (Poland)

In this paper, a fully automated 3D digitization system for documentation of paintings is presented. It consists of a specially designed frame system for secure fixing of painting with LED light sources ensuring shadow-less lighting for obtaining the texture, a custom designed structured light-based, high-resolution measurement head with no IR and UV emission. This device is automatically positioned in two axes (parallel to the surface of digitized painting) with additional manual positioning in third, perpendicular axis. Manual change of observation angle is also possible around two axes to re-measure even partially shadowed areas. The whole system is built in a way which provides full protection of digitized object (moving elements cannot reach its vicinity) and is driven by computer-controlled, highly precise servomechanisms. It can be used for automatic (without any user attention) and fast measurement of the paintings with some limitation to their properties: maximum size of the picture is 2000mm x 2000mm (with deviation of flatness smaller than 20mm) Measurement head is automatically calibrated by the system and its possible working volume starts from 50mm x 50mm x 20mm (10000 points per square mm) and ends at 1200mm x 80mm x 60mm (2500 points per square mm). The directional measurements obtained with this system are automatically initially aligned due to the measurement head's position coordinates known from servomechanisms. After the whole painting is digitized, the measurements are fine-aligned with color-based ICP algorithm to remove any influence of possible inaccuracy of positioning devices.

We present exemplary digitization results along with the discussion about the opportunities of analysis which appear for such high-resolution, 3D computer models of paintings.

The presented system is used for automatic digitization of the collection of paintings from Museum Palace at Wilanow, Warsaw.

8790-35, Session 8

Automated analysis of art object surfaces using time-averaged digital speckle pattern interferometry

Michal Lukomski, Leszek Krzemien, Jerzy Haber Institute of Catalysis and Surface Chemistry (Poland)

The detection, characterization and tracing of the development of early-stage damage of painted surfaces using non-invasive (non-sampling, non-contact) techniques is a very important task for conservation science, as works of art are usually both fragile and extremely valuable. In particular, preventive conservation in museums and historic sites needs scientific tools capable of detecting fracturing of decorated surfaces and delaminated areas at the micro-level well before damage becomes visible.

Digital speckle pattern interferometry (DSPI) has proven an especially attractive optical-based non-contact tool for the investigation of artworks made of diverse materials. The technique is very accurate, being capable of mapping out-of-plane displacements to a fraction of a micrometer. It has the capability to detect fractures, micro-cracks and surface flaws. The analysis of induced vibrations is particularly attractive as it allows for short-term characterization of components constituting a work of art. However, difficulties in the effective interpretation of speckle interferograms remain a considerable barrier in the application of the method to diagnosing surfaces on a wider scale in practice. The reason is that, on the one hand, interferograms registered for time-averaged vibrations of analysed surfaces can only be quantitatively interpreted semi-automatically, and therefore trained researchers are required to perform the analysis. On the other hand, methods based on phase modulation of laser light or employing pulsed lasers give results that are easy to interpret but require complex adjustments because of the need to synchronize laser-light modulation with the vibration of the investigated object.

This paper presents a measuring procedure and a fully automated method for the analysis of registered images that can be used in any application where submicrometer, harmonic vibrations of a diffusively scattering surface are analysed. The proposed method consists in the analysis of interferograms resulting from the recording of time averaged laser-light exposure on the investigated surface. A series of images are recorded while the object is vibrating with different, increasing amplitudes. Then the amplitude is unwrapped for each pixel of an image independently. Typically, vibrations are induced by some sort of a shaker or a sonic wave. Since small vibration amplitude is linearly proportional to the driving force, the operator of the equipment can precisely control the induced vibration amplitude. As long as the phase does not vary during the measurement, light intensity I for each pixel can be expressed using three constants A, B, and C as:

\[ I = A + BJ_0(a_0 C) \]

The value of surface vibration amplitude \(a_0\) in any point of the image can be determined by the numerical fitting of the J0 function to the recorded light intensity at this point on consecutive images recorded for an object vibrating with increasing amplitude. The calculations repeated for every point of the recorded images give the map of vibration amplitude directly. To make the fitting procedure possible, the measuring scheme based on a phase stepping method was elaborated. It allows to remove, from the above equation, the unknown constant A (the sum of intensity of illuminating and reference light in a given pixel of recorded image) and compensate a slow variation of the laser light phase observed during the measurement.

Furthermore, computationally expensive fitting of the J0 function was replaced by a method based on Hilbert transformation.

The elaborated method was tested, using a laboratory built, out-of-plane DSPI system, on specimens of painted wood in which various patterns of physical damage were artificially produced in the paint layer. A specimen of historic painted wood, with extensively cracked paint layer, was also tested. The condition of the surface was extremely heterogeneous. The results showed that the method is useful for the analysis of practically any surface using even the simplest DSPI system offering phase stepping of a reference light beam, and is highly resistant to error propagation owing to the fact that calculations are performed independently for each pixel of an image. It requires recording a series of images of the investigated object with increasing vibration amplitude and, therefore, is more time-consuming than methods based on time-averaged exposure with spatial phase
unwrapping. On the other hand, it offers a fully automated analysis of the interferometric fringe patterns without any need for reference phase modulation even for very complicated structures for which other semi-automated methods fail.

In situ diagnosis of physical state of surface of a panel painting attributed to Nicolaus Haberschrack (a late mediaeval painter active in Krakow) from the collection of the National Museum in Krakow is presented as an example of application of the developed methodology. It is established that the methodology, which offers automatic analysis of the interferometric fringe patterns, has considerable potential to facilitate and render more precise the condition surveys of works of art.

8790-36, Session 8

A simple optical method for evaluation of visual properties of surfaces

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Substantial part of the cultural object’s value is concentrated in its surface and this precious thin layer deserves the highest protection. At the same time the surface is most exposed to degradation due to environment and internal decay processes get first visibly manifested there. The best way how to protect the surface is regular monitoring of its state. Therefore the analysis and monitoring of the current state of the visual properties of object’s surface is a very important task in the field of cultural heritage conservation. Existing methods used to accomplish this goal are either based solely on qualitative assessment (photo documentation) or are unsuitable for examination of the surfaces of larger and more complex objects (spectrometer). To address this need we have developed a technique which combines inexpensive hardware (a portable flat-bed scanner) and a custom written application based on image analysis in order to enable the simplified evaluation of the state of a given surface. In this way it is possible to examine hundreds of square centimeters of surface at once, with the representative quality of the results outperforming those achieved through other methods. The scanner provides uniform and repeatable illumination of the surface and also captures the area with high resolution (only few tens of microns per pixel) and without distortion associated with usual camera lenses. In the acquired image of the surface to be analyzed, the degradation process is indicated as a shift in saturation or/brightness coordinates of data points which are characteristic of the entire selected area. These two variables are more suitable for the classification of change in appearance, as it is well known that point to point natural color variations, especially among many building stones exceed difference, shift in color due to degradation processes for given point in the course of time. Therefore the RGB (red, green, blue representation of color) image representation is impractical and conversion into different color space (HSB - hue, saturation, brightness) coordinates is a prerequisite. It is further demonstrated that results are stable and representative, which means that the information can safely be taken from any location on the object of study’s surface. Among requirements the proposed technique has to fulfill is the ability to study/analyze the same area without strong sensitivity to minute misplacement of measuring device which has to happen in the sequence of measurement in time. The requirement is easily satisfied in the case of this technique, because the large area of surface is characterized by one parameter in statistical processing and therefore providing substantial overlap of captured and processed areas, the contribution due to shift of capturing device is negligible and results are robust. It can be said that once the scanned area reaches size of so called representative area (which can be quite large for coarse textured surfaces) all measured and calculated parameters become location - invariant. The applicability of the method may cover wide range of degradation-related phenomena such as the soiling of the surface due to dust and particle accumulation, weathering phenomena, surface cleaning, assessing alteration due to conservation treatments. In conclusion, it is shown that the presented technique is capable of sensitive indication of alteration in surface visual properties for several types of degradation, can be used for monitoring of time dependent surface phenomena and to assess the action of conservation treatments.
Fast-robust-accurate: optical measurement systems for industrial applications (Invited Paper)

Robert Godding, AICON 3D Systems GmbH (Germany)

In product development and monitoring various measurements of 3D coordinates, motions or deformations are required; for example the alignment of simulations with true test results in the field of automotive development or the realization of measurements for material testing.

Optical measuring systems allow highly accurate, three-dimensional acquisition of such processes, whereby, depending on the task, different camera configurations are applied. For the determination of position and angle of an object a single image of one camera often covers everything (6DOF); for complete objects, however, multi-camera systems are essential for a total coverage.

Especially for the capture of fast movements high acquisition frequencies are partly required. Using conventional cameras mass of data are generated very quickly.

This paper describes different optical procedures and configurations for the measurement and evaluation of 3D coordinates, motions and deformations. Depending on the measuring task, the object dimensions range from less than one millimeter to many meters. Furthermore, a camera technology is presented, which reduces the data significantly by using real-time image processing. Thus, even long-time measurements with high resolution cameras at a high frequency are possible.

Besides acquisition technique and algorithmic, the sturdiness of a measurement system is crucial for the successful application of 3D metrology in an industrial environment. Preparations have to be made to guarantee a smooth operation even under adverse conditions.

The procedures and systems are illustrated by various applications. Among others the optical measurement of wheel motions during high speed testing is explained, the measurement of wind power rotor blade movements during static and dynamic tests or different measurements for material testing are described.

A webcam photogrammetric method for robot calibration

Ben Sargeant, Ali Hosseininaveh Ahmadnabadian, Tohid Erfani, Stuart Robson, Jan Boehm, Univ. College London (United Kingdom)

This paper describes a state of the art strategy for accurately calibrating a robot using close range photogrammetry. The robot (INDRo) has been designed for accurate placement of two web cameras relative to an object based on an imaging network design. This 5-DoF robot consists of a pan-tilt unit placed on two highly accurate linear motion stages mounted vertically and horizontally on an optical table in close proximity to a rotation stage. The object being observed is placed on the horizontally oriented rotation stage. In order to treat this entire arrangement as a single robot, for modelling purposes, the surface of the rotation stage is treated as a stationary coordinate reference frame and it is assumed that the rest of the robot is rotating around it. To ensure correct position of the cameras, the robot is calibrated using the following strategy.

First, a Denavit-Hartenberg (Paul, 1981) method is used to generate a general kinematic model of the robot. In order to define this model, a set of reference frames is defined relative to the rotation table, linear stages, pan tilt unit and each of the cameras. Transformation matrices are then produced to represent the relative position and orientation between these joint frames. The complete model is extracted by multiplying these matrices.

Second, photogrammetry is used to estimate the exterior orientation parameters of both cameras, which define the robot’s end effector frames, in a number of different robot orientations. In the photogrammetric process, a small camera calibration fixture is attached to the rotation table and a set of images are captured of this fixture from a variety of positions. To minimize the number of unknowns between the joint frames, two different photogrammetric projects are carried out to define a datum for the calibration fixture in a way which closely matches the robot’s first reference frame. In the first photogrammetric project, the Z axis of the datum is lined up with the rotational axis of the rotation table; and in the second project, the Y axis is aligned with the first linear stage’s direction of travel. Having defined the datum for the calibration fixture, the exterior orientation parameters of the robot cameras were estimated by using photogrammetric bundle adjustment.

Third, the relative distances and angles between each joint frame (kinematic parameters) are estimated using the general case weighted least squares method. For each position, a set of 12 equations is extracted from the robot model which represents the positions and orientations of the cameras in terms of the joint positions. This model includes 23 unknowns showing the kinematic parameters and 11 observations describing 6 exterior orientation parameters and 5 joint parameters. The unknowns are then estimated in an iterative procedure before substitution into the original matrices to produce a calibrated model.

The final model is tested using forward kinematics by comparing the model’s predicted camera postures for given joint positions to the values obtained through photogrammetry. In order to perform the inverse kinematics, a Genetic Algorithm (GA) (Goldberg, 1989) is exploited on the robot model. GA uses a set of random joint parameters as the input to the robot model and tries to iteratively minimise the feedback error, which is defined as the difference between the estimated values derived from the robot model and the desired camera posture. Joint parameter iteration is based on stochastic crossover and mutation parameters which are designed to improve the performance of GA. Results demonstrate that this approach can produce a reliable and accurate model of the robot.

References:

Investigation of a consumer-grade digital stereo camera

Fabio Menna, Erica Nocerino, Fabio Remondino, Fondazione Bruno Kessler (Italy); Mark R. Shortis, RMIT Univ. (Australia)

The paper presents a metric investigation of the Fuji FinePix Real 3D W1 stereo photo-camera. The stereo-camera uses a synchronized Twin Lens-CCD System to acquire simultaneously two images that are then displayed on the 3D display on the back of the camera. Two Fujinon 3x optical zoom lenses are arranged in an aluminum die-cast frame that is integrated in a very compact body which measures only (12 x 7 x 3) cm. The nominal baseline is 77 mm and the resolution of the each CCD is 10 megapixels.

Given the short baseline and the presence of two optics, the investigation aims to inspect the accuracy of the 3D data that can be produced and the stability of the camera.

From a photogrammetric point of view, the interest toward this camera consists in its capability to acquire synchronized image pairs that contains important 3D metric information for many close-range applications (human body parts measurement, rapid prototyping, surveying of archeological artifact, etc.). The camera has two motorized zoom lenses that are controlled by a stick/lever. The focal length can assume ten different values in approximately equally spaced steps. The characterization was carried out on three different focal lengths: (1) widest setting (i.e. the minimal focal length), (2)
central setting (widest + 4 steps), (3) tele setting (widest + 9 steps, i.e. the maximum focal length). Additionally, to investigate the possibility of in-camera distortion corrections, suspected to be only on the widest setting, a fourth calibration at widest + 1 step was performed. Calibration values at the different focal lengths are reported together with accuracy potential analyses. An in-house software was used to compute with a free network bundle adjustment solution the interior and additional parameters of left and right cameras. It’s worth to notice that for the widest focal length, the bundle adjustment did not converge if the affinity factor was not included. The object coordinates obtained from the bundle adjustment computation for each focal length were compared to the reference coordinates by means of a similarity transformation. Additionally, the article reports the investigate of the asymmetrical relative orientation between the left and right camera.

8791-5, Session 1

Monitoring structure movement with laser tracking technology
Luigi Barazzetti, Alberto Giussani, Fabio Ronconori, Mattia Previtali, Politecnico di Milano (Italy)

This paper presents the use of laser tracking technology for structure monitoring. In this field the use of such extremely precise instrument is something new and therefore still under investigation for civil structures, especially for applications carried out with unstable environmental conditions. On the other hand, as laser trackers are today very used in industrial applications aimed at collecting data at high speed with resolutions superior to 0.002 mm, they seem quite promising for those applications where numerous geodetic tools, often coupled with mechanical and electrical instruments, are usually used to analyze structure movements.

Displacement detection has a fundamental role in monitoring of structure stability and safety. Different factors (e.g. thermal variations, subsidence, water infiltration or change of the local water level, etc.) could have a direct impact on civil engineering constructions and, although in most cases movements are expected during the service ability of structures, when the movement magnitude significantly increases, this could lead to serious problems or it could be a pre-signal of forthcoming collapse.

In this work we focus on those time-dependent applications for which the deformation during data acquisition is “slow enough” such that the structure is considered fixed (note that this “time for data acquisition” depends on different factors such as materials, temperature, etc.). The goal is not a high frequency data acquisition system (e.g. fiber optic sensors, LVDTs, digital extensometers) often connected to a control unit able to track dynamic deformations, but the analysis of periodical movements (e.g. seasonal variations). These monitoring projects usually last for long periods of time (months or years).

The measurement of structure displacements (data recorded at specified intervals) can be surely considered as a special branch of Geomatics. Displacements are “absolute” when they are estimated with respect to points without a direct connection to the structure so that they are considered as stable, otherwise when points follow the structure movements “relative” data are measured. The terminology “data” includes distances, one, two or three dimensional point coordinates and angles. Direct measurements are those for which there is an initial measurement (epoch t0) assumed as reference for all the remaining ones (epochs t1, …, tn). Otherwise indirect measurements are acquired with instruments capable of measuring only the variation occurred. The final result of a measurement campaign is simply an estimate of a specific quantity and its uncertainty, i.e. a parameter that describe the quality of that measurement or in other words, its precision. Standard geodetic tools for structure monitoring are such as digital and optical levels (vertical variations), total stations and GNSS systems (3D movements), radar systems and digital cameras. Additional information is also recorded by temperature, pressure and humidity sensors, strain gauges, LVDTs, fiber optic sensors, etc.

In this work we will focus some of monitoring applications carried out with laser trackers, thus instruments mainly used in industrial applications (e.g. alignment, robot calibration, measurement on aircraft or boats, surface inspections, etc.). Common triangulation methods based on total station data combines horizontal and vertical angles measured from at least two stations. The direct measurement from only one station is often insufficient for high precision monitoring applications requiring sub-millimetric precision. The laser tracker overcomes this limitations since the distance is measured by means of an interferometer. High accuracy coordinates can be obtained by combining distances with horizontal and vertical angles (polar coordinates) and can be considered as instrument set in a single positions and able to provide precise target coordinates.

This work illustrates three real civil engineering applications where laser tracking technology was used to detect object movements. The first one is a loading test on a long beam where other data were also acquired with LVDTs in order to obtain a reference dataset for accuracy analysis. The second experiment is the stability inspection of a bridge. The last experiment is the first attempt where a laser tracker tried to substitute traditional high precision geometric leveling for monitoring an important historical building: the Cathedral of Milan. The achieved results, pro and contra, accuracy evaluations along with some practical issues are described.

8791-38, Session 1

Development of virtual pipe fitting system
Hiroshi Yokoyama, Kazuyuki Takeuchi, Hitachi Plant Technologies, Ltd. (Japan)

Many large-scale plants are currently being planned or constructed worldwide. Clients require contractors to minimize construction costs and work periods. Some of our competitors use laser scanners to conduct on-site measurements and perform detailed real-time 3D measurement of surrounding areas using Building Information Modeling (BIM) and 4D-CAD to manage work progress. However, since organizing data and linking it with work-related information takes much time and effort, it is difficult to significantly reduce man-hours and construction costs. Therefore, we are striving to streamline construction work and thus reduce construction costs by focusing on simplifying installation work, shortening installation periods, standardizing all on-site work, and improving quality and safety.

When pipes are installed at large-scale plant construction sites, pipes for adjustment called final spools are sometimes inserted between facilities that have been installed and piping that has been fastened. As such final spools, pipes of up to 1,000 mm in diameter and weighing approximately 350 kg/m are used in general, and they are delivered to sites in a state that allows for on-site processing. After delivery, on-site matching and adjustment of the final spools is then on the result of the on-site matching are repeated, and then the final spools are fitted into the spaces between facilities and piping. In the conventional fitting work, measurement of pipe dimensions, adjustment of the amount of processing, processing of final spools, and on-site matching are repeated. Using the expertise of skilled workers. In recent years, however, due to aging of such workers and shorter work periods, it is becoming increasingly difficult to perform fitting work, which is why fitting work needs to be rationalized. To streamline fitting work, repetitive processes related to on-site matching and adjustment of the amount of processing must be minimized.

We have researched and developed a virtual fitting system to streamline fitting work. With this system, first, pipe dimensions are measured using 3D measuring instruments (such as Total Station and Laser Tracker) and dedicated measurement instruments (jigs), and then detailed shapes and positional relations are reproduced on a CAD system. The adjustment of the amount of final spools is then adjusted on the CAD system. Furthermore, instructions on the amount of processing adjusted are given to the piping section, and lastly processing and pipe installation are performed.

Since pipes including final spools are available in various sizes (diameters) and wall thicknesses, multiple tools may need to be used, but this increases complexity. By making the part of the measuring instrument (jig) to be fastened to piping variable, we created a structure that satisfies the specifications of various pipes (pipe diameters and wall thicknesses).

In addition to straight pipes, curved pipes (elbows) are sometimes reproduced on the CAD system. Not only the entire figure of pipes but also detailed configurations of end faces must be reproduced in some cases. In this study, we developed a system of representing elbows and detailed configurations of end faces to make it easier to adjust the amount of processing.
Furthermore, by applying this virtual fitting system to simulated facilities (mockups), and conducting measurements, assessing the amount of processing, performing pipe processing, and installing piping, the effect on rationalization of work was estimated. With the mockup, not only ideal situations but also conditions close to those at actual sites where processing is difficult were created. The virtual fitting system was then applied to these simulated facilities.

This paper describes the details of this system and the results of its application.

8791-7, Session 2

Image selection in photogrammetric multi-view stereo methods for metric and complete 3D reconstruction

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Multi-View Stereo (MVS), coupled with Structure from Motion (SfM) methods, is a low cost technique for precise 3D reconstruction and has a wide range of applications. This technique can be a rival for laser scanners if the scale of the model is resolved. A fusion of off-the-shelf stereo imaging equipment with rigorous photogrammetric bundle adjustment, SfM and MVS methods, known as photogrammetric MVS, can provide an opportunity to generate correctly scaled 3D models without using any known object distances. Although a huge number of stereo images captured from the object contains redundant data that allows detailed and accurate 3D reconstruction, the elapsed time is increased when a vast amount of high resolution images are employed. Moreover, some parts of the object are often missing due to the lack of coverage of all areas. These problems demand a logical selection of the most suitable stereo camera views, known as vantage viewpoints, from the large image dataset.

This paper presents a method for clustering and choosing vantage viewpoints from a large image dataset intended for metric 3D reconstruction suited for industrial applications. The presented approach is capable of automatically identifying and processing the most suitable stereo images from a multi-image photogrammetric network captured by an imaging specialist. It focusses on the two key steps of image clustering and iterative image selection based on Photogrammetric Network Design (PND) and Next Best View Planning (NBVP) methods. In the first step, a four-zone cone is defined for each 3D point of a correctly scaled, sparse point cloud generated with SfM and photogrammetric bundle adjustment methods. Range-related constraints (imaging scale, resolution, camera Field of View (FOV), Depth of Field (DOF) and visibility-related constraints (point incidence angle, occluded feature area) are encoded in a PND and taken into account to cluster and evaluate the importance of each stereo viewpoint. In the second step, the vantage viewpoints in each cluster are selected based on the level of importance for each viewpoint in an iterative approach until completeness and uncertainty criteria are satisfied.

The method is developed within a software application called Imaging Network Designer (IND) and tested by the 3D recording of a gearbox and three metric objects. The metric objects used are two reference spheres and a cubic calibration object designed for calibrating laser scanners. Because the objects are texture-less, a pattern is projected onto the objects with two Pico projectors. Having captured a series of stereo images from the objects with two Nikon D700 DSLR cameras mounted rigidly to each other, the photogrammetric MVS method is applied to the images in a comparative way. Within this method, a comparison is made between IND and the baseline of the established CMVS (Clustering Views for Multi-view Stereo), which is a free package for selecting vantage images within a huge image collection. The final 3D models obtained from both IND and CMVS approaches are compared with datasets generated with an MMD Nikon Laser scanner. Results demonstrate that whilst both methods can provide high quality records of simple and complex objects, our new method, IND, can provide a better image selection for MVS than CMVS in terms of surface coordinate uncertainty and completeness of the final model for the 3D reconstruction.

8791-8, Session 2

Mosaicking thermal images of buildings

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Nowadays several thermal cameras capture images following a pinhole camera model and producing central perspectives degraded by image distortion. This paper shows how multiple images of flat-like objects or fully 3D bodies can be mapped and mosaicked with a mathematical formulation between images and objects. This work demonstrates that both geometric and radiometric components need proper mathematical models that allow the user to obtain a global product (textured 3D models, orthophotos, etc.) where the effective radiometric value in the measured temperature.

The methodology here described uses thermal and RGB images (i.e. two distinct cameras) in a global photogrammetric bundle adjustment. The procedure starts with the acquisition of a preliminary set of RGB images with a calibrated camera, where it is necessary to form a photogrammetric block with a strong network geometry. The RGB images are then oriented with standard photogrammetric methods from a set of image correspondences (tie points and ground control points to remove the rank deficiency, i.e. 7 parameters). Tie points should guarantee not only a good distribution in the images and provide reliable orientation results, but also the possibility to orient all thermal images in a new adjustment project. This means that tie points should be measured in correspondence of elements that are visible in thermal data. In addition, as thermal images have a limited field of view, the manual measurement of many tie points is highly recommended, although this can lead to a longer processing time.

The model of the building can be instead generated by laser scanning technique or photogrammetry. On the other hand, in this work we do not focus on this point as the technical literature reports many contributions about 3D modeling.

A thermal analysis is usually carried out with “RGB visual images” of the temperature distribution (applications are simple visual inspections, complex numerical evaluations, and so on). These “visual images” are obtained by transposing the temperature recorded by the IR sensor into a RGB color space. Mapping from the temperature space to the RGB space is performed by using some specific rules encoded in processing software. These RGB visual images are very flexible: they can be visualized by image viewer software, processed in photogrammetric packages, incorporated in VRML models, etc. However, when multiple images have to be fused in a single product, this kind of operation is not straightforward when the original temperature must be preserved or used in additional processing steps.

Generally standard RGB sensors can record 8-bit, 12-bit or 16-bit (new cameras even 24-bit) per channel. IR sensors, instead, usually record temperature values in the range between 20°C and 100°C and a have a sensitivity in the order of ±0.1°C. For further data processing, a thermal image can be represented as a matrix whose values are rational numbers with one digit.

In our procedure the temperatures recorded by IR cameras are encoded in a 16-bit gray value image. In other words, each temperature in the thermal image is mapped into a gray value between 0 and 65,535 following a linear model. This allows us to obtain a new RGB visual image but the advantage is given by the known mapping between gray values and temperature. This mapping can be inverted recovering temperature values in GIS analysis (e.g. when thermal orthophoto are needed).

Once thermal images are converted into gray values they can be processed as standard RGB images obtaining the 3D textured model and deriving the 3D model, from which other products can be extracted. Examples will shown 3D models textured by using a set of IR images, from which thermal orthophoto generated from multiple images and visualized in a GIS environment where exhaustive analysis (e.g. the extraction of thermal gradients) can be easily performed combining radiometry and geometry.
3. Results:

Through adoption of the SVMR outlier removal process presented in this research, it was possible to filter out the majority of mismatches. The experimental results showed that SVMR can handle both an impressive number of outliers and noise. Various experimental networks were processed with artificial outliers and noise. Additionally, the time complexity of SVMR is O(n^3) which means that the time required for this approach is only related to the size of the dataset and not to the number of outliers present, something common with RANSAC approaches.

4. Conclusion:

Results presented demonstrate that the approach developed can filter mismatches and point pairs successfully perform relative orientation using the coplanarity condition equations. The proposed methodology is particularly attractive for both the CV and the photogrammetric communities because it functions well with narrow-baseline, low-convergence as well as with wide-baseline, high-convergence images. Finally, it is noteworthy that the threshold value is better than 1/3 pixel, which is representative for many moderate-accuracy close-range photogrammetric measurement applications.

Automatic object detection in point clouds based on knowledge guided algorithms

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The applicability of digitalized 3D data imitating the real-world scenario has been realized in a variety of industrial applications which range from security to robotics to fields in medical science. The methods in 3D data processing are therefore concerned to find out appropriate solution in different conditions. In this paper, we present a novel approach which based on concept of human cognitive to guide processing. Our method turns traditional data-driven processing to a new strategy, which based on a semantic knowledge system. Robust and adaptive methods for object extraction and identification are modeled in a knowledge domain, which have been done by purely numerical strategies. The goal of the present work is to select and guide algorithms following adaptive and intelligent manners for detecting object in point clouds. Results show our approach successes in identifying the objects of interest in various data types. There have been quite a few researches on usage of knowledge in the field of object identification in point cloud. We are taking these works further and use knowledge to guide proper algorithms with best possible parameters for the detection mechanism and then use knowledge again to identify these detected geometries.

General process architecture of our system constitutes two distinct parts amalgamated seamlessly to carry out the knowledge based operations in the processing steps. The first part encapsulates knowledge through the semantic definitions of involved domains. Four knowledge domains are the base domains and should be taken into account in all scenarios. They account scene knowledge gained through human observation by scanning through the documents, site plans, CAD drawing, Geographic Information System (GIS) and so on. The knowledge domains could be expanded to others, for instance, we take data sets knowledge into our consideration. Likewise, they account the expert knowledge on processing algorithms related to the geometric behavior or topological behavior of the objects from the scene. The next part constitutes 3D processing algorithms dedicated to detect geometries. These algorithms are independent components that can work in isolations. However, they could be coupled together to create a sequence that executes to detect geometries of the entire object.

Algorithm Selection Module (ASM) has an important role within the framework of the proposed approach. This module takes expert knowledge on processing into account and combines it with other knowledge from other domains to support in appropriate algorithm selection for that particular case. An example could be “3DLineDetection” is most suitable algorithm to detect lines of a particular object in 3D, whereas “2DLineDetection” by Hough Transformation is suitable algorithm to detect same object in 2D.
environment. Thus, the knowledge about the algorithm is coupled here with that of data type and came out with the most appropriate algorithm. The system automatically evokes “3DLineDetection” for detecting line feature in 3D point cloud and “2DLineDetection” for detecting the same line feature in an image (which is basically a 2D dataset). The same goes for selecting natures of the parameters within algorithms.
 Each algorithm behave differently when combine with other algorithms. The characteristics of every algorithms and their relation with other algorithms should be taken into account while creating any chain that combines an algorithm sequence. This knowledge can only come from expert who has got this experience through numbers of simulation s/he makes. This knowledge is mapped up in the knowledge schema. Through the characteristics modeled in the knowledge base for the algorithms, a graph is created which represents all possible travel directions of the algorithms and is designed to determine the rightful flow of the algorithmic sequence.

The concept was realized through a demonstration prototype WiDOP literally standing for Wissensbasierte Detektion von Objekten in Punktwohlen für Anwendungen im Ingenieurbereich. Through WiDOP, we present a solution based on knowledge driven approach. The Solrnet is one of the two environments very different with each other in their characteristics giving enough arguments that the methodology can be applied to different environments. The platform uses rule based semantics in guiding the entire detection process in two distinct areas. First it uses geometric semantics of the objects and maps them to semantics of algorithms for guiding the appropriate algorithm to detect them. Then it uses domain rules to identify these detected geometries and classify in proper classes within the knowledge base. We thus enrich the knowledge base. The enriched knowledge base then serves to refine the detection and identification process further.

8791-12, Session 3

3D scanner point cloud denoising by near points surface fitting

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The data obtained by 3D scanners with required higher accuracy and density contain disturbing noise, this noise makes the data processing, mainly by means of triangulated irregular networks using automated procedures, more complicated. The paper presents a new method of noise reduction based on natural redundancy of continuous objects and surfaces where, however, some deformation of the object shape occurs.
The method involves a gradual choice of a selected number of the nearest points for each point of a scan, a detected surface is fitted with them and by the elongation or shortening of a beam with a given horizontal direction and the zenith angle onto the intersection with the surface a new (smoothed) position of the points is obtained. As the surface for fitting that relates them to, polyhymomials of 2nd, 3rd and 4th degree. For the better calculation stability Chebyshev bivariate orthogonal polynomials are used. These surfaces are complemented by method using the mean. The solution of surface fitting may apply the least squares method with uniform weights or weights depending on distance, but also a robust method: the minimisation of the sum of absolute values of corrections (L1 norm).
In spite of being always obtained in a certain order during the measurement, scanning data do not preserve this arrangement after their export, therefore, the procedure chosen for the searching of the neighbourhood of a point in a large point cloud (hundreds of thousands to millions of points) was the conversion of the problem of searching the neighbourhood in space (3D) into searching on a plane (2D); to this end, an algorithm was designed which is based on the application of
since it is impossible to define a universal and unequivocal fitting error. There are some error descriptors mentioned in the literature, but none of them can evaluate, if the exact solution of clouds matching has been achieved, when applied to real data. From the view of problem complexity, heuristic methods are commonly used to align 3D data. Accumulation of errors is observed, while creating a 3D model by integrating consecutive views. The problem of errors accumulation is especially severe when it affects a closed surface model. In such a case, error distribution is usually irregular because in certain parts of the model, errors are much higher than in others. So, while building a 3D model, not only the minimization of matching errors between point clouds, but also the uniform distribution of errors within the model, have to be assured.

In some cases of building 3D models, different parts of the object are required to be measured with different levels of details. Combining sensors with different resolutions enables to measure object maintaining acceptable tolerance and, additionally, measure some details with higher accuracy. In this paper we propose to use a system measuring with more than one resolution to create realistic 3D model through multistage view integration process. In case of low resolution measurement it is possible to increase the measurement volume (considering limited resolution of a sensor) which means decreasing the number of data covering the object’s surface. As a result, the whole model can be built by integrating smaller number of views than in the case of high resolution measurements. In our studies it is assumed that there is no information about data alignment at the output of a measurement system. The view integration process aiming to calculate initial transformation of point clouds is performed with the use of characteristic points (features) extraction. According to characteristic features extracted from two data sets, rigid body transformation between them can be calculated. At the end of the view integration process, an algorithm of global error minimization is applied to ensure uniform error distribution within the model and to avoid significant data misalignment. The algorithm assumes that the corresponding characteristic features between point clouds are known and according to them, it is possible to estimate distribution of errors within the model. Error descriptor is defined based on the distance between point cloud. The main goal of the algorithm is to obtain uniform distribution of the minimized error. In case of high resolution data, view integration is a more complicated task, considering smaller measuring volume and greater number of measurements. To simplify the whole process, we propose to combine multi-resolution measurements. In our approach, it is assumed that a model consisting of low resolution data can be used as a reference while integrating high resolution data. To achieve high resolution, accurate 3D model, global error minimization can be enhanced with fitting to a reference model. It means that the algorithm of global error minimization additionally has to include both geometrical and color constraints imposed by reference model. The final fitting solution is achieved with a modified Iterative Closest Points (ICP) algorithm. In this modified version of ICP there is a colour distribution in the neighbourhood of a randomly chosen point analysed to find corresponding points in reference model and high resolution point clouds. Two approaches of integrating high resolution measurements with with reference model are presented. In this paper, the results are presented together with a comparison of two the approaches.

8791-14, Session 3

**Primitive-based registration of indoor TLS data using a priori approximation of the poses**

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Many preparations of maintenance operations for industrial facilities currently now resort on to three-dimensional CAD models. The acquisition of these models is performed from point clouds measured by Terrestrial Laser Scanning (TLS). When the scenes are complex, several viewpoints for scanning, also known as stations, are necessary to ensure the completeness and the density of the survey data. The generation of a global point cloud, i.e. the expression of all the acquired data in a common reference frame, is a crucial step called registration. During this process, the pose parameters are estimated.

If the GNSS systems are now a solution for many outdoor scenes, the registration of indoor TLS data still remains a challenge. Indeed, given the actual characteristics of TLS (precision, resolution, speed), the accuracy of the global point clouds strongly relies on the accuracy of the registration protocol. Besides the current best practice to ensure the 1 or 2 cm maximum error (that is still to use total stations surveys with targets). This protocol is now the bottleneck of wide survey campaign and, in a context of industrial maintenance, its duration limits the number of 3D surveys. In this article, we present a registration approach for TLS data of industrial environments using a priori information on the poses parameters and 3D primitives reconstructed from point clouds.

In a first part we investigate the data and the a priori information on the poses. Based on these investigations, we present the state of the art of the registration methods applied to TLS data of indoor complex scenes. We then conclude on the relevance of the automatic reconstruction of 3D primitives in the scene to use them as “natural targets”.

In a second part, we detail the limitations of the current methods used to solve poses from geometric constraints between primitives. The main limitation is the effect of wrong constraints on the estimated pose parameters. We then suggest integrating the a priori information in the detection of correspondences by using a probabilistic matching score by propagating a priori distributions. Stochastic operations on non-Euclidean geometric objects require some care that we discuss; the influence of the geometric representation of the primitives is highlighted. To illustrate this care, we detail the case of the 3D lines (cylinder axis for instance) and parameters frame transforms (when using dual-axis tilt compensators).

In the last part, we present some experiments on a real dataset. First, we compare two approaches for the reconstruction of primitives (spheres, planes, cylinders) in point clouds: automatic (RANSAC) and semi-automatic (Region-Growing). Second, given the a priori uncertainty of initial estimation of pose parameters, we compute the probabilistic score of line pairs, representing the axis of the cylinder previously reconstructed.

Finally, we discuss on the several choices and proposals we have done. We conclude our work by some thoughts on the possible changes and improvements for our registration method.

Our contributions consist in:

- describing the state of the art of the existing tools and methods for registering 3D point clouds into industrial environments using natural targets.
- detailing the use of a priori information of the poses in the matching step.
- experimenting and assessing two steps of our approach: automatic reconstruction of primitives and probabilistic matching.

8791-15, Session 3

**Alignment of range image data based on MEMS IMU and coarse 3D models derived from evacuation plans**

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This paper deals with the alignment of range data, using a MEMS IMU and 3D coarse models derived from evacuation plans, in indoor applications.

The range sensor used in this study is Microsoft Kinect, which is a low-cost multisensor system. This system consists of an RGB and a monochrome IR CMOS sensor, both working in 30Hz with VGA resolution (640 by 480 pixels), and an IR laser projector. Kinect measurements are disparity values, resulting from a comparison between the reference and collected IR patterns. Having disparity values, range images are then computed in a limited range of 0.7m to 6m. Stereo calibration of the RGB and IR sensors creates a link between the color image space and the 3D space.

In a previous work, we have aligned the Kinect range data, making use of color image and object space observations (Khosravani et al., 2012). In other words, such range data were aligned, first by estimation...
of the sensor's pose by applying the structure from motion (SfM) method on color images. Then as a complementary method, such range data were aligned using the geometric information provided by the range data, i.e., using the iterative closest point (ICP) approach. The short comes of these methods were in scenarios where neither enough image features for a successful SfM can be found, nor the ICP approach could fix the sensor's pose 6 degrees of freedom. This is especially the case when dealing with corridors in indoor scenarios.

An extension to the previous work can be integration of positioning solutions (e.g. MEMS IMU) to the system, to support the sensor's pose estimation. In recent years, there has been an increasing interest in the use of such sensors for indoor navigation. IMUs are often used as foot-mounted systems and are combined with algorithms like ZUPT (zero velocity updates). Moreover, due to the existence of drift errors, other methods have to be employed, e.g. map matching algorithms using available indoor models. Peter et. al. (2011), support foot-mounted MEMS IMU navigation by a given external building shell and photographed evacuation plans.

In this study we use the same positioning solution to support the sensor's pose estimation, and to show the performance of this method in the alignment of the range data in some indoor applications. In more details, we can acquire the sensor's position from the described positioning method, and the initial orientation from the trajectory analysis in the horizontal plane. Afterwards by aligning the collected point clouds and the 3D coarse model derived from the evacuation plan (Peter et. al., 2010) either using the ICP approach or extraction of dominant planar features and analysis of the normal vectors, one can estimate a more accurate sensor's pose. The estimated poses are then directly used for the alignment of the point clouds collected at different points. This enables our next steps, which are texturing, updating and refinement of the 3D coarse models derived from the evacuation plans. Such refinement includes adding windows and features which are neglected in the evacuation plans due to the generalization process.

References:

8791-16, Session 4
A review of techniques for the identification and measurement of fish in underwater stereo-video image sequences
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The monitoring of fish for stock assessment in aquaculture, commercial fisheries and in the assessment of the effectiveness of biodiversity management strategies such as Marine Protected Areas and closed area management is essential for the economic and environmental management of fish populations. Video based techniques for fishery independent and non-destructive sampling are widely accepted. The advantages of using stereo-video have been well demonstrated. However, due to the time lag and cost of processing video imagery decreases the effectiveness and uptake. Successful current research aims to remove the human observer from the recognition and length measurement of fish recorded by underwater stereo-video surveys. The ultimate goal is to fully automate the recognition and measurement, in order to deal with the many thousands of hours of stereo-video footage that is routinely captured each year. Advances in automated techniques will substantially decrease the cost of processing and make the technology more accessible to a broad spectrum of end users.

Stereo-video systems have the advantages that the measurements are impartial and repeatable (Harvey et al., 2004), and calibration stability tests indicate very reliable levels of accuracy (Shortis et al., 2000). In recent years underwater stereo-video systems have been used in wild fish stock assessment (Watson et al., 2009) and in pilot studies to monitor length frequencies of fish in aquaculture cages (Harvey et al., 2003). Samples taken in aquaculture cages can approach 95% of the population and the measurement technique is non-invasive. Snout-to-tail and other body spans on the fish are measured from the video recordings and, using a length-weight regression (Pienaar and Thomson, 1969), the weights of the fish are estimated to an accuracy of a few percent. Commercial systems such as VICASS (Shieh and Petrelli, 1998) are widely used in aquaculture to determine size distributions based on simple length and span measurements, and thereby deduce biomass from an estimated number of fish in the cage or tank.

The next significant advances in the technology of stereo-video monitoring of wild and aquaculture fish must be the automated candidate identification and body shape reconstruction of the fish in order to directly extract volumes, and potentially the identification of individual animals to validate sampling and monitor growth. Automated measurement will also enable monitoring of the condition of fish, at least to the extent of estimating the frequencies of superficial injuries and potentially identify infestation levels or secondary infections caused by parasites such as sea lice or skin and gill flukes.

A typical approach (Tillet et al., 2000) to the recognition and measurement of fish in video sequences leads to a likely scenario of the following steps:

• capture many images without fish in the scene and compute an average;
• use frame differences and/or motion flow, with morphological operators and heuristic geometric tests, to identify candidate fish;
• employ edge detection, geometric contour sets or active contours (Kass et al., 1987) to delineate the fish in the scene;
• establish a shape of the body of the fish using an epipolar search and stereo-matching (Gruen and Baltsavias, 1988), or a semi-global matching (Hirschmüller, 2005), approach;
• predict the trajectory, track the fish and repeat the process to improve the accuracy of the surface model generation; and
• compute the biomass based on the length, and possibly span measurements, of the body of the fish.

This relatively straightforward recipe does not include consideration of algorithm complexity issues such as cluttered or dynamic background scenes, foreground or fish school occlusions and the changing body shape of the fish as they swim. The latter issue in particular requires a deformable template to model the body of the fish. One possible approach is the incremental construction of 3D meshes (Guibas et al., 1992), with deformation modelled by least squares fitting of registration points followed by re-sampling over the 3D mesh. A similar approach could use matching over registration points with a thin-plate spline model (Bookstein, 1989) allowing interpolation via a parameterised surface. An extension of this approach uses both registration points and intensity-based matching (Johnson and Christensen, 2002) to model the body shape.

This paper will present a survey and a review of the techniques used for the identification and measurement of fish in underwater stereo-video image sequences, including consideration of the changing body shape. The review will identify the common approaches and their shortcomings, leading to an evaluation of the techniques most likely to be a general solution to the identification and measurement task.

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8791-17, Session 4

A photogrammetric approach to survey floating and semi-submerged objects

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The article reports an innovative methodology for the 3D surveying and modelling of floating and semi-submerged objects. Photogrammetry is used for surveying both the underwater and emerged parts of the object and the two surveys are combined together by means of special rigid orientation devices. The innovation of the proposed method consists in performing two separate photogrammetric surveys (below and above the sea level) referencing them directly in the same coordinate system. To achieve this, special rigid Orientation Devices (ODs) were built and calibrated before realizing the survey. The devices consist in rigid rods whose length depends on the dimensions of the object to be surveyed. On each rod, two or three plexiglas water-proof plates with four circular photogrammetric targets were secured and their coordinates were precisely measured in laboratory. During the survey, these special devices are fixed to the object with at least one plate below and one above the sea level. In this way, each calibration device allows joining the two, underwater and emerged, surveys. To guarantee a reliable reference system transformation between the two object parts, a good geometric distribution and redundancy of the orientation devices on the floating object is needed. The procedure for joining the two surveys can be summarized as follows: (i) the 4 coded targets on each plate of the ODs are previously measured in the laboratory, which means that the relative position between the plates on the ODs is accurately known; (ii) the ODs are fixed on the floating object with at least one plate above and one below the water level; (iii) the coordinates of the targets on the submerged plates are measured during the underwater survey; (iv) the 4 measured targets are used for computing the transformation parameters that allow to align (roto-translate) each OD in the underwater reference system: i.e., also the coordinates of the targets on the emerged plates are known in the underwater reference system; (v) the coordinates of the targets on the emerged plates, measured during the survey above the sea level and known in the underwater system, are used for aligning the emerged part to the underwater.

8791-18, Session 4

Experiences in determination of non-rigid body motion in industrial environment using low-cost photogrammetry

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Experimental methods are an integral part of all simulation studies. Given a problem simplified to a model, one needs to verify how close the approximated system is close to a real one. So long a priori mathematical assumptions are incorrect, the model needs to be improved and re-checked with experiments.

Depending on the nature of the modelling task, different experimental methods can be employed. For metrology tasks, a preferred technique in cases where both shape of the object and non-contact measurements are of primary interest. Invaluable characteristics of optical metrology such as the speed of acquisition, area-based approach, or scale freedom, give it the flexibility to address diverse metrology problems in engineering.

Research presented in this paper is part of a project aiming at pre-industrializing a novel concept of a floating solar power plant. The objective is to identify an optimum design for the plant with respect to concentration technology and the supporting concept, to be achieved by a combination of design and experimental works.

In the following discussion we will present our experiences in using photogrammetry to understand geometric behaviour of the platform subject to wave forces and we will point out to what extent a low-cost measurement setup can be a tool in such an application. Special considerations will be given to obtainable accuracy measures, possible level of automation and pitfalls stemming from the fact that our sensors are not inherently manufactured to serve as measurement devices.

Central to our investigation is determination of motion of a swimming platform and coupling it with momentary shape of water surface. Neither of our observables represent a diffuse-like surface. The platform is covered with reflective foil and water is obviously transparent.

Observations of dynamic phenomena require adoption of suitable imaging sensors. Selecting actual measuring device for the task, desired order of accuracies, workplace constraints and last but not least financial aspects. In our case a trade-off was searched by maximizing camera spatial resolution and keeping the temporal resolution in a range that would allow us to reconstruct the motion signal.

An emerging trend among dSLR cameras to offer video functionality made them attractive for us intending to observe time series of events. In comparison to industrial cameras, dSLR’s are less rigid in terms of inner mechanics, on the other hand they are sold a number of times cheaper. In comparison to video cameras, they not only come at lower price, but also have the advantage of interchangeable lenses, and explicit control over exposure parameters.

Our imaging setup consists of three calibrated dSLR cameras. (cf. Fig. 1). All measurements are referred to an absolute reference frame. Artificial targeting was applied to survey the frame, and also to derive platform motion and water wave parameters (cf. Fig. 2). Abundant data produced during video recordings is managed in a semi-automatic manner by a set of algorithms combined in an application. Points in image spaces are detected by edge detection techniques and filtered on the basis of input point parameters (e.g. mean RGB values, size, roundness). Subpixel accuracy effects from either weighted centroiding or cross correlation enriched with polynomial fitting. Correspondence between views is established thanks to known epipolar geometry, while correspondence in subsequent time instances exploits the fact that inter-frame motion is small. Intersections are performed by the well known bundle adjustment (Gauss-Markov least squares).

Retrieval of wave parameters i.e. wavelength, amplitude and frequency, plays a significant role in modelling of water surface. In regular water waves, which is our testing environment, the parameters allow to
infer about wave heights at arbitrary positions (a feature useful for the platform designers, see Fig. 4). To restore frequency or amplitude a single point floating on water surface is sufficient (cf. Fig. 3), however, it is too little information to even speculate about the wavelength. Therefore, a set of point is distributed across the surface. These points and their trajectories are tracked so that unique length of the wave is identified.

Through analyses of results from several measurement campaigns, we will prove that low-cost photogrammetry has the potential to serve measurements when accuracy expectations are high. In spite of all the practical limitations a prosumer camera can have such as data reduction techniques or unstable camera body and lens, our experiments show that submillimeter standard deviations are just feasible. It should be however noted that presence of the above impediments increases the risk of blunders in the data, necessitates a more thorough and apprehensive quality check, hence contributes to longer processing times.

8791-19, Session 4

High accuracy low-cost videogrammetric system: an application to 6DOF estimation of ship models

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The paper presents a low cost passive videogrammetric system, composed by three consumer-grade CMOS cameras arranged in different configurations, for the analysis and study of ship model motions. In particular, the tests aim to evaluate performances of new (full scale) designed ships, modifications to existing projects or different design solutions, and validate CFD (Computational Fluid Dynamics) based codes. Several experiments were conducted to test the developed videogrammetric system. A 2m long ship model was secured with a system of thin wires and springs to the basin’s sides and different sea states were generated (zero-speed tests). Different system configurations and target shapes were tested. The paper reports the system design, calibration and testing. A procedure for evaluating the residual error of synchronization will be also shown and the improvement in the accuracy of motion measurement will be also assessed.

8791-20, Session 4

Generation of synthetic image sequences for the verification of matching and tracking algorithms for deformation analysis

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In industrial metrology solutions for object reconstruction with high spatial and temporal resolution are of increasing importance. Particularly in material testing such solutions are of special interest, e.g. for vibration analysis or crack detection, where objects cannot be signalized or textured with photogrammetric measurement targets or artificial texture. In addition to high dynamic and dense object reconstruction the estimation of 3D displacements and velocities is often required (tracking of non-signalized object points). The combination of these three demands (high spatial resolution, high temporal resolution, tracking of object-fixed points) restricts the choice of methods to image-based matching and tracking algorithms. The development of such methods has been subject of scientific research in computer vision and photogrammetry for more than 25 years, so nowadays various different approaches exist and are in practical use. In contrast, the development of strategies for the verification of the results of different algorithms is less extensive. The computer vision community uses (freely available) test datasets in order to investigate and compare different methods with respect to defined criteria, e.g. performance, robustness. Many real applications do not satisfy the requirements of extensive accuracy evaluations mainly because of the lack of defined quality parameters and the absence of reference data of superior accuracy. Accuracy evaluations for optical 3D measuring systems considering defined quality parameters (such as length measurement error, probing error, sphere-spacing error) can be provided by following the recommendations of the German guideline VDI/VDE 2634. However, this guideline does not focus on optical measurement systems that are able to track non-signalized object points. Furthermore, experimental accuracy evaluation methods for the assessment of dynamic measurement systems are complex and time intensive.

Hence, this paper presents an approach that has been especially developed for the efficient investigation of measuring systems characterized by the properties described above. The approach is based on the generation of synthetic image sequences for a number of cameras observing one (or more) moving and/or deformed objects. The objective is to rebuild the process of image capturing as realistic as possible, ideally including all geometric distortions and radiometric effects. The resulting error-free images can then be used to investigate the behavior of different image matching and tracking algorithms for example with respect to changing camera configurations or changing object texture. In a next step disturbances (e.g. occlusions or noise) can be added to the synthetic error-free images and again the behavior of different matching and tracking algorithm can be investigated.

The generation of synthetic images is based on the parameters of a (given) interior and exterior camera orientation in order to reconstruct the 3D line which is defined by a pixel and the projection center of the camera within the global system X,Y,Z. This straight line is transformed into the local coordinate system of an object (XL,YL,ZL) and intersected with the object surface which is represented by a dense mesh of triangles (TIN). The image that is used for object texturing is placed on the XL-YL plane of the local coordinate system. The relationship between calculated object intersection point and texture image is given by orthogonal projection of the object onto the XL-YL plane.

The described strategy allows for calculating images that are observing almost arbitrarily moving objects. In contrast, there are some limitations with respect to the definition of object deformations. Up to now, object deformations can only be modeled in ZL-direction of the local coordinate system.

In general, the integration of arbitrary objects, provided by CAD-models or mathematical functions, can be integrated into the image generation process.

The paper starts with a comprehensive description of the process of image generation. Questions of verification and quality of the resulting images are addressed. Then first results using synthetic image sequences are discussed. The results of the matching software PISA (Photogrammetric Image Sequence Analysis), an in-house development of the Institute of Photogrammetry and Geoinformatics (IAPG), has been compared to the results of an open source Semi-Global Matching algorithm (SGM, implementation of OpenCV).

Additional investigations with respect to the tracking functionality of the PISA algorithms have been carried out.

In general the investigations focus on the following special aspects:

- influence of object texture on matching/tracking results by using different textures for the same object
- influence of varying camera configurations (e.g. gradual increase of the convergence-angle of the cameras)
- achievable spatial resolution
- possible smoothing of matching results in case of curved objects
- accuracy of texture-based object point tracking

8791-21, Session 4

Stochastic process modeling for multiple human tracking using stereo video camera

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Recently in-depth understanding of pedestrian behavior in public space is becoming significant with regard to achieving more sophisticated space design and flow control. The difficulty in space design in big stations, for example, is that we should consider the whole congested level inside a station which changes every second and passenger’s microscopic route choice at the same time. Therefore, understanding passenger flow in detail is necessary to accomplish
good facilities planning. The same is true in shopping mall and pedestrian crossing. In order to understand such human behavior, the main problem is to comprehend individual's behavior in complex situation that people move interdependently.

Observation data from diverse sensors which are informative to understand human behavior is accumulated these days thanks to the development of sensing technology. As such data increases, a high requirement arises to acquire behavior information automatically. Automatic human tracking, however, is still challenging under the situations that people move close to each other or are occluded by others. Meanwhile some simulation models of walking behavior have made progress recently. In such models, pedestrian's choice of next step is explained by not only each individual's present position and velocity but also the interdependency as the response to the presence of other pedestrians.

This paper proposes a new method of multiple human tracking under the complex situations by integrating the various observation data and the simulation. The key concept is that the multiple human tracking problem is equal to stochastic process modeling. A data assimilation technique, widely used in many fields of geosciences, is employed as the stochastic process modeling. Since human behavior is uncertain and human is non-rigid object, stochastic tracking process is suitable. Also as the huge volumes of data is processed for tracking, sequential process is suitable.

The data assimilation technique consists of observations, forecasting and filtering. In human tracking, observations correspond to observations from sensors, filtering to pedestrian behavior model and forecasting to ordinary tracking method by image processing. The tracking process is modeled as follows. In each frame, positions and shapes of people being tracked are estimated by behavior model (forecasting step). Then estimated shapes and positions are optimized referring to the new observation data based on likelihood (filtering step). The optimization at filtering step corresponds to estimation of the maximum a posteriori probability. Particle filter is utilized for the calculation through forecasting and filtering steps.

The data assimilation system can be described in a form of general state space model. We review related works on both human tracking methods by image processing and simulation models of pedestrian behavior, respectively. According to the review, we develop a method as a stochastic process, integrating them on the framework of general state space model. For general state space model, a state vector is defined as an ellipsoid and its coordinates, which are human positions and shapes. An observation vector is also defined as observations from sensor. Stereo video camera is used to deal with complex situation, so that we acquire both color and range information. Then a system model which describes dynamics of the state vectors is formulated by using discrete choice model. The discrete choice model describes the choice of each pedestrian stochastically and deals with interaction between pedestrians. Besides, the alternatives of next step are individual for each pedestrian for each time. An observation model is also formulated for the filtering step. The observation model consists of likelihoods with regard to color and range stochastically. The likelihood of color is modeled based on color histogram matching with Bhattacharyya coefficient. The likelihood of range is calculated by comparing between the ellipsoid model and observed 3D data. Additionally, the method is expanded to achieve the long time tracking, by integrating a detection method for human appearance in observation area. The human detection is regarded as an initial setting for stochastic tracking system. The human detection method is based on Plan-View map technique. First of all, human candidates are detected and initial distributions are set as marginal probability for all candidates. And then, posterior probability distributions are updated according to observation models using range and color information from sensors. The observation models are similar as ones for tracking process. With the posterior probability distribution, expected value of human position is calculated and false positives are deleted. Finally, this initialization process is combined with the tracking process. The proposed method is applied to the data acquired at the ticket gate of the railway station and the high performance of the method is confirmed. We compare this result with other model, using Kalman filter as system model, and show the advantage of integrating the behavior model to the tracking method. The applications also demonstrate the effectiveness and efficiency to acquire passenger flow information from the tracking result. These results show that the accurate data processing is possible.

Furthermore, the proposed method can be easily applied to other situations. According to observation sites and human behavior there, different pedestrian behavior models can be utilized by replacing system model. In the same way, different sensors such as range scanner and infrared sensor can be introduced by replacing observation model. Another feature of this research is the possibility to improve behavior model by feeding the tracking result back to the behavior model. Since the automatic tracking can deal with much amount of data, enormous human choices in the real situation will be offered.

8791-22, Session 5

Metrological characterization of 3D imaging devices (Invited Paper)

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Manufacturers often express the performances of a range device in various non-uniform ways for the lack of internationally recognized standards and requirements. The metrological characterization of optical distance sensors is of primary importance to guarantee the capability of capturing a real scene. For this reason several national and international organizations in the last ten years have developed protocols for verifying such performances.

The most advanced and structured is surely the document published by the Association of German Engineers (VDI), which produced the VDI/VDE 2634. It is divided in three parts:

1. Optical 3D measuring systems: Imaging systems with point - by - point method, 2002;
2. Optical 3D measuring systems: Optical systems based on area scanning, 2012;

VDI/VDE 2634 is very oriented to the world of mechanical 3D measurements and therefore takes into account 3D measurements with short-range non-contact 3D systems based on triangulation with a single laser spot (part 1), or a pattern projection device (part 2).

An international level has ISO Technical Committee 213 working group 10 which is currently working on a draft of ISO/CD 10360-8 – “Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM) – Part 8 – CMMs with optical distance sensors.” This effort is aimed at addressing the optical distance sensors attached to the end of Cartesian CMMs, therefore it is again oriented to the world of precise short-range measurement with triangulation based device.

For the evaluation of laser systems based on direct range detection based on Time Of Flight (TOF) and Phase Deviation (PD) principles, suitable for medium and long range, the American Society for Testing and Materials (ASTM) have established in 2008 the technical committee E57, devoted to, as written in their fact-sheet, “the development of standards for 3D imaging systems, which include, but are not limited to laser scanners (aka LADAR or laser radars) and optical range cameras (aka flash LADAR or 3D range camera)”.

Most of these protocols are based on special objects whose shape and size are certified with a known level of accuracy and uncertainty. By capturing the 3D shape of such object with a range device, a comparison between the measured points and the theoretical shape they should represent is possible. The actual deviations can be directly analyzed or some derived parameters can be obtained (e.g. angles between planes, distances between barycenters of spheres rigidly connected, etc.).

The purpose of this paper is to employ a method already verified on triangulation based devices [1] and preliminary tested on medium/long range laser scanners [2], with a more extensive set of devices based both on TOF and PD.

The parameters that are intended to evaluate are: i) an estimate of the maximum resolution attainable by the device; ii) an estimate of the measurement uncertainty in different conditions due to random factors; iii) an estimate of the systematic deviation of the measured 3D coordinates from the supposed-true ones.

The system uncertainty have been evaluated in two different ways: i) by acquiring shapes known in advance like a plane and statistically analyzing the deviation of the whole cloud of 3D points from the expected position by this; ii) by repeating the same measurement several times analyzing the same pixel response in the sequence.

The first way seems more suitable for giving an overall estimate since both electric...
noise and optical factors contribute to the result, while the second is more oriented to stressing the electronic part of the system (sensor and amplification noise, A/D conversion) being not influenced by laser speckle.

The system accuracy is always evaluated in term of “relative accuracy” rather than absolute, in order to make feasible and cheaper the experimental set-up. Three ways have been experimented: i) measuring the peak distance of a group of 3D points obtained by the 3D sampling of a plane, from the best fitting plane, after eliminating the outliers; ii) 3D acquiring a certified object made by several planar elements spaced apart in known and certified way, and evaluating the average distance of each group of coplanar points from the corresponding plane; iii) evaluating the relative linear accuracy as the deviation of a set of 3D points from the shape they should describe (rather than from their actual position in space) divided by the diagonal of the range map.

The system resolution estimate is based on a translation in the 3D world of the ISO 12233 standard for evaluating the sharpness of 2D still-imaging devices. The method basically assumes to reproduce in 3D the shape of the 2D patterns on the ISO 12233 standard, which explore resolution both directly and indirectly. The direct approach analyzes pairs of lines, alternately black and white, gradually thinner. Each pair of lines (a black-to-white transition) is considered a cycle, and the pattern, given in terms of cycles (i.e. pairs) per millimeter, represent sequences of adjacent pairs whose spatial frequency linearly grows. The indirect approach reveals at what spatial frequency the system blurring starts to neglect the difference between black and white lines, confusing them in an indistinguishable gray level. The indirect method is instead based on the spectral analysis of the imaging device behavior in presence of an abrupt black-to-white transition and used the evaluation of the spectral width as an index of resolution.

All these approaches have been ported to 3D by extruding such patterns using black and white for coding z (black=high z; white=low z), using a range of variation if the field of millimeters and fractions of a millimeter for triangulation based devices, or centimeters and fractions of a centimeter for OF and radars devices, and using the gray-coded z images in place of regular images.

The custom objects specifically developed for this work are briefly described. The laser scanner analyzed and compared according to the above mentioned parameters are recent models by Leica, Z+F, Faro and Riegl.


8791-25, Session 5

Lighting estimation in fringe images during motion compensation for 3D measurements

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Fringe projection is an established method to measure the 3D structure of macroscopic objects. To achieve both a high accuracy and robustness a certain number of images with pairwise different projection pattern is necessary. Over this sequence, it is essential that each 3D object point corresponds to the same image point at every time. In the last few years the demand of fast and cost-effective systems for 3D measurements became evident. Therefore, it is recommended to measure moving objects continuously or use sensor systems in motion instead of the current start-stop regimes. However, the situation of constant correspondences between 3D object points and 2D image points over the whole measurement cycle is no longer given. One possibility to solve this problem is to restore the static situation. Therefore, the acquired camera images have to be realigned and secondly the degree of fringe shift has to be estimated. These two tasks are realized by back projection of a coarse 3D point cloud, which is created by fourier analysis of each single fringe image. If the relative 6D motion of the measurement object in respect to the sensor system is not being given, this has to be estimated by using ICP algorithms. Furthermore, there exists another variable: change in lighting. These variances cannot be compensated, but this variable has to be approximately determined and integrated into the calculation process of 3D data. The possibility to obtain an accurate measurement is not being given due to the condition that each arbitrary interferogram comprised three unknowns: additive and multiplicative intensity distortion and the phase distribution. The changes in lighting are described by the first two parameters and have to be determined for each camera pixel and each image, whereas global methods like ellipse fitting cannot be used. So, there is a trade-off problem: Two variables, but only one equation. We propose a mathematical approach to estimate these lighting changes for each camera pixel with respect to their neighbors at each point in time. This approach is based on the assumption that in most cases only very small lighting changes from one pixel to an adjacent pixel will arise. Since approximated values are used in the calculation, it is recommended to use major neighborhoods to avoid noisy maps of lighting values. Smoothness in regions with very low contrast in intensities or wide fringe periods, as well as sharp edges are required for accurate 3D measurements. Here, we present algorithms which choose the size of neighborhoods adaptively in respect to the gradients of object structure and wide of fringe period. Since trigonometric functions like sine and cosine do not have a linear slope, it is unfeasible to directly calculate the gradients. Instead, we use the estimated phase distribution of projection, which is already calculated by back projection of 3D object points into the projector plane.

To speed up the estimation of lighting values, not all pixel of the neighborhood were taken into account. Basically, values from the neighborhood two image pixels in the two image axes of the quadratic neighborhood were used. Depending on the direction of projected fringes, either axially parallel or diagonal adjacent pixels are used.

Taken together, our method results in a motion compensated dense 3D point cloud which is eligible for three-dimensional measurement of moving objects or setups with sensor systems in motion without using high-speed hardware. The algorithms were approved on simulation data, in particular with rotating measurement objects. For translational motion, lighting changes are not too high. However, the methods presented here work for these purposes, but this approach is not obligatory. So far, we already performed first experiments with real data sets. Thereby, the accuracy of the final 3D result depends on the noise level in the intensity images and smoothness of 3D structure of the measurement object.

8791-26, Session 5

A robotized six degree of freedom stage for optical microscopy

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This work represents an investigation of the possibility to use a hexapod system for optical microscopy investigation and measurements. An appropriate hexapod stage has been developed. The stage has been calibrated and used for several different optical microscopy applications. The construction of the stage is based on the classic Stewart platform and thus represents a parallel robot with 6 degree of freedom. Appropriate software is controlling the transformation of the 3 position coordinates of the moving plate and the 3 Euler angles in position velocities and accelerations of the plate motion. An embedded microcontroller is implementing the motion plan and the PID controller regulating the kinematics. By difference to the available in the market hexapods the proposed solution is with lower precision but is significantly cheaper and simple to maintain. The repeatability obtained with current implementation is 0,05 mm and 0,001 rad. A correction of the actual positioning result is done by more precise laser based triangulation with a projection on a CMOS sensor. A specialized DSP based video processing engine is used for both feedback compensation and application specific image processing in real-time. The secondary feedback measurement of the position and Euler angles is done by 3 beams fixed on the bottom plate of the hexapod which are producing 3 points on the top plate which are observed by an image sensor located in the bottom plate.
as well. The projected points allow calculation of the 3D position of the beam section with the upper plate which defines the plane of the upper plate. 3 more degree of freedom are obtained by another set of 3 beams fixed on the upper plate and oriented in a way to be focused and visible with high performance of the hexapod on the CMOS sensor. The information obtained by such a triangulation allows the solution of the back transformation problem for the hexapod stage and thus provide an independent measurement of the actual position and rotation of the upper plate.

To verify the concept some applications has been developed for specific tasks and has been used for specific measurements:

- Multiple point of view 3D stereo reconstruction with single beam microscopy – the applied algorithm is a modified version of “3D Reconstruction of Dynamic Scenes with Multiple Handheld Cameras, Hanqing Jiang at Al.”. For each collected image the information from the positioning feedback can be used for initial estimates for the reconstruction. The reconstruction process itself is implemented as a non-calibrated approach for reconstruction by including in the optimization the epipolar geometry optimization of the system around a prediction of the epipolar geometry.

- “In focus panoramic” microscopy – Due to known positioning capabilities the system can make a scan of a large area (larger than the field of view of the optical system) in a grid (e.g. 8x8, 12x8 or 16x16). In addition an auto-focusing algorithm based on maximization of the contrast is keeping each of the collected images clear with sharp edges. The results are finally submitted to a stitching procedure by Stephan Preibisch At Al. (BIOINFORMATICS APPLICATIONS X NOTE Vol. 25 no. 11 2009, pages 1463-1465 doi:10.1039/bi09184b) which produces a large panoramic image of the specimen.


- tracking of a moving droplet on an inclined surface to obtain information about speed and contact angles of the droplet (dynamic contact angle measurement – an important area in physical chemistry) as well as tracking of contact angle and droplet motion in a capillary. The algorithm is developed in our laboratory and is an edge detector based point finder. The obtained points are then used for regression with an approximate model of a drop sliding on a solid surface. The crosssection of the drop profile and the surface profile (a line observed from the side) delivers the needed geometric information (contact angles).

The main conclusion which could be derived from this work is that the proposed robotized hexapod microscopy stage with 6 DOF can be used in several area of optical microscopy to provide precise positioning of the specimen during observation. Integrating the observed results and the motion control of the stage can provide significant improvement in optical microscopy automation. The bounding windowing high-performance image processing system allows the application of the system to metrological tasks and implementation of 3D reconstruction and measurement of objects.

8791-41, Session 5

Calibration of profile laser scanner with conical shape modification for autonomous mapping system
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The profile laser scanner Sick LD-LRS1000 is a part of autonomous mapping system which is developed at the Czech Technical University in Prague. The development of the system is supported by Technology Agency of the Czech Republic under the name "Technology and system of determining the physical and spatial characteristics for the protection and creation of the environment and increase the potential of energy resources" for years 2011-2014. The aim of the project is to create measuring system which will have specific properties suitable for effective mapping of medium-wide areas (units to tens of square kilometers). The main components of the system are: platform and carrier - unmanned airship with autonomous control. Measuring platform is designed and optimized especially to run on airship. It is mounted in the damped double gravitational gimbals and it has modular concept which allows employing different sensors and changes of its amount and position. The only limitation is total weight, which shouldn’t exceed 15 kg (carrying capacity of airship). Currently complete equipment consists of INS / GPS navigation unit (IMAR iTracer – F200), laser scanner (SICK LD-LRS1000) with conical modification, digital camera in the visible spectrum (Olympus E-PM1) and professional thermometric camera (FLIR A615). The selection of carrier was based on our specific requirements such as carrying capacity on the first place, long flight time, safety (in case of failure there is no danger of straight fall, airship staying heavier than air therefore it will drop smoothly to the ground without jeopardy people’s health or equipment) and flight characteristics such as stability of flight in terms of vibrations and possibility to flight at low speed.

The airship ACC15X made by airshipclub.com is 12m long with maximum diameter 2.8 m filled by helium of volume 57 m3. Operating speed 30 km/h and maximal 55 km/h with high-rise accessibility 1000 m. Movement is provided by two side electro motors with propellers. Whole system is powered by an engine generator that can work about 3 hours.

Due to planned usage in airborne mapping, unique laser scanner is being developed. Conventional linear laser scanner is modified into form of conical laser scanner. In case laser scanner stays linear, about 60% of scanning plane, in which we would measure points, would stay unused. By modification plane into the cone, we could use even laser beam direction to calculate coordinates on the surface. The other advantage of this modification is that with one sensor we could scan backward and forwards together at the same time. This modification will case in reducing the point cloud shadow zones in rugged environments.

The Sick LD-LRS 1000 laser beam divergence is pretty large (2.8 mrad), because of its primary usage in safety application see e.g. [1]. That’s why we use spherical mirror with large radius to reduce laser beam divergence. The focus point of mirror is about 80 meters. Publications on bore-sight calibration of cameras and laser scanners are accessible. We use approach presented in [2] for camera calibration purpose. We plan to use approach presented in paper [3] for laser scanner bore-sight calibration. We need to extend the approach for using laser scanner with conical modification. At first we need to accurately and with known accuracy determine the spatial pose of the mirror in the laser scanner coordinate system (laser scanner inner calibration).

The suggested procedure of laser scanner inner calibration will be presented in the paper. It is based on scanning of a plane in a various pose of the laser scanner and then finding of the optimal parameters of mirror pose with respect to measured points least square fitting to a plane and an ellipse (cone section) simultaneously [4]. Because the observations and parameters of observation equation are mixed together and each condition includes more than one observation, the most general combined adjustment model must be used see [5].

References
An improved calibration method for structured light projection measurement system

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The accurate calibration for a 3D profile measurement system based on structured light projection is important to the system measurement accuracy, however, system calibration is always complicated and time-consuming. A novel fast method is proposed to calibrate the measurement system. The measurement system includes the Panasonic 3CCD camera (DV-30), the Cannon projector(SX60) and image collection card (RGB_20B) etc. The resolutions of the camera and the projector are 572x582 pixels and 1400x1050 respectively. The color more fringes projected in the projector is 1400x1050 pixels too. The AOC LCD monitor(19 inch), as a 2D target pane, is 1440x900 pixels. Frist, LCD monitor displays chessboard pattern designed by computer programming, camera collects 1 image; then LCD monitor displays white pattern, projector projects horizontal and vertical color more fringes to the LCD monitor, camera collects 2 images respectively. The minimum cost network flow Phase-shifting algorithm is used to establish a highly accurate correspondence between camera pixels and projector pixels, and generate projector images. Then, freely move the LCD monitor to other 5 or 8 places, get camera images and projector images which are set for camera and projector calibration using 2D pattern plane–based method respectively. Compared with classical techniques which use expensive equipments such as two or three orthogonal planes, LCD monitor is easy-to-use and flexible. And experiments show that calibration accuracy is improved by 4 times, because LCD monitor is flatter than ordinary calibration pattern. In comparison with traditional projector calibration method, this method decreases the number of images acquisition from 8 to 2 in each place and increases the processing speed. Putting the camera calibration and projector calibration together, the complex calculation process of the integration of traditional camera calibration and projector calibration can be simplified. Experiments have been done based on the proposed technique and good results have been obtained. This work was supported by National Natural Science Foundation of China (Projector no. 51075322).

A background light resistant TOF range finder with integrated PIN photodiode in 0.35µm CMOS

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The Time-of-Flight (TOF) method has been recognized as one of the most promising approaches that can contactless measure the distance between the sensor and the object if a real-time sub-centimeter resolution is demanded. Furthermore, state-of-the-art (SOTA) TOF sensors can integrate up to several thousands of pixels. The maximal pixel number that can be integrated on a die depends mainly on the single pixel size. Hence, it has been put much effort to minimize the pixel area. However, the size reduction is usually paid for limited accuracy and/or higher background light sensitivity. In particular, the background light problem represents the main drawback of TOF sensors being successfully suppressed only in several publications up to now.

Within this work a single pixel Time-of-Flight (TOF) based range finder is described. The working principle of the sensor is based on correlating the received optical signal with a reference clock in 16 discrete phase steps. The sensor is fabricated in a 0.35 µm CMOS process occupying an area of 45x60 µm at 50% fill factor. It takes advantage of the integrated PIN photodiode, representing the first reported TOF device done in this technology with a PIN detector. Due to considerably extended space-charge region (SCR), the PIN photodiode reduces the capacitance to ~1/4 of a typical PN junction in CMOS. Considering the TOF approach described in the following, a noise reduction of 50% is gained over the same TOF pixel without a PIN photodetector. Furthermore, due to an inherently large SCR, the PIN photodiode achieves 3dB cut-off frequencies in the hundreds of MHz range, independent of the wavelength of the incident light. This in turn ensures excellent photodetection properties in visible as well as in near infrared range.

Apart from the benefits concerning the PIN photodiode, the hereby used sensor circuit successfully copes with a large ratio between extraneous dc light and received modulation signal. The circuit consists of an inverting amplifier which regulates photodiode voltage, mitigating thereby the influence of its capacitance. Current sample and hold circuit serves to sample the background light current and subtract it in the integration phase. This is the key component for the background light suppression whereby the architecture relies on the approach presented in previous publication. However, the influence of the kT/C noise of CS&H introduces a current going into the correlator circuit which in turn reduces the integration capacity. In contrast to previous work, in order to minimize the kT/C noise influence, the integration process is interrupted and the dc photogenerated current is resampled in predefined time intervals. If sampled often enough, this noise source can be practically neglected. This approach together with double metal-insulator-metal (MIM) memory capacitors amounting to 400 fF each, improved the maximal integration time by several orders of magnitude over the previous results done similarly.

In case a high-pixel count circuit is demanded, the power consumption of every unit needs to be optimized to mitigate potential temperature rise of the pixel. Previous best results in this area that was done using similar approach amounts to 900 nW but exploiting a 180 nm CMOS process. Using the same circuit in 0.35 µm CMOS technology, such low power consumption would not have been achievable. In order to keep up with the results the previous results, by means of only one more transistor the pixel circuit is turned completely off when not integrating. This lessens the average power consumption from 5 µW to only 500 nW in typical operation mode.

When it comes to measure the sensor performances, in contrast to commonly used TOF characterization methods, the measurements are carried out with help of a single-mode 4.3 µm optical fiber together with a 635 nm laser source. The optical fiber was adjusted to illuminate only the optoactive area of the pixel under test. To characterize the influence of the background light, an additional dc laser source was coupled by a combiner. Such a measurement architecture ensured the most accurate characterization which is independent of used optics, modulation light source and setup adjustments. Exploiting this measurement setup, the measured standard deviation of 1 cm was recorded if the pixel is illuminated with 10 nW optical power being integrated for 2.2 ms (16 phase steps in total, 137 µs each). Needless to say, if illuminated with more optical power and/or integrated longer, the 1 error reduces accordingly. Furthermore, thanks to the smart control and double MIM capacitors, the maximal measured integration time per single phase step is slightly below 1 ms, being an improvement by the factor of 40 over the previous work. The background light influence on the measurement distance can be neglected even if the dc light is by the factor of 600 larger than the modulation signal.

We can draw the conclusion that in terms of integration time capability, the hereby presented work outperforms the previously reported approach by the factor of 40. Furthermore, the integration of the PIN photodiode enabled the noise reduction, so that the pixel achieves 1 of only 1 cm for a 2.2 ms long integration of 10 nW modulation light. If modulated with stronger light and/or integrated longer, the error can be accordingly reduced to the lower sub-centimeter range. However, we could not compare the results with the previous publications, because of the newly introduced measurement setup. At the same time the pixel power consumption is reduced over 4 amounting typically to 500 nW. On top of this, low production costs of 0.35 µm CMOS, qualify this TOF single pixel to be embedded in a prospective high-count pixel array.
8791-30, Session 7

Optical sensor feedback assistive technology to enable patients to play an active role in the management of their body dynamics during radiotherapy treatment

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Introduction

Patient motion during treatment is well known to be one of the primary factors limiting radiotherapy success, with the risks most pronounced in the modern safety critical complex therapies that promise the greatest benefit. In this paper we describe a real-time visual feedback device designed to enable patients to take an active role in the management of their body position, pose and motion. In addition to technical device details, we present pilot trial results.

Materials and methods

The device uses an in-house developed real-time Fourier profilometry structured light optical sensor system, described by Price et al. [1], as the back-end surface topology measurement technology, although in principle this could be substituted for any system meeting the necessary performance specifications. Our system is composed of three independently operable sensor heads which combine to give a ‘wrap around’ view of the patient body surface (Figure 1).

The device is able to display the deviation of a patient’s current location from a chosen reference surface using three intuitive graphical displays of increasing level-of-detail, selected to match the patient’s personal preference or capability: a basic single parameter ‘traffic light’ display, an abstract colour-coded residual deviation ‘lamina’, or a realistic ‘3D surface’ display (Figure 2d-f respectively). Display technology and user interface design was guided by formal engagement with national patient and consumer representatives.

In the trial data we present here, the displays were calibrated to the displacements normally executed by the patient. These are readily determined in an initial training session, during which the standard deviation (SD) of every measured body surface point from its mean displacement is calculated. We then set the individualized colour-coded target bounds for patients to keep within relative to these values. Body surface points that remain within ±1 SD appear green, +1 to +2 SD amber, -1 to -2 SD pale turquoise, >+2 SD red and <–2 SD blue (Figure 2). Of course, these figures can be easily replaced by absolute values.

A simple experiment was conducted to measure the frame rate, data throughput and latency of the device. We captured and processed 1000 frames measuring a static anthropomorphic phantom, using both single and concurrent triple sensor feeds. The frame rates – the number of measurements each second – were calculated by creating timestamps when each new surface measurement was rendered. The data throughput is then simply the number of bits per measurement (512x512 floating point x,y,z surface point triplets) multiplied by the frame-rate. System latency (the time taken from image capture to reconstructed surface display) was found by comparing a timestamp given to images at capture with the clock time when the derived surface data was rendered.

A pilot study (regional ethics committee reference 10/H1208/5) was conducted to determine whether the use of visual feedback could help radiotherapy patients to control and ultimately reduce the amplitude of their respiratory motion during treatment. The study used ten healthy participants recruited from within The Christie NHS Foundation Trust, each of whom consented to one training session and two study sessions using the feedback device under simulated radiotherapy treatment conditions.

Results

The mean and standard deviations of the full system performance characteristics – that is from image capture, through all processing to display - are shown in Table 1.

Table 2 shows the mean values summarizing the motion signal amplitudes captured during the use of each visual feedback graphical display, averaged across all participants in the study. It shows a decrease in the amplitude of motion when visual feedback is used, but also highlights a reduction in the variability of the amplitude. It shows that motion managed with the lamina display has, on average, lower amplitude than the other visual feedback displays.

Figure 3 shows an extreme example from the dataset, as a case study and also to illustrate a training effect with the device. With visual feedback in session 2 we see the characteristic decrease in respiratory amplitude but an over-compensatory increase in frequency. By the third and final session the relative increase in respiratory frequency is more modest, and similar to others in the study. This progression shows subject adaptation to the devices over a small number of sessions.

Conclusions

We have presented the technical details of a visual feedback device for use during radiotherapy to assist patients in achieving and maintaining setup pose and position to the tolerances operated in clinical practice. The device can operate with single or multiple body surface data feeds, via a hierarchy of display modes. It is characterized by true real time performance at very high spatio-temporal data densities.

Pilot trial results show that subjects did indeed feel comfortable with and benefit from this assistive technology, with detailed abstraction of complex dynamic surface data being the most effective in terms of enabling subjects to control and reduce their respiratory amplitude across their extended body surface.

References


8791-31, Session 7

Technique for real-time frontal face image acquisition using stereo system

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The project is aimed at methods and technology development for the solution of a task 3D geometric reconstruction of a person on a set of photographic images in the systems of noncooperative identification of the person by video cameras. Most of the existing systems for person recognition based on face photograph use two-dimensional images. Such systems have high recognition characteristics when working with so called frontal person photograph. But if a face image is not frontal the quality of recognition becomes significantly worse.

It is necessary to compensate for the effect of a change in the posture of a person (the camera angle) for correct operation of such systems. Some approaches for overcoming this problem are developed. One technique proposes to store a set of person face images at different angles for further using for identification. Such an approach requires the maintenance of a large number of two-dimensional images, which in turn decreases the productivity of the system of recognition. Another techniques try to transform a non-frontal photograph into frontal one by detecting some face features for face orientation estimation and transformation. But without accurate face 3D model recognition is more modest, and similar to others in the study. This progression shows subject adaptation to the devices over a small number of sessions.

Another approach is based on the use of dynamic programming techniques. The preference was given to the second approach, as in the case of problem areas on the surface (for example, homogeneous lighting or shading part of the face) global method expands the zone of incorrect detection of the surface in contrast to the local method. And besides that, the performance of local and global methods of dynamic programming was significantly higher. Another advantage of the local method is the possibility of parallelizing of calculations, using the CUDA technology.

To reach better quality of surface 3D reconstruction additional face
3D data and delivers visual feedback of the current measurement principle. It allows a hand-held, motion-robust acquisition of precise sensor for the electrode position determination. The sensor is based Polhemus is 3.39 mm. The standard deviation of the electrode positions acquired with positions on the head model employing the Polhemus digitization. This data served as ground truth. We then determined the electrode localization of the sources.

We investigated the precision of the standard method for determining the positions can be reconstructed from the acquired EEG data. For this step, the positions of the EEG electrodes have to be known. The standard method to determine the electrode positions employs a digitization pen (Polhemus Fastrak, [Polhemus Inc, Colchester, VT, USA]) which is guided by hand. Each electrode center to be touched by the tip of the digitization pen in a predetermined order and the 3D information about its position is digitally stored. However, this method shows severe drawbacks: Commonly, more than 60 electrode positions need to be determined. This leads to an elongated procedure during which a motion of the electrodes usually is unavoidable – the patient or the EEG equipment might move. Further, such an interactive method is user dependent and hence different environmental parameters, such as varying staff members performing the position measurements, may yield different results.

In more detail: The source locations can be reconstructed from the acquired EEG data. For this step, the positions of the EEG electrodes to have to be known. The standard method to determine the electrode positions employs a digitization pen (Polhemus Fastrak, [Polhemus Inc, Colchester, VT, USA]) which is guided by hand. Each electrode center has to be touched by the tip of the digitization pen in a predetermined order and the 3D information about its position is digitally stored. However, this method shows severe drawbacks: Commonly, more than 60 electrode positions need to be determined. This leads to an elongated procedure during which a motion of the electrodes usually is unavoidable – the patient or the EEG equipment might move. Further, such an interactive method is user dependent and hence different environmental parameters, such as varying staff members performing the position measurements, may yield different results.

An error in the determination of the positions leads to an error in the calculation grid on the basis of the already obtained solutions, - upgrading the method of CUDA - sharing settings with GPU memory and use the CUDA for the detection of the face and eyes.

8791-32, Session 7

Improved EEG source localization employing 3D sensing by “Flying Triangulation”

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With electroencephalography (EEG) a person’s brain activity can be monitored over time and sources of activity localized. This information can be used to allocate brain regions showing deviant activation, for example brain areas causing epileptic seizures. In certain situations only a surgical removal of these brain regions may improve the patient’s health. For this purpose, a precise localization of the responsible sources is crucial. We present a method which highly improves the EEG source localization in comparison to state-of-the-art methods.

In more detail: The source locations can be reconstructed from the acquired EEG data. For this step, the positions of the EEG electrodes have to be known. The standard method to determine the electrode positions employs a digitization pen (Polhemus Fastrak, [Polhemus Inc, Colchester, VT, USA]) which is guided by hand. Each electrode center has to be touched by the tip of the digitization pen in a predetermined order and the 3D information about its position is digitally stored. However, this method shows severe drawbacks: Commonly, more than 60 electrode positions need to be determined. This leads to an elongated procedure during which a motion of the electrodes usually is unavoidable – the patient or the EEG equipment might move. Further, such an interactive method is user dependent and hence different environmental parameters, such as varying staff members performing the position measurements, may yield different results.

An error in the determination of the positions leads to an error in the calculation grid on the basis of the already obtained solutions, - upgrading the method of CUDA - sharing settings with GPU memory and use the CUDA for the detection of the face and eyes.

8791-33, Session 7

3D building modelling from multiple view oblique images

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Applying 3D information has become popular everyday in people’s daily life, especially the applications of 3D building models. Remotely sensed data has obtained great attention for the purpose of generating building information owning to its fast and relatively cheap data collection and processing. Nadir viewing sensors was typically used for detecting buildings. From those data only rooftops of buildings can be detected whilst the façade information is quite limited. Data from terrestrial views are sometimes available, but roofs are not visible from them.

Airborne oblique imagery became a new data source recently, which is taken from aeroplane from tilted angles. Thus they can present the information of both building roofs and façades. The combination of roof and façade information is expected to be valuable for 3D building modelling. With the development of new techniques on oblique data collection system afterwards, oblique images are widely captured and processed over the world. Therefore it is feasible and valuable to develop an automatic way for 3D building modelling from oblique images.

This research aims at developing methods for modelling urban buildings from multi-view airborne oblique imagery. Façade planes and roof planes are extracted first from the original images. As the oblique images are available from multiple views, 3D features such as corner points and 3D line segments are also extracted. An inverse-procedural
model is then adopted to generate the building model integrating building planes and the 3D features.

Image features are analysed and selected to distinguishing building façades from other objects such as roofs or ground. In the proposed method, multiple overlapping images viewing the same direction are required to detect façades facing that direction. Façades are detected adopting evidences of façade texture from single image and height gradient from multiple images. Evidence of façade texture mainly relies on vertical and horizontal structures. The process of looking for this evidence include identifying the directions of vertical and horizontal plane structure in the image patch as well as testing their density. Evidence of height gradient is extracted from the point cloud generated by a dense image matching technique. The point cloud is projected into original images to assign each pixel the height information. Façade hypothesis are generated combining the two evidences in each single image. Since pixels implicitly bear height information, the hypotheses are formed in the object space so that façades are verified by testing the 3D hypotheses from multiple images.

Due to the lack of structures from building roofs, the roof planes are extracted from classified voxels rather than original images. Image features from individual oblique images and 3D geometric features derived from matching in those images are projected onto voxels. Then, they are segmented and classified into buildings, vegetation ground and ground. Roof planes are extracted from voxels classified as buildings.

3D vertical and horizontal lines are also extracted from images. Those features are used as constraints in the modelling process. Till now, procedural modelling has mostly been used for creation of virtual buildings. However, we use the inverse procedural approach to reconstruct the existing buildings from extracted features, façade planes, roof planes and 3D lines. Shapes grammars and components set are initially built. The grammar interpreter automatically determines the selected components and the correct grammar parameters.

A study area of a European city is selected to test the proposed approach, composing buildings with flat roofs, gable roofs and complex combination of them. The reconstructed models are assessed by using the evaluation method in ISPRS benchmark, main focus on the accuracy of plane heights and roof planes. The quality of the segmentation was based on a comparison of roof plane label images. The completeness and correctness of the extracted roof planes are reported on a per-plane basis. The geometric error in planimetry is evaluated by determining the RMS errors of the planimetric distances of the extracted roof plane boundary points to their nearest neighbours on the corresponding reference boundaries. The height difference is derived by comparing two synthetic DSMs generated from the 3D building models, based on the height differences between reference planes and all corresponding extracted planes.

8791-34, Session 8

A study of systematic errors in the PMD CamBoard nano

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Three-dimensional imaging has gained vast attention and popularity in our society. Since the release of the Microsoft Kinect, new markets for 3D imaging beyond the conventional industries such as photogrammetry, computer vision, and robotics are beginning to emerge. Modern 3D spatial imaging methods include laser scanning, stereo imaging or structure from motion, and 3D cameras. The scan time delay, complex moving parts, and high cost of laser scanners limit its usage to advanced user groups, who are interested in scanning static objects. Stereo vision techniques are computationally intensive and require parallax to compute 3D information; this result in bulkier systems and shadows in the 3D data. A single 2D camera can be modified around a point cloud for calculating direction. Façades are detected by using the distance to the object at high frame rates and has the potential of extending the range through varying the modulation wavelength that triangulation based systems are lacking. Every pixel can also provide the distance to the object at high frame rates and has the potential of calculating 3D information on-the-fly. Every pixel is capable of measuring its usage to advanced user groups, who are interested in scanning indoors and outdoors. This paper investigates the systematic errors of this new sensor, which is important for evaluating this sensor’s potential for more advanced operations. To quantify the range repeatability, two PMD nanos were tested independently, and it was discovered that the measured ranges are showing two separate clusters (Figure 1). The reason behind this bimodal distribution in the range measurements is studied in this paper. The nano is also found to be highly sensitive to the object’s reflectivity. Under certain imaging conditions, biases up to 20 cm between adjacent black and white area was measured (Figure 2). Besides having a low planimetric resolution, the accuracy of 3D TOF camera suffers from significant scene-dependent distortions known as scattering and the nano is no exception. Some plane-based scattering tests have been done and the magnitude of the scattering distortion is quantified.

As the PMD is based on CMOS technology, every pixel has its own amplifier and analog-to-digital converter; therefore every pixel can have a different latency for the signal readout. In addition, the nano has a non-coaxial and non-symmetric emitter/receiver dual. This can result in pixels closer to the emitter to measure distances shorter than pixels that are farther away. To study these sensor dependent systematic errors the bundle adjustment with self-calibration approach is adopted. Typical 3D TOF camera calibration usually involves targets to calibrate the lens, principal distance, and principal point offsets, and either signalized targets or planes for calibrating the range errors. In a model-based calibration approaches as such, it is usually assumed that all the pixels share the same intrinsic parameters. In this paper, a modified approach is tested where only conventional 2D camera calibration parameters are assumed to be common among pixels, and range calibration is carried out pixel-by-pixel using the point-on-plane constraint. To ensure proper weighting and accounting for parameter coupling, the extrinsic, intrinsic, and object space parameters are solved simultaneously in the same least-squares adjustment. Results from our calibration showed significant improvements to the camera’s geometric quality over the manufacturer’s calibration. This may not come as a surprise, as the lenses of the nanos on the market are not individually calibrated, but shares the same intrinsic parameters.

8791-35, Session 8

Correction of a phase dependent error in a time-of-flight range sensor

Johannes Seiter, Michael Hofbauer, Milos Davidovic, Horst Zimmermann, Technische Univ. Wien (Austria)

Time-of-Flight (TOF) range sensors have the ability to determine the distance of an object without contacting it. Some of these TOF distance sensors proved to be very insensitive to background illumination such as sunlight. This makes the TOF distance measurement method interesting for industrial as well as automotive applications.

A typical TOF measurement setup consists of a control logic block generating a modulation signal. This modulation signal is emitted by an illumination source and travels to an object, where a portion of it is backscattered to the sensor. The sent and received optical signals are correlated by phase variation of the sent optical signal in dedicated phase steps in each pixel. Afterwards the complex amplitude of the fundamental wave of the measured phase triangle can be obtained by means of the Fast Fourier Transform (FFT). The phase delay of the optical signal due to the finite speed of light matches the angular phase delay of the counterpart and is capable of functioning for parameter calibration, the extrinsic, intrinsic, and object space parameters are solved simultaneously in the same least-squares adjustment. Results from our calibration showed significant improvements to the camera’s geometric quality over the manufacturer’s calibration. This may not come as a surprise, as the lenses of the nanos on the market are not individually calibrated, but shares the same intrinsic parameters.
In the measurement setup we used for determining the phase error, the FPGA generates the modulation signal and the reference clock. While the reference clock is routed directly to the camera chip, the modulation signal is fed to the waveform generator, whereby its phase is even to be minimized to 12.9μrad, i.e. 2.45cm. By minimizing N, a systematic distance error is induced. In case of 16 or more phase steps its influence can be neglected. However, when reducing N to 4 the maximum systematic error increases to a total of 23.95cm at a modulation frequency of 12.5MHz. Its shape is sinusoidal and periodic with N.

This error is caused by undersampling the triangle’s high-frequency harmonics. A high correlation triangle consists of an infinite number of harmonics of which amplitudes fall with 1/n^2. If N is set to m, harmonics from the (m+1)th order upwards will distort the sampled triangle due to aliasing. This effect is negligible for N≥16. However when a system should operate with a smaller N a crucial distance error arises.

In other publications a similar phase dependent distance error was found; however those papers do not use the FFT to acquire the phase shift. The error is corrected by means of a look-up table instead.

Furthermore the error curves acquired in these publications were obtained by measuring real distances while moving objects in front of the sensor. By determining the phase error in other publications, it might depend on other error sources, e.g., contrast of the object, background light, etc. In contrast to that we used a measurement setup where the phase and optical power could be set independently.

Since our measurements showed that the shape of this error is mainly sinusoidal, with (3a) and (3b) two analytic correction equations were introduced to remove the distance error. These equations can easily be implemented by a coordinate rotation digital computer (CORDIC) function to an ASIC device. Such algorithms are often used since they only need a small number of summing and no multiplication units. Only a few constants are needed for the computation, leading to a smaller amount of memory compared to a lookup-table. This subsequently helps to minimize the power dissipation of the range sensor.

All parameters of equation (3a) and (3b) were fitted to match the distance error curve. By subtracting (3a) and (3b) from the distance measurement result, the distance error could be minimized by 79.77% and 89.76% for (3a) and (3b), respectively. The remaining maximum phase error is 25.4μrad which corresponds to an absolute distance error of 4.85cm for a modulation frequency of 12.5MHz for (3a). In case of using the equation (3b) under the same conditions the error can even be minimized to 12.9μrad, i.e. 2.45cm.

In this work we investigate a phase dependent error of a TOF distance sensor. We use a measurement setup with which we can determine the error isolated from other error sources. This is done by varying the phase electrically by means of a signal generator instead of mechanically by the movement of an object. The error is successfully corrected with the aid of an analytic function that can be efficiently implemented in an ASIC by a CORDIC function. Using this approach, the systematic phase error can be minimized by 89.76% from original value, i.e., to a total distance error of 2.45cm.

8791-36, Session 8
Correction of the temperature dependent error in a correlation based time-of-flight system by measuring the distortion of the correlation signal
Michael Hofbauer, Johannes Seiter, Technische Univ. Wien (Austria); Milos Davidovic, Technische Univ. Wien (Austria) and Avago Technologies Fiber Austria GmbH (Austria); Horst Zimmermann, Technische Univ. Wien (Austria)

The number of applications using 3D cameras has steadily increased in recent years. One possible implementation that proved to be highly immune to background light (BGL) is a correlation based time-of-flight (TOF) system [1]. However, these cameras show a temperature dependent error induced by the illumination source. Most of these illumination sources consist of an array of LEDs. This bandwidth and also their rise and fall times are strongly influenced by the temperature of the LEDs. This bandwidth variation results in a temperature dependent error, being particularly a problem during the heat up phase. For optical light sources the measured distance can drift in the range of ~20 cm.

One way to eliminate this error is to measure the length of a known reference path during operation [2]-[4]. This method works sufficiently well in a large operating range. However, it requires additional hardware and therefore causes additional costs. In [2] several correction methods were investigated for a previous generation of our distance measurement sensors. In this work we present an approach to correct this temperature dependent error which does not need any additional hardware for the sensor presented in [1].

The following describes the functional principle of correlation based TOF systems. A light source emits a modulated optical signal. Backscattered light from the scene is then correlated with a reference clock on chip. The phase shift between the backscattered light and the reference clock is directly proportional to the distance of the object. Due to the rectangular shapes of the correlated signals the operation results in a triangular-shaped waveform. The phase of this triangular waveform corresponds to the phase between backscattered light and the reference clock and is therefore proportional to the distance of the object.

If the shapes of the received light signal changes, the corresponding correlation triangle will accordingly alter its shape as well. Simulations of correlation triangles have been done for light signals with different rise and fall times. The light signal was modeled as a rectangular signal that is low pass filtered by a 1st order low-pass with a cutoff frequency f3dB. Increasing rise and fall times result in shifting the correlation triangle and subsequently in shifting the measured distance. Additionally to the phase shift the shape of the triangle changes so that for increasing rise and fall times the triangle becomes smoother. In our approach we make use of this fact to correct the temperature dependent phase shift. The smoother the triangle is, the smaller is the amplitude of the harmonics relative to the amplitude of the fundamental wave. Since the amplitude of this harmonic can be measured during runtime it can be used to correct the temperature dependent error. For this correction method the second harmonic is used, since this is the largest one. Only the even harmonics exist due to the symmetry of the triangle.

The measurement setup that is used to test our approach consists mainly of a control logic (including an FPGA), an arbitrary waveform generator, and a single mode laser source. The FPGA generates a reference path during operation [2]-[4]. This method works sufficiently well in a large operating range. However, it requires additional hardware and therefore causes additional costs. One way to eliminate this error is to measure the length of a known reference path during operation [2]-[4]. This method works sufficiently well in a large operating range. However, it requires additional hardware and therefore causes additional costs. In [2] several correction methods were investigated for a previous generation of our distance measurement sensors. In this work we present an approach to correct this temperature dependent error which does not need any additional hardware for the sensor presented in [1].

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the hereby presented approach will be presented. In contrast to the
original measurement, the corrected version does show a strongly
reduced bandwidth dependent error in a wide range of operation
without requirements for additional hardware. The presented approach
will therefore considerably reduce the temperature dependent error.

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8791-39. Session PS
Easy to use hand-gesture-based optical remote control: basic principle and
recognition results
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In the proposed paper, the concept of an easy-to-use optical remote
control will be introduced and results of different gesture recognition
methods presented. The novel general-purpose remote control we call
“SmartPointer” has data-facelike shape and emits infra-red (IR) light
with a particular spatial pattern. A cost-effective IR-sensitive receiver
unit in the vicinity of the devices to be remotely controlled records the
spatio-temporal intensity changes while a gesture is being carried out.
The SmartPointer is applied intuitively without the necessity to learn
explicit gestures and allows the control of basic functions of different
devices by simply conducting gestures by hand.

The basic principle of the hand-held optical remote control is illustrated
in Fig. 1, the necessary steps to process the recorded data are
depicted in Fig. 2.

For the gesture recognition, the gesture trajectories are appropriately
scaled in size, centered and transformed into gesture representations
based on the trajectories arc lengths in order to eliminate the different
time scaling of rapidly and slowly conducted gestures. The recognition
approach based on normalized arc lengths also helps eliminate the
rather large intra- and inter-personal trajectory variabilities for the same
intended gesture.

In the proposed paper, hand gesture recognition results based on
different matching methods will be compared with one another. The hand
gesture test set comprises 29 different gestures for the control of
different basic device functions (e.g. “start”, “stop”, “up”, “down”, etc.)
as well as numerals and several characters. Results will be presented
derived from experiments with 25 uninstructed test persons aged
7 to 85 years who repeatedly (10 times) carried out each of the
29 gestures. As opposed to traditionally applied methods like linear
and quadratic correlation-based approaches based on the matching of
Cartesian coordinates, better results were achieved by matching the
direction angles of a gesture’s trajectory to a reference. With this
approach an average recognition rate (true positive rate, TPR) over all
7,250 gestures of 90.1 % has been reached so far (investigations are still
in progress). The overall false positive rate (FPR) is 6.0 %. While
many gestures (e.g. “up”, “down”, “right”, “back”) are almost always
correctly recognized (e.g. TPR = 99.5 %), some of the gestures are more
difficult to recognize (e.g. TPR = 80.8 % for the character “g” and TPR =
76.0 % for “y”). This is due to the high similarity of these gestures
with other gestures of the test set, resulting in rather high FPR values
(e.g. FPR = 10.2 % for “g” and FPR = 14.4 % for “y”). Preliminary
results for all 29 gestures are given in Table 1. Optimization work is
still being carried out. One of the findings is that the apprehended
negative influence of age-related tremor on the recognition rate is not
significant.

8791-40. Session PS
2D and 3D documentation of St.
Nicolas baroque church for the general
reconstruction using laser scanning and
photogrammetry technologies combination
Tomáš Kremen, Bronislav Koska, Czech Technical Univ. in
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The total reconstruction of a historic object is a complicated process
consisting of several partial steps. One of these steps is acquiring of
high-quality data for preparation of project documentation. If these
data are not available from previous periods, it is necessary to proceed
to a detailed measurement of the object and to create required drawing
documentation. New measurement of the object brings besides
its costs also several advantages as complex content and form of
drawings exactly according to the requirements together with their high
accuracy.

St Nicolas Church is situated on the Old Town Square in Prague in the
Czech Republic. It is a significant Baroque church from the 18th
century built by Kilian Ignac Dientzenhofer. The church facade and roof
require an overall reconstruction at the moment. A complex historical
building exploration took place in the church on this occasion. The
guide of this exploration was an overall assessment of state of the
object a consideration and planning of its reconstruction. One task
of this historical building exploration was creation of a new drawing
documentation.

Extent of the new drawing documentation was set in the following way:
1. ground plan of the object
2. two horizontal sections of the main tower
3. longitudinal and cross section through nave with projection on both
sides
4. orthogonal view of all four facades
5. ground plan of the roof
6. orthophotos of all facades and nave

All in scale 1:50 with depiction of details bigger than 50 mm.
The last, but the most demanding part of the documentation was the
3D model of the whole church exterior in the same distinction as the
2D outputs.

On the basis of consideration of the object size, position, requirements
on extent, accuracy and particularity of making documentation and
time requirements from the investor it was decided that the main
measurement method will be the 3D scanning supplemented by the
terrestrial and aerial photogrammetry.

The church is situated in the historic center of the town and it is partly
placed into the street front. Standpoints for measurement of the
lower facade parts were chosen in the street front of the church.
Standpoints for measurement of the upper facade parts, the roof and
the places hidden from the ground were chosen on the roofs and
towers of the surrounding buildings. Only the nave was measured
in the interior. The standpoints were chosen on the nave floor and
on the nave galleries. The HDS 3000 scanning system was used for
measurement of the church exterior. The HDS 3000 scanning system
was used as well for measurement of the basic shape of the nave,
because the nave dome is 50 m high. The Surphaser 25HSX scanning
system was used for measurement of the lower parts of the nave
and of the galleries and for measurement of the roof directly from the
church towers.

The DSLR Canon EOS 5D Mark II digital camera with several
objectives was used during the photogrammetric measurement. Both
the object interior and the object exterior were photographed. The
Sony NEX-5 digital camera with an objective with a SONY 16/2.8
SEL fixed focus placed on the UAV Mikrokopter Hexa2 was used for
photogrammetric measurement of the hidden areas on the object
(roofs, various corners on the upper parts of the object).

The measured data from the scanning systems were connected,
cleaned and processed in several softwares for working with point
clouds. Output of this processing were point clouds of the individual
facades and sights of the church interior. These clouds served as a
main data for making a classical 2D CAD documentation. The drawing
documentation of the south facade see Fig. 1 The detail of this drawing
see Fig. 2.

The SmartPointer is applied intuitively without the necessity to learn
explicit gestures and allows the control of basic functions of different
building systems. This is due to the high similarity of these gestures
with other gestures of the test set, resulting in rather high FPR values
(e.g. FPR = 10.2 % for “g” and FPR = 14.4 % for “y”). Preliminary
results for all 29 gestures are given in Table 1. Optimization work is
still being carried out. One of the findings is that the apprehended
negative influence of age-related tremor on the recognition rate is not
significant.

In the proposed paper, hand gesture recognition results based on
different matching methods will be compared with one another. The hand
gesture test set comprises 29 different gestures for the control of
different basic device functions (e.g. “start”, “stop”, “up”, “down”, etc.)
as well as numerals and several characters. Results will be presented
derived from experiments with 25 uninstructed test persons aged
7 to 85 years who repeatedly (10 times) carried out each of the
29 gestures. As opposed to traditionally applied methods like linear
and quadratic correlation-based approaches based on the matching of
Cartesian coordinates, better results were achieved by matching the
direction angles of a gesture’s trajectory to a reference. With this
approach an average recognition rate (true positive rate, TPR) over all
7,250 gestures of 90.1 % has been reached so far (investigations are still
in progress). The overall false positive rate (FPR) is 6.0 %. While
many gestures (e.g. “up”, “down”, “right”, “back”) are almost always
correctly recognized (e.g. TPR > 99 %), some of the gestures are more
difficult to recognize (e.g. TPR = 80.8 % for the character “g” and TPR =
76.0 % for “y”). This is due to the high similarity of these gestures
with other gestures of the test set, resulting in rather high FPR values
(e.g. FPR = 10.2 % for “g” and FPR = 14.4 % for “y”). Preliminary
results for all 29 gestures are given in Table 1. Optimization work is
still being carried out. One of the findings is that the apprehended
negative influence of age-related tremor on the recognition rate is not
significant.
Orthophotos were created on the basis of the acquired images and the space model of the object created from the 3D scanning. This space model was created in the form of a triangular network. The result quality of the created orthophotos depends on quality and particularity of this model.

The last result of the geodetic works was a 3D CAD model of the church exterior. This form of the model was required for creation of visualizations of the planned reconstruction works and adjustments of the church facade. It was a very extensive CAD drawing with a detailed depiction of even very small details both of the building itself and of its decorations. The result model is created by combination of the CAD drawing (walls, window sills, ...) and triangular networks (column heads, statues, window decorations). 3D model is shown in Fig. 3 and its detail in Fig. 4.

Procedures of measuring and creation of 2D and 3D documentation will be presented in the paper. Attention will be focused on their problematic parts like interconnection of the measurements acquired by various technologies, creation of orthophotos and creation of the detailed combined 3D model of the church exterior.

8791-42, Session PS

Relative orientation of videos from range imaging cameras

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In this paper we investigate the determination of camera relative orientation in videos of dynamic scenes involving both object and camera motion from a Time of flight range imaging camera [1]. We present a framework based on integration of the range and intensity data to determine the parameters of the camera relative orientation. We implement a robust adjustment framework to distinguish the static parts of the scene from the independently moving objects.

Range imaging cameras provide range and intensity measurements of the scene for the entire image frame. The spatial resolution and accuracy of the range imaging cameras are limited [2]. However, the simultaneous observation of range and intensity with high temporal sampling can potentially solve the problems in dynamic scene analysis even in cases with low texture in either intensity or the range channel.

In the context of dynamic scene analysis it is essential to differentiate the static parts of the scene from the individual moving objects. The problem becomes very challenging in presence of both camera and object motion. Therefore it is essential to determine parts of the scene which belong to the static background.

In image sequences involving both camera and object motion, the parameters of relative orientation have been computed using feature matching in a robust framework like RANSAC and M-estimators. In addition to feature matching, optical flow has been used in conjunction with Hough transform, global motion constraints and motion segmentation for determining camera relative orientation. In range data, iterative closest point (ICP) has been used for determining the camera relative orientation parameters, however ICP is sensitive to outliers.

Our approach is based on integration of the optical flow and range flow constraints for computing the camera relative orientation. The optical flow is based on the brightness constancy constraint, while the range flow relates the motion of a rigid body with the change in range. By combining optical flow and range flow equations with image motion under perspective projection, we obtain a relation between the 3D velocity of each object point with the intensity and range derivatives. Consequently relating the camera motion parameters with the movement of each object point we get a linear relationship between the 6 parameters of the camera relative orientation and the temporal and capstal derivatives of the intensity and range. Each pixel in intensity and range provides one constraint for determining camera orientation parameters. We solve these constraints for the entire image using a robust adjustment to remove the effect of the outliers which are mainly the independent moving objects.

We present the results from our algorithms on scene involving both the camera motion and the independent moving objects. The scene is captured using an SR3000 range imaging camera with a resolution of 144x176 pixels. Results show that we are able to determine the orientation parameters even in instances with low texture in intensity or the range channel. Furthermore the robust adjustment framework enables to recognize the presence of the independent moving object thus differentiating the static background from the moving objects.

We show 3 examples: one containing a scene with moving object and a static camera. The first example demonstrates especially the computation of the flow [3]. The second example contains a static scene observed by a moving camera. This demonstrates the inclusion of the motion constraint in the flow estimation. The final example demonstrates the robust framework for differentiating between the camera and object motion.

Automated Visual Inspection

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8791-64, Session PS

Fast car/human classification methods in the computer vision tasks
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Recently a trend toward greater intellectualization of modern video surveillance systems has observed. One of the most important tasks, which such systems should solve, is the automatic identification of moving objects types. In urban areas the main classes of such objects are human and vehicles. At the present time a large number of papers devoted to this topic are published. The approaches which are used there can be conditionally divided into two groups. Methods of the first group are common methods of the object classification, and are not tied to specific classes. The appearance of the object is described by a set of descriptors (histogram orientation gradient [1], the descriptors of special points, SIFT [2] and SURF [3], etc.), and then in terms of the consequence of these descriptors a decision is taken about the type of the object according to a pre-imd procedure of training on the marked video database. The advantage of this method is the simplicity of introduction of additional classes, the disadvantage is the computational complexity. Methods of the second group are specific to the problem of the car/human/other classification. The used features of objects allow us to divide these classes of objects effectively. The advantages of these methods are the computational efficiency and ease of implementation. The selection and quantity of the used features vary within a broad range. So, in the papers [4] and [5] thirteen features in total are described, including the measure of the variability of the object shape in its lower-thirds (high variability is typical for people in the movement of the legs when walking, and is not typical for cars). In the paper [6] two criteria describing ratios of sums for vertical, horizontal and diagonal contours are used. Features based on the contours showed higher level of robustness regarding the good or poor quality of the primary object detector compared with the rest of the features.

In this paper four statistical criteria are presented. Integration of their values allows to get efficient automated car/human classification (cyclists and a group of people are also included in the “human” class). As the features used for the object classification, eight statistics calculated by approximated Sobel mask of the image derivative were chosen. These eight statistics depend on the length, contrast and relative position of significant brightness difference of the object image in three directions (vertical, horizontal or diagonal). According to the eight statistics four one-dimensional statistical criteria are built. They describe the ratio of the lengths and the contrast of vertical, horizontal and diagonal circuits, and also the ratio of the second central moments for the horizontal and vertical circuits.

Each of the four statistical criteria makes it possible to assess whether the selected object belongs to the specified class or not. Bayes’ theorem allows us to estimate the probability that the object belongs to the specified class by integration of the results of the four criteria. Using Bayes’ integration or increases the accuracy and reliability of the classification. Also classification methods such as linear classification or logistic regression are implemented and compared with Bayes’ integration.

Thus, on the one hand, the selected features effectively implement decisive rules car/human/other. On the other hand, Bayesian integration of four different criteria allows reducing false positive and false negative probabilities to CCA 0.03.

References

8791-65, Session PS

Identification of bacteria species by using morphological and textural properties of bacterial colonies diffraction patterns
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Statistical analysis of bacteria colonies Fresnel patterns recorded in the optical system with converging spherical wave illumination was proven to be suitable for highly effective bacteria species classification and identification. The method was verified to be cheap comparing to other techniques and fast comparing to traditional methods. It also does not require expert knowledge nor expensive reagents and therefore it can be widely used in microbial diagnostics, food control or environment contamination monitoring.

The Fresnel patterns of bacteria colonies naturally contain set of the diffraction rings, where the number, size and spatial structure of these rings depend on the bacteria species and are unique for each species. In the previous research of the bacteria species identification method diffraction patterns were partitioned into 10 rings (concentric annulus-shaped zones) of equal thickness. This approach will be further called fixed ring ROI (Region Of Interest). Mean value and standard deviation of pixel intensities within each fixed ring ROI are further used as features for classification. As ROIs are fixed rings and features are basic statistics of pixel intensities within each ROI the method does not allow for interpretation of obtained results. Therefore the proposed method has been extended with morphological ROIs of the diffraction patterns in place of currently used fixed rings. This approach will be further called morphological ROI. Morphological properties of the image are simply shape properties of the image and so in our case morphological ROIs are intrinsic sets of the diffraction rings of the Fresnel patterns.

Algorithmic techniques that allow for shape detection are used for finding the morphological ROIs. Naturally existing shapes within each diffraction pattern are detected and used as ROIs in further analysis instead of fixed ring ROIs. Morphological ROIs contain valuable information about spatial structure of the patterns which was lost by fixed ring ROIs. For each morphological ROI numerical characteristics are calculated. Those characteristics are morphological features describing shape and texture features describing surface of the ROIs. Those features are used instead of mean value and standard deviation of pixel intensities in further statistical analysis.

Two reasons can be given for modification from fixed ring ROIs to the morphological ROIs. The first was to give possibility of interpretation of the pattern characteristics identified by visual inspection of the Fresnel patterns of bacteria colonies, while latter was to compare classification performance assessment between two approaches: fixed ring ROIs with basic statistical features and morphological ROIs with possible to interpret morphological and texture features.

The method workflow includes Fresnel patterns recording in the optical system with converging spherical wave illumination. Pattern recording is followed by image processing that consist of pattern region marking, partitioning into ROIs, pixel intensities normalization and feature extraction. After that the statistical analysis based on feature selection, classification and classification performance assessment method is performed. Feature selection was performed with ANOVA (Analysis of Variance). Classification models were built with use of LDA (Linear
Discriminant Analysis), QDA (Quadratic Discriminant Analysis) and SVM (Support Vector Machine) classifiers.

Cross-Validation technique was used as classifier performance assessment method.

The examination was performed on various bacteria species (Salmonella enteritidis, Staphylococcus aureus, Staphylococcus intermedius, Escherichia coli, Proteus mirabilis, Pseudomonas aeruginosa and Citrobacter freundii). For each of the species under study we acquired about 50 samples.

Optical-electronic system for express analysis of mineral raw materials dressability by color sorting method

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Color sorting method is the most versatile of the radiometric enrichment methods, and is widely used in processing of mineral resources, solid domestic and industrial waste, as well as agricultural crops. This method of minerals enrichment is based on the use of real-time analysis of the minerals optical characteristics like color, shine, transparency and reflectivity by advanced videoinformation systems.

Though the use of machine learning methods in existing color sorters, they are mainly effective for simple tasks: in the case of a pronounced color contrast of mineral objects, sorting by several color tones, or sorting by homogeneity of one of the colors. However, this promising method doesn’t work correctly and doesn’t allow achieving the high sorting quality if necessary to distinguish of subtle color shades, or to separate minerals with complex surface or internal structure (e.g. samples with relief structure, which make the secondary shadows in the picture, or partially transparent and heterogeneous mineral samples).

Commonly disregard for singularities receiving and processing of color images (e.g. color interpolation methods) as well as features of the used color models (RGB, YUV, HLS etc.) become reasons of mentioned disadvantages of color sorting method. Singularities receiving and processing of color images determine the range of possible for recognizing color shades for each specific separator. Features of the used color model identify the position and breadth of the border for distinguishing colors.

Moreover, though the active using of color sorting method and different kinds of mineral processing equipment for separation of solid minerals various types, still there are no dressability estimation methods (except for direct testing equipment) as well as selection criteria in favor of one or another sorter for solving a particular enrichment task.

This paper deals with description of the organization principles of mineral raw materials dressability by color sorting method.

Feature of the proposed solutions is that the analysis of dressability is performed simultaneously using of three color models: RGB, YUV and HLS. The color model most suitable for sorting of particular mineral raw materials type is then determined. In addition besides of the “color” the possibility of using others selective features that characterize the minerals surface structure is analyzed.

The paper also is paid attention to the principles of the working area illumination and to color settings technique for express analysis organization. Mentioned factor are important for effective analysis of different mineral raw materials types and for choosing the optimal kind of separation equipment.

Experimental studies of the proposed analysis principles were conducted using specimens of gold ore on a specially developed prototype.

Pattern coding strategies for deflectometric measurement systems

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Background:
Fraunhofer IOSB in cooperation with the KIT Vision and Fusion Laboratory is developing several applications for deflectometric surface geometry measurement. Applications range from the reconstruction of coin-sized metal parts to the inspection of full-sized cars and the utilized algorithms and technology varies accordingly.

Depending on the application different post-processing steps allow for the detection of local or global defects, provide a reconstruction of the surface geometry or can match the data against a reference model[1]. But before further processing the measurement data, the question must be asked, as to how reliable is the measurement.

Regardless of the application, a deflectometric measurement is always based on a structured code pattern for position coding. A camera observes the reflection of these code patterns on the surface under inspection and the decoded pattern allows to extrapolate the optical path between camera and display device. This method requires the surface under inspection to be a functional part of the optical path.

However, as the optical characteristics of the surface are unknown beforehand, this contributes significantly to the uncertainty of the measurement.

Disturbances of the code pattern come from both photometric and geometric distortions as well as obvious noise sources such as sensor noise and stray light. Most of these error sources can be eliminated by the right choice and configuration of the equipment and parameters of the coding method. However, some error sources are inherent to the coding method itself[2].

Phase-Shifting:
Phase-shift coding has proven itself in applications from synthetic aperture radar to magnetic resonance imaging and is also the coding method of choice for deflectometry. Phase-shift coding employs a sequence of incrementally shifted sine patterns and, as its name implies, evaluates the phase of the signal. The used phase-shift coding for deflectometric measurement is in many respects beneficial. First, it is relatively insensitive to changes in the amplitude of the signal, such as it occurs with staining of the specular surface. Second, the use of sine patterns makes it, up to a certain degree, insensitive towards blurring of the pattern. Despite the robustness of phase-shift coding, there are still many sources of error to consider.

Previous work addressed some specific sources of error, e.g., Fischer[3] evaluated the influence of the camera sensors characteristics on the noise of the measured phase signal, or Hibino et al.[4] investigated the impact of nonlinear distortions of the sine patterns, to name a few. We provide an overview of these previous work and focus on the parameters of a deflectometric setup with the objective to give practice-oriented guidelines for optimizing the deflectometric data acquisition.

On the other hand, some applications require to trade off one parameter to maximize another, e.g., obtain a higher accuracy in exchange for a longer data acquisition. We show examples of use cases and discuss the prospects when optimizing for a specific parameter.

Phase-Unwrapping:
For further optimization we will discuss the closely linked task of phase-unwrapping the initially ambiguous phase data. There are numerous approaches to the problem of phase-unwrapping as each application presents different challenges for the algorithms[5]. We will discuss these methods with focus on the application in deflectometry.

Additionally, we will evaluate these strategies with real world examples.

REFERENCES:
Technique for positioning moving binocular vision measurement system and data registration with ball target

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With the rapid development in computer vision, 3D measurement, especially for large-sized work-piece, has become more and more popular. However, there exist several problems when applying machine vision in industrial measurement. Firstly, the viewing angle of camera is limited by camera lens and chip so that the vision system can only view part of work-piece. Even using multi-camera measurement system can only broaden limited viewing angle. To get the overall surface information of an object requires measuring the object from different views. Data registration can be realized by calibrating motion relationship between different views. The point clouds obtained at each position must be transformed into global coordinates from each local coordinate so that these point clouds can be patched together to generate final data set.

At the moment, there are several ways to unify local coordinate into global coordinate and get overall surface information of the object. Firstly, utilizing rotary table or controlling displacement by use of precise mechanical equipment. This method has higher splicing precision but poor adaptability, which makes it difficult to realize the online detection. Secondly, labeling marked points on the object. This is the common method that is not suitable for soft and vulnerable objects. Besides 3D information of the object under the marked points is not available so that a later surface fitting processing has to be applied. Another way of unifying coordinate is introducing transit and level calibrating device or additional visual system, but it is also expensive. At present some researchers introduce intermediary target to unify global coordinate. The most common used target is planar target, which is easily made and used. However, it leads to large deformation when the perspective angle is too large or even unobservable, which limits the registration accuracy and range measurement.

This paper proposed a ball-based intermediary target technique to position moving machine vision measurement system and to realize data registration under different positions. Because of ball has special contour features such as continuity, it is widely used in multi-camera network calibration. It is more flexible and can eliminate planar target’s problem that deformation appears when the perspective angle is too large. However, Balls are projected onto the image as ellipses, not standard circles. The center of the ellipse is not coincidence with ball center’s perspective image, which leads to position error of ball center and then leads to position error of the camera.

The paper is organized as follows. Section 2 gives the basic principles of ball-based intermediary target technique. The simulation results are discussed in detail in Section 3. Two experiments, a positioning accuracy analysis of ball center and MVMS are described in Section 4. Section 5 concludes the paper.

On the reduction of the lateral localization uncertainty of targets inside a LIDAR beam

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In the proposed paper, the two methods will be used to perform measurements from a LIDAR sensor to the target, which is moving through a beam. In this method, the target velocity components are perpendicular (lateral) and parallel (axial) to the beam axis and are determined separately. While the axial velocity component can be derived directly from the distance measurements, the lateral one is calculated from the width of the beam at the measured distance and the time the target needs from entering (first detection) to leaving (last detection) the LIDAR beam. The target’s velocity vector is then used as measurement input for the Kalman-based tracking algorithm. The second method makes use of the echo signal and enables the consecutive measurements of the target, which is moving through a beam. The resulting signal amplitude function and the known LIDAR beam profile are then correlated in order to finally deliver the velocity vector of the target. However, this method is receptible to the reflectivity function of the target, which depends upon the angle of incidence, the surface shape and roughness. When the beam profile is rotationally symmetric across the LIDAR-beam axis, both methods deliver information from which lateral side the target entered the LIDAR beam. However, this information can be provided by the sensor network. In the proposed paper, the two methods will be investigated for a LIDAR beam (full-angle beamwidth 2 × 2°) and different targets and target velocities. The achievable improvements in lateral localization uncertainty compared to the classical approach with the target position assumed to be located on the beam axis will be quantified. The results will be validated by those from experimental measurements.
is a method that can recover the orientation and reflectance values of the inspected surface from multiple scene acquisitions, under varying illumination directions. This method has the advantage, over conventional stereovision, that it does not incorporate the solution of the correspondence problem and thus it allows the pixel surface reconstruction with significant time efficiency and reduced computational requirements.

The developed system is composed of a low-cost off-the-shelf camera with 640x480 pixels resolution, and eight light emitting diodes. The selected camera has manual focus, permitting the acquisition of images in manual variation, the colors are addressed through the photometric stereo algorithm. The dimensions of the developed system are height = 32.20 mm, width = 27.70 mm and length = 39.90 mm, making it one of the smallest photometric stereo systems reported in literature. The light emitting diodes are controlled via an Arduino nano board and are synchronized to the image acquisition through software control. Moreover, the photometric stereo system is encircled into a cylindrical tube, which was designed taking into consideration the field of view and the working distance of the camera and thus no ambient light is present during the measurements. The direction of illumination is recovered by locating the reflection or the brightest point on a mirror sphere, while a flat-fielding process compensates for the non-uniform illumination. In the current version of the system the classical photometric stereo technique is applied in order to recover the three-dimensional surface normals, while the Frankot Chellappa integration method is used for the depth data recovery.

This miniature device, although could easily be treated as a handheld device, was designed for mounting onto a robotic gripper. One problem that had to be encountered was the estimation of the optimal image plane position, which derived from the flush structure of many fabrics. The camera does not present any focus control functionality and the depth of field is very shallow due to the macro mode operation. For these reasons, a focus metric is evaluated in order to automatically define the proper gripper position. This metric is based on the Brenner’s focus measure. Its performance has been compared against other well-accepted focus metrics, like the energy measure, the energy of Laplacian and others, presenting equivalent results on the extraction of the optimum image plane, but with reduced time requirements, up to almost four times fold.

The functionality of the developed photometric stereo system has been also been tested with objects that have been used in similar works, presenting equivalent results to the more bulky systems reported in these works. Its small size makes the developed system a very promising tool for applications with space restrictions, like the quality control in production lines or scene interpretation based on structural information, or in applications where easiness in operation and lightweight are required, like those in the Biomedical imaging field, and especially in dermatology.

8791-51, Session 10
Multi-view line-scan inspection system using planar mirrors
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We demonstrate design, setup, and results for a line-scan stereo image acquisition system using a single area-scan sensor, a single lens and planar mirrors attached to the acquisition device. The inspected object is moving relatively to the acquisition device and is observed typically under two or more different angles at the same time. Depending on the specific configuration it is possible to observe the object under a straight view, i.e., looking along the optical axis, and one or more skewed views. We consider configurations with two and three views: (i) straight mirrors, i.e., with the surface being parallel to the optical axis, and (ii) mirrors tilted with respect to the optical axis. In both cases, the mirrors are oriented parallel to the transport direction. The relative orientation between an object and the acquisition device automatically fulfills the epipolar constraint typically required in stereo vision. This means, an alignment of images by epipolar rectification is not necessary and the search of stereo correspondence is directed along image columns oriented in transport direction.

In the case where the mirrors are oriented parallel to the optical axis, the optical paths of the skewed and the straight views remain the same, so that we can consider both the skewed views and the straight view for imaging. Thus, using two skewed mirrors, we obtain three focused images of the inspected object, each containing one pixel of the surface. Although, the depth resolution of this setup is limited by the size of the chip, as for larger depth resolutions the mirrors need to be placed further away from the optical axis, resulting in the image being projected further away from the center of the chip.

Tilting the mirrors allows for an increase of the stereo baseline and results in a significant increase of the depth resolution. Theoretically, in this setup the depth resolution is not limited by any hardware factors such as the chip size or the lens focal length. By placing and tilting the mirrors appropriately one can achieve almost any large depth resolution. One possible disadvantage of this approach is the gradual defocusing of the straight view, which increases with the tilt of the mirrors. Although this could pose a problem in setups where the straight view needs to be considered, the defocusing is not so dramatic for most reasonable mirror tilts and thus the straight view can be used at least as a reference. Note that for symmetrical tilting of the mirrors, both skewed views remain in focus all the time.

The choice of sensor lines to be extracted from the CMOS chip depends on various factors, such as the number, position and size of the mirrors, the optical and sensor configuration, or other application-specific parameters such as the desired depth resolution. The relationship between the configuration and the achievable depth resolution is derived theoretically. The, an appropriate set-up for the inspection of printed matter and small parts is presented. The image processing pipeline applied to the extracted sensor lines is explained in details.

The effective depth resolution achieved using off-the-shelf components is approximately ten times smaller than the spatial resolution for straight mirrors and two times better than the spatial resolution for tilted mirrors. Practical results are provided for the analysis of small deformations of printed matter, industrial inspection of small parts and optical variable devices, i.e. holograms.

8791-54, Session 10
Reconstruction of specular surfaces via probabilistic voxel carving
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Reconstruction of strongly specular surfaces based on a single or multiple camera images is an inherently difficult problem, which has not yet been solved in a general case. Most known methods impose strong limitations on either the observation conditions or on the properties of the reconstructed surface. For example, a setup of a most well-known deflectometric inspection requires that the camera remains fixed with respect to the object during multiple shots, while several patterns are demonstrated on a calibrated screen nearby.

Despite those limitations, the deflectometry is becoming the method of choice in many applications, such as the inspection of large reflective. The extreme sensitivity of the specular reflection to the changes in the surface gradient allows deflectometry to compete in accuracy with much more expensive interferometric measurements.

In our work, we attempt to systematically build a framework for a more general case and extend the quality of deflectometry to the reconstruction of moving objects (such as car bodies on a conveyor belt). Another immediate application would be in the situations where only static patterns are available (which is e.g. the case in the emerging infrared machine vision, where fast and inexpensive variable pattern generators are not available).

Our approach is based on the recently proposed Normal Vector Maps (NVM) [1] used within a context of a consistent probabilistic voxel carving framework [2]. The NVMs based on multiple camera observations and the a priori known surface properties such as continuity, smoothness, or even a CAD model, enter a non-linear factorized energy functional, defined over a voxelized volume. The optimization problem is then solved using the loopy belief propagation (LBP) algorithm, accounting for the specific of this higher-order Markov Random Field (MRF). The result is the most probable surface,
which may in principle be disconnected, contain holes, self-occlusions, etc.

In our paper, we start with a brief introduction of the measurement setup, then provide some details on the construction and use of the NVMs. Next, we discuss the structure of the energy functional and its properties, and give an overview of the implemented LBP scheme. Finally, we present the first results obtained with the synthetic scenes and quantify the runtime and the accuracy of the algorithm.


8791-55, Session 11

Pattern and form recognition of statistically distributed defects on functional optical surfaces

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The inspection of the surface quality of optical components is an essential characterization method for high power laser applications. We report about two different mapping methods based on measurement of Total Scattering (TS) and phase contrast microscopy. The mappings are used for the determination of the defect density distribution of optical flat surfaces. The mathematical procedure from data points to a defect area and to the form of objects will be illustrated in details. The involved differential operators and the optimized sub routines adapted to a large number of defects will be underlined.

For the decision about the form of the objects, a parameter set including the "fill factor", "edge ratio" and the "polar distance" will be involved. For the decision about the form of the objects, a parameter set including the "fill factor", "edge ratio" and the "polar distance" will be involved. For the decision about the form of the objects, a parameter set including the "fill factor", "edge ratio" and the "polar distance" will be involved.

The derived parameter set is used to define a feature vector for each defect. The feature vector is used to discriminate materials work in the near-infrared spectral range (NIR), as the reflected light in this range gives information on the molecular bindings. If a precise distinction between different materials is needed, hyperspectral cameras are usually acquired. Here, spectral and spatial information makes hyperspectral imaging systems also applicable to automated visual inspection tasks.

While the high spectral resolution provided by the high number of spectral channels is the main advantage of hyperspectral imaging systems, the coarse spatial resolution and low frame rate are its drawbacks. When using hyperspectral images in automated visual inspection systems, light reflected by different objects or several parts of a single object is mixed due to the high speed of the objects and the low frame rate of the camera. Hence, different objects and materials are usually found in the field of view of one pixel, which reduces the capabilities of an inspection system. Thereby, many industrial constraints concerning speed and resolution cannot be met.

By adding a multispectral or monochrome camera, which meets the requirements for resolution and frame rate, the desired spatial information can be obtained. The additional image is fused with the hyperspectral image and a classification in the required spatial resolution is possible. In this paper, a new method for fusing images of different spectral and spatial resolution is proposed. The image signals are regarded as mixtures of different material signatures and combined in a common model. The problem of mixing and its inversion are known as spectral mixing and unmixing from the field of remote sensing. The mixing coefficients which represent the contribution of each material to the overall signal are assigned to each pixel. By the spectral unmixing procedure, the mixture is attempted to be inverted and, as a result, the relative contribution of each material is determined. The mixing coefficients can be used as feature vectors for a subsequent classification process. Spectral unmixing is based on the assumption that the reflected spectrum of a pixel is composed of a mixture of different signals originating from different endmembers. These endmembers are usually pure materials. In conventional spectral unmixing, the mixing of signals takes place only within each pixel. This approach will be extended by spatial unmixing. This allows images with different spatial resolutions to be merged.

There are different mixing models which are based on different mixing assumptions. One of them is the linear mixing model, which assumes that the observed signal is a linear combination of the endmember signals. Another model is the non-linear mixing model, which does not assume a linear combination of the endmember signals. In this paper, we will focus on the linear mixing model.
constraints. The linear mixture model is the simplest approach, which assumes different signals emitted from various materials to be additively superimposed. Nonlinear mixing models like the bilinear mixing model account for other effects like scattering and multiple light-material interactions. The mixing models are extended by additional constraints and relations to represent also spatial mixtures and to combine individual images acquired with different spectral and spatial resolutions into one common model. Here, the specific spectral sensitivity of each channel of the cameras is modeled as a linear combination of spectral channels in a base resolution. The spatial resolution of a sensor is affected by the region, out of which a signal of a pixel is composed and linked to the point-spread function of the sensor.

The extended model can be used to jointly unmix image signals of different spatial and spectral resolutions. Thereby, an improvement of the unmixing result can be achieved in applications where there is sufficient spectral information, but too low spatial information. The proposed method is fully based on the mixing model which has been established in remote sensing applications for object classification. Hence, many remote sensing methods can also be used for analysis of the material composition in visual inspection.

The proposed method is evaluated with simulated and measured data yielding a significant improvement of the unmixing result. Linear and nonlinear mixing models are investigated to demonstrate their advantages and disadvantages regarding the use in the extended model. The subsequent classification using the mixing coefficients are compared to other classification approaches, which do not require a spectral unmixing procedure.

8791-58, Session 11
Model based image restoration for underwater images

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The inspection of offshore parks, dam walls and other infrastructure under water is expensive and time consuming, because such constructions must be inspected manually by divers. Underwater buildings have to be examined visually to find small cracks, spallings or other deficiencies. Such inspection tasks are not only time-consuming and complex but also involve human inspection divers.

Automation of underwater inspection depends on established water-proved imaging systems. Most under water imaging systems are based on acoustic sensors (sonar). The disadvantage of such an acoustic system is the loss of the complete visual impression. All information embedded in texture and surface reflectance gets lost. Therefore acoustic sensors are mostly insufficient for these kinds of visual inspection tasks.

Imaging systems based on optical sensors feature an enormous potential for underwater applications. The bandwidth from visual imaging systems reach from inspection of underwater buildings via marine, biological applications to exploration of the seafloor. The reason for the lack of established optical systems for underwater inspection tasks lies in technical difficulties of underwater image acquisition and processing. Lightening, highly degraded images make a computational post processing absolutely essential.

Problem of underwater imaging

The increase of camera based automation solutions in industry, surveillance and research in the last decade is outstanding. But this development does not reach underwater inspection tasks. The reason therefore apart from technical problems like water-resistance and energy supply is poor visibility and hence highly degraded images. Degradation of imaging results is basically caused by three factors.

Absorption: The energy of a light ray traversing a column of water is attenuated by water itself and small particles within the water. This mechanism is called absorption. The loss of energy of light rays crossing water, effects low intensities of imaged scene objects. Light attenuation by absorption causes also changes of imaged colors. Wavelength dependent absorption of light causes color shifts and thus bluish or greenish images.

Scattering: Absorption is not the only form of light-water interaction. Light rays interact with water and its inherent particles also in form of scattering. Scattered photons get deflected into another direction. Thus a single light ray in a designated direction gets attenuated by scattering but the energy within the light field does not get lost. Scattering causes two effects with respect to imaging. First, rays coming from an object surface get fanned out and consequently the image gets blurred. On the other hand light rays reach the optical sensor which were never reflected by the object surface but scattered by water. In consequence the resulting image receives an additional intensity increase without additional information about the scene objects. This additional image intensity appears as bright haze.

Particles: Particles located in water degrade the quality of optical imaging. As seen, small particles are an issue for absorption and scattering. However, big particles -- particles which are much bigger than the wavelength of the interacting light ray -- degrade the quality of images in other way. Parts of scene objects are covered by such particles. Particles within water diminish the signal-to-noise-ratio (SNR). For all image restoration tasks the signal-to-noise-ratio limits the possible quality of restored images. As a consequence the density of large particles determines the capabilities of optical underwater imaging systems.

Model based image restoration

In this article a novel model based image restoration approach will be presented. It is based on the ‘Dark Channel Prior’ approach (He, Kaiming; Sun, Jian; Tang, Xiaoou 2010: Single Image Haze Removal Using Dark Channel Prior. In: IEEE Trans. Pattern Anal. Mach. Intell.) and adapted to the given application problem. The presented method for model based image restoration combines adapted one-shot depth estimation, a color correction approach and a distance dependent deblurring filter.

Imaging Model: Basis for the image restoration is an efficient but physical model of the radiative transfer through the medium water. The image intensity at a given pixel can be expressed by this model in a closed-form, where the parameters of the model are physical quantities like the reflectance coefficient, the scattering coefficient and the distance to the imaged object surface.

One-Shot Depth Estimation: The basic ideas of the depth estimation are the assumptions of ‘Dark Channel Prior’. Adapting these ideas to the conditions of underwater imaging is the second part of this article. The assumption of the dark channel prior is that in each image patch there is an image point with no signal, i.e. only the intensity of the backscattering component is imaged. With this assumption and an adapted wavelength dependent compression step it is possible to get an estimation of the distance to the object (depth map).

Color Correction: With the help of the model and the estimated depth map it is possible to invert the model to reconstruct the origin colors. This reconstruction is ill-posed and must be regularized. A regularization term will be introduced in this article.

Depth Dependent Image Deblurring: The greater the distance to the imaged object surface the wider the point-spread-function (PSF). Consequently the response characteristic of the imaging system is not shift invariant. Thus a mechanism different from simple inverse or wiener filtering must be implemented. Therefore a deblurring approach is applied on the image for each depth value of the estimated depth map. In a following image fusion step the reconstructed and color-corrected image is computed.

8791-59, Session 11

Automated real-time search and analysis algorithms for a non-contact 3D profiling system

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The purpose of this research is to develop a new means of identifying and extracting geometrical feature statistics from a non-contact precision-measurement 3D profilometer. Autonomous algorithms have been developed to search through large-scale Cartesian point clouds to identify and extract geometrical features. These algorithms are developed with the intent of providing real-time production quality control of cold-rolled steel wires. The steel wires in question are non-contact stress-straining steel wires for reinforcement members. The geometry of the wire is critical in the performance of the overall
For this research a custom 3D non-contact profilometry system has been developed that utilizes laser displacement sensors for submicron resolution surface profiling. Optimizations in the control and sensory system allow for data points to be collected at up to an approximate 400,000 points per second. In order to achieve geometrical feature extraction and tolerancing with this large volume of data, the algorithms employed are optimized for parsing large data quantities. The methods used provide a unique means of maintaining high resolution data of the surface profiles while keeping algorithm running times within practical bounds for industrial application. By a combination of regional sampling, iterative search, spatial filtering, frequency filtering, spatial clustering, and template matching a robust feature identification method has been developed. These algorithms provide an autonomous means of verifying tolerances in geometrical features. The key method of identifying the features is through a combination of downhill simplex and geometrical feature templates. By performing downhill simplex through several procedural programming layers of different search and filtering techniques, very specific geometrical features can be identified within the point cloud and analyzed for proper tolerancing. Being able to perform this quality control in real time provides significant opportunities in cost savings in both equipment protection and waste minimization.

In order to handle real-time data analysis a significant portion of the computational search algorithm is handled by the graphical processor unit (GPU). By parallel processing search iterations and effectively spreading the sampling of data, algorithm run times are greatly reduced. In order to further reduce algorithm run times, repeating geometrical features use exponential smoothing to predict the next geometrical features expected position. By doing so, the search algorithms initializations begin very close to the actual search solution. Along with these efforts to minimize search algorithm run times efforts have been taken to reduce the computational load of the templates that are used in identifying geometrical features. In order to create a light weight template for geometrical features, the templates are made in a branching procedural scheme. Each geometrical feature in consideration is broken down into several geometrical attributes. The shorter runtime geometrical attributes such as frequency variations are used first most to identity potential geometrical features. Once a potential geometrical feature is established, several different geometrical attributes are tested to see if there exists a match between the template and the considered region.

These efforts to improve feature recognition in 3D Cartesian point clouds have broader impacts in computational surface analysis and metrology than the current applied research of cold-rolled steel wires. By developing a light weight and accurate means to autonomously recognize features in 3 dimensional space, many opportunities are made available in computer visioning systems and automated surface metrology analysis without having to limit data density.

8791-60, Session 12
A semi-automatic measurement system based on digital image analysis for the application to the single fiber fragmentation test
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The computational prediction of the effective macroscopic material behavior of fiber reinforced composites is a goal of research to exploit the potential of these materials. Besides the mechanical characteristics of the material components, an extensive knowledge of the mechanical interaction between these components is necessary in order to set-up suitable models of the local material structure. For example, an experimental investigation of the micromechanical damage behavior of simplified composite samples is necessary to understand the mechanisms, which causes matrix and interface damage in the vicinity of a fiber fracture.
To realize an appropriate experimental setup, a novel semi-automatic measurement system based on the analysis of digital images using photoelasticity and image correlation was developed. Applied to specimens with a birefringent matrix material, it is able to provide global and local information of the damage evolution and the stress and strain state at the same time. The image acquisition is accomplished using a long distance microscopic optic with an effective resolution of two micrometer per pixel. While the system is moved along the domain of interest of the specimen, the acquired images are assembled online and used to interpret optically extracted information in combination with global force-displacement curves provided by the load frame. The illumination of the specimen with circularly polarized light and the projection of the transmitted light through different configurations of polarizer- and quarter-wave-plates enables the synchronous capturing of four images at the quadrants of a four megapixel image sensor. The fifth image is decoupled from the same optical path and is projected to a second camera chip, to get a non-polarized image of the same scene at the same time.
The benefit of this optical setup is the opportunity to extract a wide range of information locally, without influence on the progress of the experiment. The four images are used to obtain information on the stress distribution based on photoelasticity, while the fifth image delivers the local strain as outcome of an image correlation algorithm and enables the observation and documentation of the visible damage phenomena. The acquisition of five different images at a time allows for the application to materials with time-dependent mechanical behavior which is an important added value of the developed measurement optics. The experimental setup is applied to the so-called single fiber fragmentation test, which is a commonly used test to study the damage phenomena of single long-fiber reinforced specimens in transparent matrix material. When a tension load is applied to the specimen at low strain rate, damage of the fiber arises without a considerable failure of the matrix material. An effect of the fiber, a load transfer of the surrounding matrix material and the appearance of a characteristic stress distribution as well as evolving matrix and interface cracks can be observed. Using the described measurement system, it is possible to estimate the stress and strain distribution of the matrix material in the vicinity of the fractured fiber. In combination with the documentation and classification of the damage phenomena this enables the interpretation of the stress redistribution process inside the composite. This knowledge can be used to analyze the correlation between micromechanical phenomena and the effective macroscopic material behavior as well as to identify parameters of constitutive models for interface failure. The article demonstrates the potential of the measurement system and presents the results of its application to the single fiber fragmentation test. To point out the concluded facts, the results of differently manipulated specimen of epoxy matrix material with an embedded glass fiber are compared.

8791-61, Session 12
Automatic area based registration method and its application to the surface inspection of steel industry products
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In this document we describe the automated application of an area based registration method to the surface inspection of steel industry products as a tool used to solve an intermediate mosaicing problem, in a direct approach to the registration problem involved.
All the results have been checked over three different steel industry products in two different real projects. The objective of the first project is the detection of pores and inclusions in a previous brushed fringe of 3mm depth and 60 mm width on the surface of continuous casting slabs. The objective of second project is the submicrometric waviness measurement for coated products using microscopic laser triangulation. The necessary resolution to carry out the surface inspection and the high length of these products means that all the interest area can not be fitted into the field of view of the camera. It is necessary to acquire an image sequence of the moving target to obtain a full image of the product surface by means of a 2D image mosaicing process.
We decide to use an area based methods instead of feature based method because the products analysed not always show classic relevant features. However, the main problem of area based methods is that there is high probability that the results of a matching process will be incorrect if a block without any relevant detail is used. To deal with this problem a method is proposed to select a salient block. A salient
block is defined as a block containing relevant information to drive into a correct matching between a couple of consecutive frames of a video sequence. The selection of the size and the position of the block in the reference frame are focused on ensuring a smooth unimodal similarity surface when using a zero mean normalised cross correlation metric and a block as a region of interest. We have checked that the maximum correlation value is reached abruptly in a small range of pixel around the maximum similitude point in correlation surfaces obtained from blocks containing non relevant information. In the other hand, salient blocks usually drive into unimodal smooth similarity surfaces with small sensitivity to noise in contrast with the ones obtained from non remarkable blocks. Unimodality of the similarity surface also allows the use of fast search algorithms based on the unimodal error surface assumption, obtaining high computational cost reduction, and subpixel accuracy achievement by means of classic bidimensional interpolation of the correlation surface. In this work a Three Step Search Algorithm modified for working with similarity surfaces is used with high computational time reduction compared with classic full search strategies using a fast normalized cross correlation computed in the frequency domain and sum tables. Computational time reduction is important because the registration is only an intermediate step in the applications described. Once the registration is finished further processing time is required in the detection and measurement processes. The method described to select a salient block is based on the direct correlation obtained between the surface kurtosis coefficient measured over the block autocovariance surface and the same coefficient measured over the similarity surface, obtained from the cross correlation between the block and the search window. Using this correlation, a statistical analysis of the surface texture could be developed, selecting the size and the position of the block whose probability to contain a non salient block is lower than a selected value. Although the proposed method is based on a previous analysis of a set of images, a fast block saliency measure is also proposed to allow an on-line block saliency measure application of the method described. This fast saliency detector is based on a subsample strategy using a matrix of 9x9 points equally spaced to calculate the surface autocovariance of the selected block in the reference image. In conclusion, it has been proposed a block saliency detector that can be used in the automated application of monomodal area based methods to solve the intermediate mosaicing existing problem in the projects described. This method allows high computational cost reduction in comparison with fast normalised cross correlation methods computed in the frequency domain, thanks to the use of fast search algorithms based on the unimodality of the correlation surface. The fast calculation method proposed allow its on-line application as a kind of salient block detector not only in the specific steel industry projects described, but in other correlation based registration applications.

8791-62, Session 12
Investigation of fluorescence spectra disturbances influencing the classification performance of fluorescently labeled plastic flakes

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Plastics belong to the most versatile materials and have become indispensable in modern society. Their production requires the strategic resource oil and a huge amount of energy. Not only the need for an economical use of fossil fuels due to environmental reasons and their steadily rising costs, but also landfills overflowing with plastic waste urgently require the widespread implementation of plastic recycling technologies. A key point in the production of recycling products with highest quality from shredded residue is the high purity of the plastic waste to be recycled, e.g. for the automotive industry. Therefore, reliable and efficient sorting processes of mixed plastics are indispensable. In the proposed paper a promising approach to automatically identify and sort waste plastics that eliminates the known drawbacks of existing systems (e.g. NIR spectroscopy) will be presented. By incorporating specifically designed fluorescent dyes (“markers”) into the virgin plastics with concentration levels in the ppm range during manufacture, unique features in the optical spectra emitted from the plastics can be induced. Our laboratory prototype uses a high power LED of a specific wavelength to illuminate and activate the fluorescent markers in the labeled plastics, and a fast SPECM VNIR ImSpector V10E hyperspectral line scan imaging system (FWHM spectral resolution = 3.2 nm; spectral sampling = 0.65 nm, spectral range = 400-1000 nm; acquisition rate 42,000 spectra per second) and acquires the optical fluorescence spectra emitted from small plastic flakes. The acquired signals are then passed to the classification routines in order to generate the control commands for the mechanical sorting unit. Automated plastic sorting systems are economically successful only if they achieve a high mass throughput at small error rates (<5%). Speed limitations of the mechanical sorting process and the need for a sufficiently long excitation/exposure time call for a system design with several parallel streams of shredded plastic waste.

In the proposed paper we will quantify the classification performance of the measurement system in different scenarios. For this reason, the fluorescence emission spectra of 4 currently available and specifically designed fluorescent markers incorporated in pure plastics were acquired. Linear superpositions of the 4 spectra according to a simple 4-bit binary coding scheme were used to represent 15 different code combinations (code 0000 excluded). This represents the “best case” situation with equal intensities of the main peaks of the 4 marker spectra and without any changes in spectral shape due to various influences (see below). The 15 spectra were corrupted with realistic CCD sensor noise, which includes read noise, thermal noise and the Poisson-distributed photon noise. The noise model parameters were determined from measurements using our laboratory prototype system. The best case scenario simulation revealed that classification algorithms based on e.g. spectral cross-correlation (SCC) or spectral linear unmixing (SLU) deliver classification error rates of ER = 0 % for low-intensity signals with signal-to-noise ratios (SNR) larger than approximately 5dB. Detailed information will be shown in the proposed paper.

In practice, several imperfections exist which provoke changes in both, the marker intensities and spectral shapes. Some of the reasons are known to the marker injection process (variation of production concentrations, imperfection extruding, chemical interactions of the markers with the plastics and with one another, etc.), others arise from the different geometry, surface roughness and color (absorption and reflectivity functions) of the small plastic flakes. When only marker intensity changes are considered in the simulations, the error rate ER does not increase compared to the best case scenario (see above) if the marker intensity fluctuations stay below ± 40%.

Spectral shape changes of the plastics are more difficult to consider. While changes in the marker spectra due to chemical interactions are virtually impossible to predict, we can successfully model spectral changes caused by different plastics. In order to do so, we measured the spectral responses of the same plastic type for low-intensity signals with signal-to-noise ratios (SNR) larger than approximately 5dB. Detailed information will be shown in the proposed paper as a function of marker intensity fluctuations and spectral shape changes as well as SNR. The results are important for the specific assignment of certain marker (code) combinations to pure and colored plastic types in order to minimize the overall classification error.

8791-63, Session 12
Development of automated endoscopes for dimensional micro-measurements

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Increasing demands for product quality and outsourcing of production in the automobile industry lead to increasingly tight tolerances for the components. In the area of metal-mechanics these tolerances are particularly dimensional and require frequent uncertainties in the micron region. For optical instruments this means microscopical resolution. Dimensional measurement with uncertainties of some microns is nothing new, state of the art equipment in fact goes far below. The task becomes difficult if the measurements have to be carried out in an industrial production environment - and deep inside a bore hole. This paper describes the development of an automatic measurement
system for internal dimensions of brake master cylinders, specifically the development of (1) endoscopes, (2) illuminations for edge detection (3) integration with other sensors, actuators and controllers.

The most demanding part was the endoscope development, because, surprisingly, no commercial product for microscopic view and precision measurements was found on the market. As the market for such measurement machines is very small, and as the requirements were different for each endoscope, the budget allowed only the development of prototypes, using readily available optical components.

Borders between faces with different orientation of metallic structures can be difficult to detect. A satisfactory metrological performance can be achieved only with carefully shaped illumination, even if it consists of simple LEDs (light emitting diodes).

The automation was responsible for the largest part of the overall cost, coming from the desire for a high throughput of the measurement machine, even when operated by not highly qualified personnel. With the safety requirements satisfied, such a device ends up as a pretty complex equipment. Nevertheless, these aspects will be mentioned only for completeness, because standard components and methods were applied.
Optomechanical Nanoindentation: combining atomic force microscope indentation with optical coherence tomography (Invited Paper)

Dhwajal C. Chavan, Jianhua Mo, Mattijs de Groot, Anna Meijering, Johannes de Boer, Davide Iannuzzi, Vrije Univ. Amsterdam (Netherlands)

Several pre-clinical studies have already emphasized the potentiality of both atomic force microscope (AFM) indentation and optical coherence elastography (OCE) in the medical field. AFM indentation and OCE, are typically regarded as complementary techniques. OCE can measure the mechanical properties of individual tissue layers, but only over large indentation areas. On the other hand, AFM indentation can assess local mechanical properties, but it lacks the ability to distinguish between the contributions of different layers. Here, we present our recent efforts to bring these two techniques together. Our instrument is based on an AFM-like probe obtained by carving a microcantilever on top of a femur (femur-top configuration). Underneath the cantilever, the femur hosts two optical fibers. One of them is coupled to an interferometer that can remotely measure the bending of the cantilever with nanometer precision. The other fiber, aligned with the hollow tip at end of the cantilever, serves as the OCT probe. The instrument brings the tip of the cantilever in contact with the sample, indents the sample with a calibrated stroke, and simultaneously assesses, via OCT, the degree of deformation induced by the stroke in each different layer of the sample. Indentation tests performed on phantoms confirm that it works according to design with resolution of ~2 nanometer for cantilever deflection and ~15 nanometer for sub-layer deformation. This study paves the way for the development of a new generation of instruments for material analysis, with potential applications, among others, in the medical field, where it could be used to assess the elasticity of tissues and cells down to intracellular components in pre-clinical research and clinical practice.

Optical coherence tomography for non-destructive analysis of coatings in pharmaceutical tablets

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Film coating represents an important and widely used unit operation for manufacturing of solid dosage forms in the pharmaceutical industry. This process is generally referred to applying a thin continuous layer of solid on the top of a tablet or a granule containing active pharmaceutical ingredients (APIs). Initially film coating was primarily used for visual attractiveness, taste masking and brand recognition. Recent developments in coating technology, however, are pointing towards modified-release coatings (functional coating) to improve product stability and shelf life, as well as to control the drug release. Functional coatings facilitate formulators to modify the dependency of the initial drug release kinetics on the pH making the coating resistant to gastric juice through enteric coating. The coating process is a challenging operation in terms of attaining the desired amount of coating thickness and coating uniformity. Insufficient coating can result in ineffectue gastric resistance, whereas the drug release can be seriously delayed when the dosage form passes into the small intestine due to applying too much coating. Therefore, thickness and homogeneity of the coating are critical parameters regarding the drug release rate, and consequently a direct or indirect monitoring strategy of the coating thickness is essential. Basically measurement methods can be categorized in destructive and non-destructive. Scanning electron microscopy (SEM) or confocal laser scanning microscopy (CLSM) are assigned as destructive since a cut through the tablet is needed. Consequently, these methods cannot be applied as quick monitoring methods. The required tool should resolve the structure of the dosage form without destruction.

Vibrational spectroscopy techniques, such as near-infrared (NIR) and Raman spectroscopy, offer an attractive possibility to monitor processes. The quantitative determination of the coating thickness by NIR and Raman has already been demonstrated for offline product characterization and in-line product characterization. In combination with multivariate data analysis (MVDA) these methods allow real-time non-invasive and quantitative process monitoring. The major drawback of vibrational spectroscopy is that it does not provide an absolute value of the coating thickness, but needs calibration based on primary measurement data. Consequently, the prediction of the coating thickness is only as good as the primary measurements and the calibration procedure.

These disadvantages could be overcome by tomographic methods which provide spatially (transversally and axially) resolved information of the coating. Several tomographic techniques are available such as X-ray computed microtomography (XµCT), magnetic resonance imaging (MRI), terahertz pulse imaging (TPI) and optical coherence tomography (OCT) [1]. Most of them were successfully applied for the analysis of tablet coating. However, only TPI and OCT acceptably fulfill the requirements of an in-line measurement system. Among others, the main requirements are short acquisition time, high spatial (transverse and axial) resolution, high sensitivity regarding the detection of coating layers and impurities, large penetration depth, separation of sensor head and processing module and low investment costs.

The characterization of pharmaceuticals has served as core field of the development of TPI. It has the advantage of enabling a strong contrast in pharmaceutical relevant excipients. Terahertz radiation easily penetrates through excipients used for pharmaceutical tablets. The transversal and axial spatial resolution is limited to 50 and 40 µm, respectively. The high potential of TPI as in-line coating process measurement was already shown by May et al. [2]. They successfully applied an in-line sensor for terahertz measurements, which is capable of measuring film coatings ranging from 40 µm to 1 mm.

Since the coating thickness of most commercially available pharmaceutical tablets ranges from 5 µm to 200 µm, a better axial resolution than provided by TPI would be preferable. This can be achieved with OCT, which has the additional advantage over TPI that it is easier deployable. However, the main advantages of OCT compared to other tomographic techniques are its very fast acquisition rate, good transversal resolution and extremely high axial resolution. This makes it a promising candidate for real-time imaging. With the aid of OCT it is not only possible to measure the absolute coating thickness, but also to detect inhomogeneities, defects, inclusions or voids in the coating or substrate material. The off-line application of OCT for determination of coating thickness and detection of inhomogeneities was already studied and compared to other measurement techniques [3,4]. In this work the possible application of OCT as in-line method for monitoring pharmaceutical tablet film coating is studied. Firstly, the feasibility of OCT for analysis of tablet coating is examined. Off-line investigations of several different commercially available tablets with film coating are measured using two different SD-OCT systems. Secondly, the influence of a moving tablet bed on OCT images was studied by considering a moving sensor head along the tablet bed. The impact to the movement on the OCT image is discussed theoretically and verified with experimental data.


The combination of digital holography with microscopy techniques prospects a new powerful tool for quantitative phase contrast imaging of semi-transparent as well as reflective micro structures. Digital holographic microscopy (DHM), due to its intrinsic advantages such as dynamic, label-free and non-destructive properties, has been found particularly suitable for microscopic applications in life science and especially for quantitative live cell imaging. Although in the recent years commercially available DHM setups have become more and more sophisticated, in the essence all these systems offer only maps of specimen-induced phase changes, thus deliver either average refractive index or thickness of the investigated structure. To achieve truly three-dimensional imaging the information from multiple complex field images captured for different illumination directions with respect to the sample have to be merged using optical diffraction tomography (ODT) and one of the tomographic reconstruction algorithms, e.g. filtered back projection or filtered back propagation. By this means three-dimensional distribution of refractive index variation in the investigated object can be provided that can next serve as the convenient contrast agent for visualization as well as quantitative studies of living cells reaction.

Even though DHM-based tomographic techniques have the potential to become an established tool for characterization of life science objects, they still suffer from a few weaknesses resulting from the fact that, like all other tomographic methods, they are based on acquiring images from different angles of observation. This poses a requirement of either varying the illumination direction or rotating the specimen. Number of various approaches has been so far reported to deal with this problem, among others trapping of cells with micropipette or altering the angle of illumination using a galvanometer scanning mirror. In our study we method utilizing a fiber capillary for the specimen rotation has been chosen as the most suitable one. Using this approach it is possible to perform the measurement in a complete angular range and at the same time there is no risk of perturbing the sample. On the other hand, the basic drawback of this approach is that even though the axial and radial run-out of the capillary itself can be easily eliminated by careful mechanical adjustment, it is impossible to fully eliminate movement of the investigated cells inside it. Moreover the used capillary introduces a cylindrical wave aberration that severely distorts quality of the obtained phase images of the objective. The aberration is especially strong because the choice of an inner cell culture medium is the result of its biological properties, thus its refractive index cannot be properly matched to the capillary and that causes a strong diffraction and refraction effects on the inner interface of the capillary.

In the ODT the final accuracy of the obtained 3D refractive index distribution strongly depends on the quality of the individual phase maps forming a tomographic measurement series, then the crucial condition for a successful tomographic reconstruction consists in minimization of the mentioned effect of capillary induced aberration. In this paper we report an aberration correction method that allows for numerical elimination of the mentioned phase distortion using areas of hologram, which have not been affected by the specimen. The crucial element of the wave aberration correction is the spatial localization of the characterized specimen in accordance to the geometry of capillary. Only then the aberration can be accurately removed as it varies in different planes along the optical axis. Therefore the proposed correction procedure involves: (1) automatic focusing of the measured specimens in the capillary geometry, (2) propagation of the measured wave aberration and (3) compensation of the aberration. To test performance of the proposed numerical correction method an experiment has been conducted where holograms of living cancer cells were registered in DHM setup employing self-referencing with large lateral shear of the object beam. The obtained results have proven that elaborated method allows for significant improvement of the quality of the obtained phase images, thus has the potential to become a part of the prominent tool for high-resolution quantitative 3D imaging for life science applications.

**8792-5, Session 1**

**Spatial light interference microscopy and tomography (SLIM & SLIT)** *(Invited Paper)*

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Three-dimensional visualization of cellular structure will greatly...
improve the understanding to the cellular functioning and disease. Imaging cells in 3D has been largely limited to fluorescence confocal microscopy, where many times the specimen is fixed [1]. The out-of-focus light is rejected by a pinhole in front of the detector and the 3D information is gained by a transverse (x-y) scan and a longitudinal (z) scan. Deconvolution microscopy is another choice for 3D imaging, and an alternative to confocal microscopy. In this case no pinhole is needed and the 3D information is gained by the acquisition of a stack of images corresponding to different sections in the specimen. The deconvolution operation restores the original structured from the “blurred” image data. Quantifying optical path-lengths permits label-free measurements of structures and motions in a non-contact, non-invasive manner. Thus, quantitative phase imaging (QPI) [2] has recently become an active field of study and various experimental approaches have been proposed. Advances in phase-sensitive measurements enabled optical tomography of transparent structures, following Radon transform based reconstruction algorithms borrowed from X-ray computed imaging. More recently, QPI-based projection tomography has been applied to live cells [3-5]. However, the approximation used in this computed tomography fails for high numerical aperture imaging, where diffraction and scattering effects are essential and drastically limit the depth of field that can be reconstructed reliably [6]. Due to the combination of white light illumination, high numerical aperture, and phase-resolved detection, in addition to suppressing the speckle effects that generally degrade spatial coherence, optical coherence tomography (OCT) [7] has the ability to provide optical sectioning [7-9]. Thus, the out-of-focus blur is suppressed by the micron-range coherence length which overlaps axially with the plane of focus. In order to obtain a tomographic image of the sample, we performed axial scanning by translating the sample through focus in steps that are at least twice smaller than the Rayleigh range and with an accuracy of 20 nm. Based on first order Born approximation, a linear shift invariant model was developed, which extends diffraction tomography [10] to white light, imaging applications. References

or not at all. Hence, there is a plane or sheet within the strongly scattering sample, which is illuminated with a higher intensity than the surrounding volume. The shape and intensity of the interferogram making up this plane can be manipulated with the bandwidth of the white light source and the angle of incidence, respectively. We will show the first results of our structured illumination setup and demonstrate how to achieve narrow white light interferograms of high intensity for the fluorescence wavelength.


8792-8, Session 2

Quadrirwave lateral shearing interferometry as a quantification tool for microscopy. Application to dry mass determination of living cells, temperature mapping, and vibrational phase imaging

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We report the use of a wavefront sensor to measure the scalar electromagnetic field in the exit image plane of a microscope. Results are then used to give quantitative information about the sample, like its dry mass (living cells), temperature (plasmonic nanostructures or resistive microire), or Raman spectrum (polystyrene beads associated with CARS microscopy).

A Quadri-Wave Lateral Shearing Interferometer (QWLSI) is an efficient tool for measuring wavefront gradients and thus phase gradients of optical beams along two perpendicular directions.

Post-processing integration then allows obtaining the complete phase spatial distribution of the beam with a high spatial resolution. Measured QWLSI signals are achromatic, and thus compatible with the white-light illumination pathway of conventional wide-field microscopes. By placing a QWLSI on the exit image plane of such a microscope, we are able to measure the complex field spatial distribution in this plane, and then to retrieve the quantitative optical path difference (OPD) of the observed sample, thanks to an additional reference measurement. Here, we show that we can extend the technique to new applications, were given phenomena produce a sample-induced change in the phase of the exit optical beam. More precisely, we used direct refractive-induced OPD, thermal-induced OPD, and resonant vibrational-induced OPD to produce phase contrast images of living cells, temperature distribution of complex patterns of nanostructures, and Raman spectra of polystyrene beads, respectively.

Consider first the results we obtained on living COS7 cells. It has been shown that the OPD, once integrated over the cell surface, is proportional to the dry matter within a sample. We thus monitored the integrated OPD during a temporal time-lapse that covered two successive cycles, showing coherent linear evolution of the cell dry mass with time. We thus demonstrated that the OPD distribution of a living cell can be used to monitor its dry mass during the cell cycle.

Our second example of application deals with heat generation arising from nano-structures illuminated under the resonant plasmonic condition, in a comprehensive and quantitative manner. The idea is based on the measure of the thermal-induced refractive index variation of the medium surrounding the source of heat (generally water). Measuring thermally-induced OPD allowed us to map the temperature distribution around the source of heat. We also map the heat power density delivered by the source and retrieve the absorption cross section in the case of a light-absorbing structure. Heat generation was produced by illuminating the nanoparticles under their resonant plasmonic condition. Another example was based on an electrically-driven resistive microwire as the thermal source.

A last example we would like to present deals with wide-field vibrational phase imaging (coherent anti-Stokes Raman scattering imaging). In that case, we measure the specific resonant OPD of a micrometric poly-styrene bead. Spectrally-dependent responses allow us to determine both the real and imaginary parts of the nonlinear third order susceptibility of the bead, and then to retrieve its Raman spectrum.

8792-10, Session 2

Corneal surface reconstruction by using heterodyne Moiré method

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The refractive power of the cornea is over two-thirds of the total refractive power of the human eye. A slight variation of the corneal surface can significantly affect the normal human vision. So, the corneal surface reconstruction techniques offer an important, constant, and indispensable information for the optometry. The corneal topographer can display the step-height map and the refractive power map of the corneal surface. Besides the fundamental functions of the kerometer, the corneal topographer can also judge every kinds of the astigmatism. Furthermore, due to the ability to reconstruct the whole field of the true corneal surface profile, many diseases of the corneal or the eyeball can precisely be diagnosed to reduce the wrong or missed diagnoses. The accuracy and the sensibility of the corneal topographic map critically determine the precision of the diagnoses and therapy process. Therefore, in this paper, we propose a low-cost, simple, and high resolution corneal topographer by using the Talbot effect, projection moiré method, and heterodyne interferometry. A laser diode is expanded and collimated by a beam expander, then obliquely passes through linear grating with a projection angle. This linear grating is obliquely self-imaged on the tested corneal surface with first Talbot distance, and forms the deformed grating fringes which are resulted from the height distribution of the corneal surface. The deformed grating fringes on the corneal surface are imaged on the second grating by an imaging lens and forms the moiré fringes. The contour of the moiré fringes is related to the grating pitch, the height distribution of the corneal surface, the projection angle, and the viewing angle. The moiré fringes recorded with a CMOS camera located behind the second grating. If the first grating is moved with a constant velocity along the grating direction, every pixel on the CMOS camera records the signals which behave like the heterodyne interferometric signals, so they can be extracted by the same method as heterodyne interferometry. Every pixel records a serious of sampling points of the sinusoid wave, the corresponding phase of the optimal sinusoid wave can be obtained by the least-square sine fitting algorithm on IEEE 1241. The phase distribution of the corneal surface can be obtained by 2D phase unwrapping. Substituting it into derived equation, the height distribution of the corneal surface can be reconstructed. This method includes the features of projection moiré method, Talbot effect, and heterodyne interferometry, so it has the merits of high stability and high resolution. The feasibility has been proved by experiment in which we measure an artificial eye at first. The complete measurement which is available for human eyes just needs to use a super luminescent diode (SLD) with suitable wavelength and corresponding optical components. The proposed corneal topographer can reconstruct the whole corneal topographic map and do not have any aspherical errors resulted from the reconstruction algorithm. And the optimized corneal topographic map can be realized by an automatic measurement system. The influences of grating periods and the optical configuration on measurement results will also be discussed. The achievement of this research can provide eye doctors better information of corneal curvature and corneal topography, and consequently enhances the diagnosis accuracy.
Noninvasive inspection of skin lesions via multispectral imaging

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When studying the optical properties of nevi and melanomas, two are the main interest areas: the kind of molecules present in these lesions, and the localization within the skin structure. Usually, the main clinical aspect of melanomas is the marked brownish-black pigmentation due to macromolecule of melanin. Optical features such as the absorbance spectrum, generally depend on the molecular, supramolecular and aggregate-level structure. As other neoplasms, melanoma has an anomalous biological behaviour, which is reflected in several clinico-morphological aberrations. The pigmentation anomalies usually observed in melanomas are not necessarily due to an excessive melanin production, but also to the presence of aberrant melanosomes, or to the presence of neoplastic pigmented cells at different depth within dermis and dermis, even in layers where usually nevus cells are not found.

Historically suspected diagnosis of melanoma was made by clinical inspection following the ABCD rules. In the last thirty years, a non-invasive diagnostic tool, dermoscopy, has been developed to increased diagnostic accuracy. With this it is possible to magnify skin lesions and highlight features not visible to the naked-eye. Recently, new diagnostic tools have been proposed. Some studies demonstrated that emission and reflectance spectra could be used to differentiate neoplastic from normal skin tissue using an appropriate classification model. Among these techniques, multispectral (visible and infrared) examinations were employed and a number of systems were implemented.

Method

The system we developed, comprises a multispectral CCD camera with a KAF 6303e (Kodak), UV enhanced, with high quantum efficiency till 1100 nm, front side illuminated transparent gate true two phase technology sensor, with 3072x2048 pixels, of 9x9micron. Full Well Capacity is 100 ke, the Dark Current 0.5 e-/pixelsec, Quantum Efficiency a 450,550,650 nm: 40, 55, 64 and Fill Factor: 100% , and 16 2” interferential filters (LOT oriel). spaced at 50nm from 350 nm to 1100 nm, typical peak transmittance of 80-90% and FWHM of 40-50 nm. Illumination was provided by halogen lamps. The images were radiometrically calibrated, using a Barium Sulfate reference. Image resolution on target is about 10 microns. In collaboration with the Regional Melanoma Referral Center, for each pigmented lesion analyzed, a clinical and a dermoscopic image and a set of images at different wavelengths were acquired. Suspicious lesions were surgically removed the histopathologic data were provided.

Results

The pigment network is a grid-like network consisting of pigmented “lines” and hypopigmented “holes”. It is due either to melanin pigment in keratinocytes, or in melanocytes along the dermo-epidermal junction. The pigment network can be either typical or atypical representing a key features in the dermoscopic differential diagnosis between melanocytic nevi and melanomas. With the system developed, the pigment network is best visible in the 750 nm image. Moreover at this wavelength this feature is also well detectable for some melanocytic nevi and some melanomas where it was not obvious with the dermoscopic examination. However, with this new technique, the main difference between malignant melanomas and healthy nevi, is the fact that in the first case dark structures are still discernible in the image at 950 nm, whereas the last band in which structure are perceptible in nevi is the 850 nm. The blue-white veil (an irregular blue pigmentation with an overlying white, ground-glass haze) that is reflected in several clinico-morphological aberrations. The pigmentation anomalies usually observed in melanomas are not necessarily due to an excessive melanin production, but also to the presence of aberrant melanosomes, or to the presence of neoplastic pigmented cells at different depth within dermis and dermis, even in layers where usually nevus cells are not found.

Conclusions

A new device for early diagnosis of melanoma has been developed using a multispectral imaging system acquiring high spatial and spectral resolution images in the visible, and NIR range. The images acquired reveal layering of structures in the epidermal and dermal layer. Such images have been correlated with dermoscopic and histopathological data. Some differences between healthy skin and melanoma lesions have been detected and investigated. A model based on light penetration in turbid media explains image contents and helps understand the features observed. The research is ongoing and aims at defining a new semiotics for such images. The project is supported by the Tuscan Regional Health Research Program 2009.
8792-13, Session 3

Label-free biochemical characterization of bovine sperm cells using Raman microscopy

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Raman spectroscopy is a non-invasive technique that allows a biochemical analysis of the cellular components. This spectroscopic technique is based on the inelastic scattering of laser photons upon interaction with the sample molecules and allows the characterization of the properties and structure of the molecules from their stretching and bending vibrational transition. Raman spectroscopy is more suitable for in vivo or in situ studies of aqueous samples, compared to infrared spectroscopy, as water has really weak Raman scattering properties. Additionally, it does not require any label or marker, as the fluorescence for instance, allowing the rapid and non-invasive analysis of the samples in situ. It offers detailed information on the conformation, composition, and molecular interactions of important cellular macromolecules, such as DNA and proteins, and can be used to characterize and study individual living cells with sub-micrometric resolution [1-3]. For these reasons, Raman spectroscopy has been used as a powerful tool to investigate different biological tissues and living cells [4-5].

In this paper, we present the first Raman spectroscopy-based method for sensitive biochemical characterization of bovine sperm cells. A bovine sperm cell is divided in two regions: the head and the tail. The head (typically 5x3 μm²) anteriorly contains the acrosomal vesicle and in the centre a highly condensed haploid nucleus. The long motile tail (flagellum) has a filamentous core with many mitochondria spiralled around it in the neck region. In this work, by analysing separate Raman spectra from the nucleus, acrosomal vesicle and tail of single sperm cells, we are able to identify characteristic Raman features associated with DNA, protein and lipid molecular vibrations for discriminating between different location inside the cell with sub-micrometric resolution. In particular, pronounced Raman bands around 785 cm⁻¹, 1009 cm⁻¹, and 1481 cm⁻¹, assigned to nucleic acids and DNA backbone, characterize the nucleus Raman spectrum. The acrosomal vesicle spectrum shows higher bands corresponding to proteins: the Amide I (1600-1550 cm⁻¹) and Amide III (around 1200-1300 cm⁻¹) and lipids: C-H vibration at 1450 cm⁻¹. The tail spectrum is characterized by a peak around 751 cm⁻¹ previously assigned to mitochondria.

Finally, we used the Principal Component Analysis (PCA) for the interpretation and classification of the Raman data. PCA is a dimension reduction technique, which uses an orthogonal transformation to convert a set of spectra (correlated variables) into a set of uncorrelated orthogonal variables called principal components (PCs) [6]. The first few principal components account for the highest variance in the data and are often used for visualizing the primary and diagnostic spectral differences between the classes. By using PCA analysis we demonstrate that our Raman spectroscopy facilitates spectral assignment and increases detection sensitivity, opening the way for novel bio-imaging platforms.


8792-14, Session 3

Highly sensitive and reproducible near-infrared SERS sensors based on core-satellite nanostructures

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The excitation of surface plasmons in metallic nanostructures provides an opportunity to localize light at the nanoscale, well below the scale of the wavelength of the light. The high local electromagnetic field inhomogeneities play a key role for the high sensitivity of SERS. The use of this nanofocusing effect are exploited in surface enhanced Raman spectroscopy (SERS). At narrow interparticle gaps, so-called hot-spots, the nanofocusing effect is particularly pronounced. Hence, the engineering of substrates with a consistently high density of hot-spots is a major challenge in the field of SERS. Here, a simple bottom-up approach is described for the fabrication of highly SERS-active gold core-satellite nanostructures, using electrostatic and DNA-directed self-assembly. It is demonstrated that well-defined core-satellite gold nanostructures can be fabricated without the need for expensive direct-write nanolithography tools such as electron-beam lithography (EBL). Self-assembly also provides excellent control over particle distances on the nanoscale. The as-fabricated core-satellite nanostructures show strong and highly reproducible SERS activity superior to that of a commercial Klarite® SERS substrate and an ability of detecting target analytes, e.g. benzethanol, at concentrations down to 1 nM. The amount of DNA necessary to achieve a dense coverage of core-satellite metal nanostructures over 1 m² was calculated to be 0.42 nmol. Assuming a typical cost for small-scale customized DNA synthesis of US$2.00 per nmol the overall DNA cost to cover 1 m² would be less than $1.00, showing the commercial viability of DNA-directed fabrication techniques for the production of nanosensors. In addition, chemical synthesis offers nearly unlimited control over the size, shape, and composition of metal-nanoparticle building blocks, while DNA-generated self-assembly strategies allow for the development of complex assembly processes, far beyond the simple two-step process reported here. This work represents a simple proof-of-concept experiment leading the way to a plethora of nanostructures with tailored properties towards applications such as sensing and photovoltaics. SERS-active metal nanostructures, functionalized with probe molecules sensitive to local environmental conditions have recently also been used successfully to map properties such as pH and redox potentials, both in vitro and in vivo at micrometer resolution. This opens up an additional application field for investigating the molecular function of complex functional nanostructures as the core-satellite structures presented here.

8792-15, Session 3

Optical approach in characterizing dental biomaterials

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The purpose of this paper is to present initial results of a research collaborative program between three institutions from Zagreb (School of Dental Medicine, Institute of Physics, and Institute RuTer Bo’ković). Within the scope of this program, it is planned to investigate and find guidelines for the refinement of the properties of dental biomaterials (DBs) and of procedures in restorative dental medicine. It is also planned to identify and model the dominant mechanisms which control polymerization of DBs. The materials to be investigated include methacrylate based composite resins, new composite materials with amorphous calcium phosphate, silorane based composite resins, glass-ionomer cements and giomer properties.
Investigation of the physical-chemical properties of dental biomaterials (DBs) is a basis for establishing the clinical use guidelines. To obtain good clinical results, the DBs should have maximum degree of polymerization and minimum polymerization stress. Magnitude of the polymerization stress of DBs is determined mainly by their volumetric shrinkage (also by viscoelastic behavior, by restrictions imposed to polymerization shrinkage, and by irradiance used during photoactivation). Thus, the polymerization shrinkage of DBs is recognized as one of the main reasons for developing marginal leakage between a tooth and filling material. Other relevant properties which have to be investigated include thermal expansion, degree of conversion, color stability, translucency, microhardness, etc. Most of the listed properties can be determined by applying optical measuring techniques such as digital laser interferometry, spectroscopic and microscopic methods as well as by temperature measurements during polymerization. For example, the expansion and contraction changes of DBs during and after polymerization process can be accurately measured using laser interferometry method. For determining degree of conversion, Fourier transform infrared spectroscopy has been proven to be a reliable method. Microhardness of polymerized samples can be determined by optical microscopy and Vickers test.

In this work, we present an optical hybrid system that is still under development at the Institute of Physics and can be expected to provide a relevant information about a various types of DBs of interest. The system consists of a specially designed sample holder device (also suitable for high-viscosity DBs) used with setups for interferometric, spectroscopic and temperature measurements at video sampling frequency. Preliminary results of the ongoing investigation are reported and discussed.

8792-9, Session PS
Visualization of deformation by secondary speckle sensing
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Measuring deformation and vibration in machinery design is a vital concern. Each type of machine can be optimized for its economic, material and even personal consequences. Usually, deformation is measured using interferometric methods, ranging from shearing interferometers, electronic speckle pattern interferometry or holographic interferometry. These methods present the advantage of being capable of mapping the movement or the vibration of the tested sample in a large area simultaneously, typically at video rate. On the other hand as a main drawback, they are purely interferometric methods meaning that constraints, such as coherence of light, used for the testing impose limitation to the system. Typically the need for a path length matching between reference and object beam poses limitations on the working distance between the measuring system and the sample. Moreover, the system needs a certain mechanical stability that sometime can be troublesome to obtain. In a different type of sensors we have, for instance, accelerometers or Doppler based vibration sensors. The first ones need contact and thus have clear limitations and they influence on the measurement. Doppler vibration sensors use to work on short ranges. Both types of sensors can measure only in a single point and thus an array of sensors is needed for area measurements.

In this contribution we propose a new technique based upon a multipoint speckle imaging using the correlation statistics of speckle patterns. This method has been successfully used for remote vibration measurements [1,2] in single object spots. Additionally the high versatility of the method permits a wide variety of applications, such as biological applications for measuring biometrical parameters [3]. The system is capable of interferometric accuracy, although it relies on self-interference, shown as speckle patterns on the detector plane. Therefore, most of the constraints imposed by interferometric setups no longer apply. A camera is used to capture images at the desired frame rate, a collimated laser and a diffusiveoptical element, achieving a high number of inspection points opens the possibility for analyzing simultaneously a plurality of inspected points. Proper adjustment of the optical parameters (aperture size and shape) can deal with the measurements at different locations of the object’s surface with no crosstalk between the outputs for each inspected point. The data from the different inspected locations can be analyzed separately or integrated to provide a global surface change in shape.

The system has two major advantages. On one hand, it uses few hardware elements, making the system easily portable and compact. On the other hand the system needs a laser source with relatively low degree of coherence, as interference is done on the tested surface itself and no external coherent reference is needed. As a main gain from these characteristics the system can be packed in a compact enclosure and it can operate at an arbitrary distance from the inspected object, limited only by intensity available on the detector and sensor’s sensitivity. The system can work at frame rate allowed by the camera in the selected region of interest. Therefore, a rate of few hundreds of Hertz is achievable even with low end cameras. The system’s operation rate can be improved with specialized high frame rate cameras and/or by reducing the region of interest (typically increasing the frame rate inversely proportional to the window size).

In this communication we show the details of the method in theoretical and practical aspects as well as implementations for vibration and deformation measurements. The experimental demonstration shows the potential of the method for inspection in large variety of environments and conditions.

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8792-34, Session PS
Characterization of photopolymers as optical recording materials by means of digital holography microscopy
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Photopolymers are light-sensitive materials, i.e. altering their optical properties when exposed to light with specific characteristics. For this reason they are often used for holographic recordings. In this paper, photopolymers were characterized by means of Digital Holography Microscopy (DHM). DHM is a very powerful technique, it allows measurements of both amplitude and phase of an object and it is based on interference between two laser beams: a reference beam and an object beam. Due to their different optical path, two beams interfere and the obtained hologram consists in interference fringes. The hologram is acquired by a CCD camera and then, by a mathematical analysis, is possible to obtain optical phase and amplitude of the object beam [1]. DHM is suitable for photopolymers characterization [2,3], allowing contemporary measurement of the variation of phase, i.e. variation of real part of the refractive index, and amplitude. This latter information is useful for evaluating the transparency of the post-written sample and any damage in case the power of exposure is likely to cause a variation in the absorption of the polymer, or which is the inverse part of the index. Moreover, the reconstruction procedure is applied to the whole area captured by the CCD. So, it is possible measure the phase variation, and therefore variation of refractive index (n), over a large area.

Two different photopolymers, sensitive to light at wavelength of 532 nm, have been characterized. Sol-gel technique was used because it allows formation of a matrix with material with low refractive index and keeps photo sensitive monomers with high refractive index (High Refractive Index Species HRIS) dissolved. At the same time, the system's operation rate can be improved with specialized high frame rate cameras and/or by reducing the region of interest (typically increasing the frame rate inversely proportional to the window size). The system's operation rate can be improved with specialized high frame rate cameras and/or by reducing the region of interest (typically increasing the frame rate inversely proportional to the window size). Two samples obtained was called R01
Forskolin, or 8-(4-chloro-phenylthio)-2’-O-methyladenosine-3’,5’-cyclic grown on nanogratings (NGs) and stimulated by Nerve Growth Factor, biochemical signals by specific molecular pathways. PC12 cells external physical stimuli (geometry, stiffness, roughness, etc.) in Cells feel the local topography by contact interaction, transducing scaffold presenting a variety of geometrically-defined physical cues signals of different nature, consisting of biochemical and/or biophysical correct wiring. Cells are able of sensing and responding to many plays an essential role in defining the nervous system network and Ricerche (Italy) and Scuola Normale Superiore di Pisa (Italy).

Ilaria Tonazzini, Sandro Meucci, Fabio Beltram, Marco

Results for both B01 and R01 polymers at an output power of the green laser of about 140 mW, are shown in Fig. 1 (a) and (b), respectively. At the same time, no significant amplitude variation was observed.

In order to fix the induced refractive index change, a further step was required. It is a photo-bleaching process: photopolymers were exposed to a lamp for approximately three hours. After this process, we observe a further variation of refractive index of about one order of magnitude with respect to the final value showed in figures 1 (a) and (b). In particular, n=0.02 for B01 sample, and n=0.04 for R01 sample. These values are quite comparable with commercial photopolymers [4]. In conclusion, we can affirm that both new photopolymers presented a very high refractive index variation due to the light exposure. Thus the materials could be suitable for holographic recordings. Moreover, they offer the advantage of being easy to make and inexpensive.

References:

8792-57, Session PS

Interaction of neuronal cells with nanotopographies
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The micro-/nano-environment in which neuronal cells reside in vivo plays an essential role in defining the nervous system network and correct wiring. Cells are able of sensing and responding to many signals of different nature, consisting of biochemical and/or biophysical probes, over a wide range of length scales. Many of these stimuli are provided by the extracellular matrix (ECM), which acts as a cellular scaffold presenting a variety of geometrically-defined physical cues on the order of micron and sub-micron scale, known as topographies. Cells feel the local topography by contact interaction, transducing external physical stimuli (geometry, stiffness, roughness, etc.) in biochemical signals by specific molecular pathways. PC12 cells grown on nanogratings (NGs) and stimulated by Nerve Growth Factor, Forskolin, or 8-[4-chloro-phenylthio]-2’-O-methyladenosine-3’,5’-cyclic (8CPT-2MecAMP) show different outputs in response to topography(1). Nanogratings can indeed be used to transfer a traction signal, which is integrated by the cells resulting in cell stretching, polarization and alignment to the nanostructures. This was linked to a modulation of focal adhesion maturation, and related to contractility signal cascades(2,3). NGs are then coupled to primary mouse hippocampal (HC) neurons, in particular to ubiquitin ligase E3a (Ube3a)-KO neurons, a model for the rare genetic disorder Angelmann syndrome. Recent data suggest that the loss of Ube3a expression may result in abnormal brain connectivity, which we hypothesize might result from pathological contact interaction with the ECM. Mechanotransduction is here characterized as axon guidance in neuropathological conditions for the first time.

References

8792-58, Session PS

Reducing measurement uncertainty of instruments based on the phenomenon of surface plasmon resonance
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The optical measurements based on the phenomenon of a surface plasmon resonance (SPR), are used for the chemical and biological analysis. SPR arises in a thin metal film with negative dielectric permeability (high electroconductivity), which is located on a transparent dielectric substrate. As a metal sensitive layer for SPR use gold, because this metal have high conductivity and chemical inertness.

The analysis of references and our researches showed that increase of accuracy of measurements, and also and productivity of devices, it is possible to reach reliability a thermostabilization of a measuring cell, increase in measuring channels, and also improvement of a sensitive element. The value of an error of results of measurement is influenced essentially by temperature deviation, both object of measurement. In the course of measurement this error can increase, owing to a difference of temperatures at the moment of the beginning of measurements and at the moment of their end. The purpose of our work was reduction of an error of results of optical measurements.

The result of the carried-out researches, it was offered to use a thermostabilization not only object of measurement, but also all measuring equipment, including capacities with studied substances. Thermostabilization allows to increase accuracy of measurements of concentration of studied substances in 5 times and to define also nature of proceeding reactions.

8792-59, Session PS

Visualization of permanent marks in progressive addition lenses by digital in-line holography
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Progressive addition spectacle lenses (PALs) have been commercially available over around the last 55 years after the release of the first Varilux PAL in 1951. Since then, the optical performance of PALs has attracted the attention of manufacturers, practitioners, technicians and users, especially nowadays where customized PALs are very fashionable.

Typically, the multifocal profile in PALs is on the front lens surface of a semi-finished lens provided by the manufacturer. The multifocal profile varies gradually from a minimum value in the upper (distant vision correction zone) to a maximum value in the lower (near vision correction zone).
correction zone). As a consequence, the multifocal profile is a smooth and continuously increased surface power providing the necessary addition for near vision and without any visible steps or abrupt disturbances in vision.

Thus, the semi-finished lens containing the suitable multifocal design and refraction is selected from a stock of lenses according to a given final user. Once selected, the multifocal profile is properly oriented and the back lens surface is finished (ground and polished) to produce a given spherocylindrical power and axis with respect to the multifocal profile. Both surfaces together compensate the refractive error of the ending-user.

A critical issue in the production of ophthalmic lenses is to guarantee the correct centering and alignment of both front and back lens surfaces throughout the manufacturing and mounting processes. Aimed to that, PALs are supplied with two types of markings for layout, power verification, dispensing, and identification purposes. Removable markings are inked on and permits the identification and verification of the lens zones (essentially, distant, near, and corridor zones). Permanent markings are engraved upon the surface and provide the model identification and addition power of the PAL, as well as to serve as locator marks to re-insert the removables marks again if necessary. Both marks are placed at standardized locations at the lens.

Because of their enduring characteristic, permanent marks are the most important ones. Both mineral glass and lightweight plastic PALs are marked at various stages of production for internal tracking purposes as well as for finally produce the permanent marks. The marking process includes engraving lens moulds, semi-finished lenses, and polished lenses before coating by using either mechanical marking or laser engraving systems. These permanent marks must be clearly visible to the trained optician but relatively unobtrusive to the eyeglass ending-user. For instance, for marks created in the mould or directly on an uncoated lens, the mark should have enough depth so that it does not become invisible by the coating processes, and for marks created on the coated lenses, the marks must be very precise with very clean edges in order to eliminate the risk of coating delamination during wear and cleaning of the lens.

Although the permanent marks should be visible by simple visual inspection, those marks are often faint and weak on new lenses providing low contrast, obscured by scratches on older lenses, and partially occluded and difficult to recognize on tinted or anti-reflection coated lenses. Due to this, visualization and identifying of permanent marks could be impossible with the naked eye and particularly for the less experienced technician. For those reasons, there are several PALs marking readers in the market allowing identification and visualization of several PALs characteristics such as the initials of the manufacturer of the lens or company logo, fitting reference points, the addition power, the identifying symbol of the lens model, any customized mark, the material code, etc. The marking readers use a good light source and two different filters depending on the PAL's material: it is common to use a green filter with clear bright field illumination for plastic lenses and two different filters depending on the PAL's material; it is common to use a green filter with clear bright field illumination for plastic lenses and dark field illumination (ring lighting with black background) for glass lenses to locate the marks. The reason for this double filtering option is that the glass engravings are finer than those in plastic lenses and can be better visualized under dark field illumination scheme.

Here, we present an extremely simple visualization system for permanent marks in PALs based on digital in-line holography. Light emitted by a superluminescent diode (SLD) is used to illuminate the PAL which is placed just before a CCD sensor. Thus, the CCD record an in-line hologram incoming from the diffracted wavefront provided by the PAL. Since the PAL is essentially transparent (weak power, the identifying symbol of the lens model, any customized mark, the material code, etc.) the marking readers use a good light source and two different filters depending on the PAL's material: it is common to use a green filter with clear bright field illumination for plastic lenses and dark field illumination (ring lighting with black background) for glass lenses to locate the marks. The reason for this double filtering option is that the glass engravings are finer than those in plastic lenses and can be better visualized under dark field illumination scheme.

8792-60, Session PS

Visualizing affect of mono and divalent ions on formation of native collagen fibrils via SEM and AFM

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Salt collagen interactions were tried to be visualized by scanning electron microscopy and atomic force microscopy. AFM is new high resolution technique which offers significant information on the fibrillary assembly and ultrastructure of collagen fibrils, which may provide insight into both the physiological and eventually changed pattern of collagen fibrils after the treatment of various salts. With this technique we were able to identify unambiguously collagen bundles and were able to determine their diameter. These results led us to differentiate the coiling pattern of collagen when treated with various salt concentrations. The quaternary structure of collagen fibres, i.e., the assembly of the individual fibrils to form thicker bundles, has previously been determined using ultrastructural analyses, mostly by scanning electron microscopy. Thereby, it has been shown that indeed the size and in particular the diameter of the collagen fibres varies not only between the different collagen isotypes, but also within one isotype between different tissue types, e.g., the collagen bundles of the dermal connective tissues are different from that of tendon or ligaments, thus it has been proven to be good technique for such interaction as compared to other microscopic techniques. SEM and AFM both confirmed about changes took place in structure of collagen after treatment. The lateral resolution obtained with AFM examination of biological samples is very close to that provided by a high resolution scanning electron microscope. However, in the case of AFM, such a resolution is directly obtained in air, on naked fibres. The high resolution in the Z-axis allows one to obtain precise information on the ‘overlap’ and ‘gap’ zones. With AFM it was convenient to measure a 4-nm difference in level between the ‘gap’ and the ‘overlap’ zones. Such a finding would not be possible to estimate with an electron microscope. So from AFM it was found that there are no significant differences in the reliefs observed from native and reconstituted fibres, except for the depth of the ‘gap’ zones, which is more important in the case of both treatment processes. Such differences have been correlated with the degree of dehydration of the fibres. These gaps were very large in case of Na2SO4 and dense in case of NaCl. So it can be concluded that both salts form deep and dense interaction with collagen hence they are effective for preservation. It was very much convenient to measure a 4-12nm difference in level between the ‘gap’ and the ‘overlap’ zones. Such a finding would not have been possible to estimate with an electron microscope.

In summary, in our study we present circumstantial evidence that AFM analysis as a novel morphological technique can successfully be applied to analyze detailed collagen structure at nanoscale. Scanning electron microscopy was also used to analyze collagen bundling differentiating effect of salts found to be totally different from each other.

8792-61, Session PS

Apodized photon sieves for phase-contrast nano-imaging of living cells

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X-ray phase-contrast imaging is a particularly powerful technique for studying internal structure of weakly absorbing materials such as thin biological samples in vivo and without destruction. Recent technological demands for high resolution imaging in life sciences made X-ray phase-contrast microscopy a rapidly developing field, facilitated by the construction of the third generation synchrotron light sources and the advances in manufacturing technologies of X-rays focusing optics. We present a type of compound diffraction lenses “Zernike apodized photon sieves” (ZAPS) used as the objective of X-ray phase-contrast microscope for imaging biological samples in vivo and without destruction [Opt. Lett. 35 (21), 3610, 2010; Acta Phys. Sin. 60(8), 080703, 2011]. Use of the ZAPS to generate phase-contrast is an
attractive method of implementing phase-sensitive imaging due to the simplicity and ease in alignment. The ZAPS is a single optic that integrates the appropriate ±π/2 radians phase shift through selective zone plate shift in a region of an apodized photon sieve pattern ratio function can be shown by using nanoparticles (such as Quantum Dots) and suitable wavelength of optical radiation. Among the different methods of optical imaging Fluorescent Molecular Tomography (FMT) is a non-invasive method for imaging the biological tissue at cellular level. Fluorescence molecular imaging is a non-invasive technique to visualize biological process at cellular and sub-cellular levels, which is widely used in clinical fields such as small animal imaging. In particular, fluorescence molecular tomography (FMT) is applied for localizing and quantifying specimens labeled by the fluorescent nanoparticles. FMT is accomplished by irradiation the sample with lasers and collection of fluorescent light emitted in all 360 angles. By reconstruction of obtained fluorescent intensity, the distribution of the fluorochrome concentration within the sample is obtained. The problem of reconstructing map of the fluorescent concentration from the interior of a turbid medium can be divided into two steps: the forward and the inverse problems. One of the main goals of optical imaging is giving light source distribution on surface of objects. The Forward problem seeks to determine the photon density on the surface of the subject. Material and method: In present study we sought the algorithm to determineForward problem that is used for image reconstruction of FMT system. For this purpose diffusion equation is solved by using numerical method which is fast, flexible and useful for fluorescent tomography. Image reconstructions FMT image reconstruction. The Finite element method is a fast and flexible numerical technique which is used to solve diffusion equations. Therefore the aim of this article is to develop a fast forward algorithm using a finite element method for the FMT imaging system. In this study, FMT system was implemented in tomography method. The computer code is developed and written in MATLAB programming to estimate the intensity on the object’s surface. The algorithm is based on diffusion approximation numerical solution and is evaluated by phantom experiment. Results: The results are compared with Monte Carlo (MC) and analytical method and validated by the data that were obtained from tissue-like phantom for known optical properties. Comparison of numerical and analytical data shows that our algorithm is accurate and faster than analytical algorithm and comparison our data and data obtained from MC shows good correlation. The results showed the significant correlation coefficients ($R > 0.92$), which demonstrated the high accuracy of the algorithm. We have presented an approximate algorithm that solve the 2D diffusion equation in homogeneous turbid phantom like tissue. The algorithm can be used as part of the reconstruction program using FMT.

8792-16, Session 4
Characterization of a bioinspired elastin-polypropylene fumarate material for vascular prostheses applications
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The major problems associated with vascular prostheses are non-biodegradability of the implant, small caliber related thrombosis and neo-intimal hyperplasia. In this respect, polypropylene fumarate (PPF) may be a promising candidate due its complete biodegradability besides good mechanical properties.

In order to improve mechanisms of cell-polymer interaction, a surface functionalization process is here proposed. An elastin based coating has been performed onto 3D porous PPF scaffolds, with the aim to enhance endothelial cell proliferation, besides reduce platelets adhesion, smooth muscle cell growth and, finally, overgrowth of neo-intima and thrombosis.

Briefly, bovine elastin (E1625 from Sigma) has been suspended in Tris buffer (20mg/ml) and deposited onto 3D porous (mean pore size 40 micron, distance among pores 20 micron) scaffolds of PPF, previously prepared with stereolitography. The incubation of elastin onto PPF was performed at 37°C for 72 hours. The presence of the protein onto the scaffold after deposition has been evaluated by TGA, FTIR, SEM and AFM analysis. The biodegradability of the graft has been also evaluated up to 2 months in vitro.

To test the functionality of this coating, endothelial (HUVEC) cells have been seeded onto the functionalized scaffolds and their adhesion, smooth muscle cell growth and overgrowth of neo-intima and thrombosis.

FTIR analysis was used to qualitatively characterize the functional groups of elastin and PPF, and to confirm the presence of elastin bound to the PPF scaffold. Elastin coated PPF scaffolds were also observed at SEM, which revealed the formation of fibers aggregates (mean fiber diameter 8 micron).

In terms of biodegradability, PPF based scaffolds were kept in buffer solution (PBS) at 37°C up to 60 days, and their weight was monitored over time. A mass lost of 25% was observed, revealing good resorbability properties of this material.

In conclusion, a bioinspired PPF based material was widely characterized, in order to highlight its properties of biodegradability and affinity with elastin protein; these promising results allow to test this innovative materials as biodegradable stent for vascular application.
In situ 3D monitoring of collagen fibrillogenesis using SHG microscopy

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Introduction

Type I collagen is a ubiquitous protein that is the main component of connective tissue. Synthesized by cells as triple helices, collagen self-assembles into fibrils in vivo and in vitro to form three-dimensional (3D) networks. This assembly mechanism depends critically on the collagen concentration, as well as pH, temperature and ionic strength of the solution in vitro. Thorough characterization of collagen fibrillogenesis is of crucial importance to understand the biosystem organization of tissue formation and tissue remodeling and to design new biomaterials.

To that end, it is necessary to overcome the limitations of conventional imaging techniques that are either invasive or lack specificity. For this purpose, we continuously monitored the dynamics of collagen fibrils formation by multiphoton microscopy, using second harmonic generation (SHG) intrinsic signals from fibrillar collagen [1]. SHG is a coherent nonlinear optical process, which occurs at twice the excitation frequency and is specific for dense and non-centrosymmetric macromolecular structures. SHG microscopy is therefore a structural probe of collagen fibrils [2-5] (or aligned collagen molecules [6, 7]).

Materials and methods

Fibrillogenesis was triggered by increasing pH to 6.5 ± 0.3 or 7.5 ± 0.3 by addition of NaOH, in order to tune the kinetics of fibrillogenesis. A drop of sample was then placed between two glass coverslips and directly visualized using SHG microscopy without any staining. SHG imaging was performed using a high numerical aperture objective (40x, NA 1.1), to achieve about 0.36 µm lateral resolution and 1.2 µm axial resolution at 860 nm excitation. SHG image stacks were recorded sequentially in the forward direction every 10 to 20 minutes for several hours / overnight. In some experiments, we added stained silica nanoparticles to the solution to investigate surface-mediated fibrillogenesis [8]. These stained nanoparticles were visualized using Two-Photon excited fluorescence (2PEF) signals that were detected in another channel of the microscope, in the backward direction.

2PEF/SHG images were then analyzed using ImageJ software or Python. As a first step, we basically applied median filter to eliminate the background noise, stacks were then projected along z-axis and the extent of the fibrillar network was quantified by calculating the area fraction of pixels with SHG signal. No thresholding was necessary at the background noise, stacks were then projected along z-axis and the extent of the fibrillar network was quantified by calculating the area fraction of pixels with SHG signal. No thresholding was necessary at

Discussion

These results show that SHG microscopy is a powerful technique for in situ monitoring of collagen fibrillogenesis without any staining. Compared to confocal reflectance microscopy, it advantageously exhibits a high specificity to fibrillar collagen and thus provides structural information at sub-micrometer scale. Compared to highly resolved techniques such as electron microscopy, it advantageously exhibits a wider field of view and enables imaging of liquid solutions, without any preparation. Moreover, correlated SHG - TEM imaging showed that SHG microscopy is a highly sensitive technique and can detect small fibrils with diameter down to 50 nm.

Reference

internal scaffold from escaping. Careful optimization of laser writing conditions led to an attractive processing window with 1-mm/s writing speed, representing a two order of magnitude improvement in fabrication time compared to our previous work. Computer-controlled, 3-axis motion stages (piezoelectric Physik Instrumente Narmagnac air-bearing ABL-1000 positioning stages) were used to translate the sample relative to the laser, interfaced by CAD-based 3DPolli software. Scaffolds were fabricated on 8-mm diameter circular coverslip (1.2-mm thickness) to enable their loading in walled Labtret sample holders to facilitate cell seeding and fluorescence microscopy characterization.

In confocal fluorescence microscopy of laser-fabricated niches seeded with rat mesenchymal stem cells, the progenitors of muskulo-skeletal cells, cells were observed to migrate towards the niches, climbing the perforated walls of the niche, and adhere inside the internal scaffold microenvironment. Stem cells which appeared flat on the outer monolayer, were seen to become more round after invading the niche since filipodia of the cells can adhere to the scaffold in all directions. The cells appear to home to the niches, with colonies forming in and around the niches, demonstrating that stem cells appear to favor the laser-formed 3D niches, designed to mimic the extracellular matrix within the human body. Our preliminary results show that, at 6 culture days, stem cells proliferate preferentially in the microscaffold areas with the highest surface density available for adhesion. Strong background autofluorescence from the Bis-based ZZ2000, hindered the detection of fluorescence markers of stem cell proliferation and differentiation. However, in the Irg-based polymer, we found significantly less background signal, enabling us to accurately resolve fluorescence markers within the microscaffolds. As such, our current focus is to use exclusively the Irg-based ZZ2080 polymer, with an objective of demonstrating the effect of mechanical and geometrical properties of the laser-formed microscaffolds on stem cell differentiation.

8792-19, Session 4

Deciphering the dialogues at the cell material interface (Invited Paper)
Paolo A. Netti, Istituto Italiano di Tecnologia (Italy) and Univ. degli Studi di Napoli Federico II (Italy)

Cell and material interact through biochemical and biophysical signals, including matricellular cues, topography, mechanical and hydrophobicity. The development of novel biomaterials able to control cell activities and direct their fate is warranted for improving implants performances, engineering biological tissues in vitro, advanced cell cultures plates, and for cell sorting and differentiation. It is well known the crosstalk that occurs at cell-material interface has a profound influence on cell behaviour. However, the complete deciphering of the cell-material communication code is still far to come. Although a plethora of biochemical and biophysical signaling acting at the cell-material interface have been reported in the recent literature, the way to properly present them to elicit a given cell response still remains largely unknown. Indeed, a variety of material surface properties have been reported to affect the strength and the nature of the cell-material interactions, including biological cues, topography and mechanical properties. Novel experimental evidence indicate that these three different signals participate in the same material-cytoskeleton crosstalk pathway via adhesion plaques formation dynamics. Adhesion plaques are submicrometric molecular clusters that are visible at the cell-material interface and their size and dynamics strongly affect the material-cytoskeleton crosstalk via the effect of mechanical deformation of the nucleus mediated by the cytoskeleton tensional status. Decoding the effect and the interaction between the material properties and the dynamics of the adhesion plaques is now required to unravel the material-cytoskeleton-cell fate chain. In this lecture the basic signals that control the dynamics of cell-material interface will be discussed along with the strategies to correctly display and deliver them to the cell. Example of cell-material communication and miscommunication will also be presented.

8792-20, Session 4

Dynamic Imaging of Intracellular Motion Characterizes Three-Dimensional Living Tissue (Invited Paper)
David D. Nolte, Purdue Univ. (United States)

Living cells are complex machines with many actively moving parts. The broad range of motions relate to the broad range of cellular functions and are ideal biomarkers for characterizing subcellular processes. While subcellular motions are routinely explored in two-dimensional live cell culture, it has been much more difficult to extract motion information from inside three-dimensional living tissue. Digital holography is intrinsically an interferometric approach that is phase sensitive to subtle motions inside living cells. Furthermore, by using low-coherence light, nonlinear signals can be isolated from specified depths, enabling a new three-dimensional imaging approach that uses the endogenous cellular motions as image contrast for functional imaging. The optical approach is label-free and noninvasive, and captures characteristic speeds that span three-orders of magnitude. Dynamic imaging is a general 3D optical imaging technique that can be used to measure dynamic properties of a wide variety of biomaterials.

We are currently exploring applications of dynamic imaging in drug screening on multicellular tumor spheroids that are grown in bioreactors. Differential spectrograms are obtained through the applications of reference pharmaceuticals on tumor tissue. The spectrograms provide a unique fingerprint of the action of the drug on the tissue and are used to perform phenotypic profiling of drug mechanisms of action. Dynamic imaging has also been applied to single cells such as porcine oocytes, and to tumor explants to test the efficacy of chemotherapy for personalized cancer care.

8792-21, Session 4

Development and characterization of nanocomposite biomaterials for laser-activated tissue bonding and drug release (Invited Paper)
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Stimuli-responsive polymeric biomaterials have attracted much attention for their prospective application in several fields including biomedicine, biotechnology and biosensing. As a rule of thumb a stimuli-responsive system is capable of undergoing conformational and chemical changes on receiving an environmental signal. Exemplary stimuli include temperature, pH, light, ultrasounds, magnetic fields, ionic and supramolecular interactions, and redox potential. As a consequence of their action several alterations in relevant material properties such as dissolution or formation, modifications in size and in shape, and enhanced or reduced physical and chemical characteristics can occur.

Here we discuss the exploitation of a light stimulation produced by a laser source to “activate” biomaterials hybridized with suitable photothermal enhancers. We will present into more details two exemplary laser-activated biomaterials, which we have recently developed and characterized as viable solutions to critical issues in tissue repair and drug delivery applications.

Laser-assisted tissue repair or laser welding has been proposed to close chronic accidental and surgical wounds. Typically, laser light is delivered 1) to a wound site to be repaired which has been stained with an exogenous optical absorber or 2) to a photosensitive responsive medical dressing (e.g. patches, stents, etc) placed in intimate contact with the tissue to be repaired, in order to produce a photothermal effect. The endogenous tissue or the externally applied dressing respond to the thermal stimulus producing different chemostructural modifications such as denaturation and fusion, which can mediate the repair of the wound. An exemplary application is corneal laser welding, which is obtained by staining the cut edges of a stromal tissue with the photosensitizer Indocyanine green and by irradiating them with a near-infrared laser light to produce collagen denaturation and reorganization.
of the noncollagenous components, which can ultimately sustain wound closure and tissue fusion. We have recently engineered an hybrid bioadhesive consisting in a chitosan film doped with gold nanorods (GNRs) that can be activated by NIR laser light. These films (0.1 mm thick, transparent, and reddish brown) were found to be flexible, resistant, and stable in a physiological environment. The use of GNRs provides amplified optical absorbance of the laser light due to efficient plasmon bands in the NIR window, where tissue components and chitosan are mostly transparent. Upon laser irradiation a well-localized photothermal effect can thus be produced in the film, which is in turn stimulated to produce adhesion with a proximal tissue surface (e.g. arterial wall, tendon, lens capsule). Optimal irradiation conditions were observed with laser pulses in the millisecond timescale and about 1 W power, while at lower power and longer pulse durations, the laser-induced temperature was not stable at these temperatures. We proved the possibility of regulating both GNRs and micelles plays here only a structural role and is not the main factor to control the drug release. The photothermal response of the nanocomposites contained inside the sponge triggers a contraction in proximal micelles, thus promoting the expulsion of the drug that in turn is released from the sponge to the external environment. Specifically, the thermosensitive micelles, composed of poly(e-caprolactone)-poly(ethylene glycol)-poly(e-caprolactone) (PCL-PEG-PCL) copolymer, underwent a 35% reduction in their volume almost instantly when the temperature dropped slightly above the physiological value while the chitosan enwrapping both GNRs and micelles plays here only a structural role and is stable at these temperatures. We proved the possibility of regulating the temperature generated in the sponge by laser illumination with a continuous wave diode laser light through a variation in the laser intensity (in the 0.3 - 0.5 W cm-2 range) and with a linear relationship within the temperature range of interest for the activation of the release (40 – 45 °C). The peculiar physiochemical and structural properties of the nanocomposite sponges impart a number of interesting features to this drug release system, including the possibility of spatially confining the therapeutic treatment as well as of precise control of the amount of released drug as a function of duration and power of the excitation light.

References

Fabrication of 3D tissue equivalent: an in vitro platform for understanding collagen evolution in healthy and diseased models

Francesco Uricchio, Giorgia Imparato, Costantino Casale, Sara Scamardella, Paolo A. Netti, Istituto Italiano di Tecnologia (Italy)

In this work we aim at fabrication of living 3D tissue in vitro by methods of a scaffold based-bottom-up tissue engineering strategy. We tested the following hypothesis: (i) it is possible to realize a viable thick tissue completely made up by endogenous extracellular matrix (ECM) preserving both extracellular cell and cell-ECM cross-talking; (ii) de novo synthesized endogenous collagen network can be imaged and analyzed by means of non linear optical techniques; (iii) the final 3D tissue can be used as a living platform in vitro to study biophysical and biochemical phenomena that influence tissue remodeling. The fabrication of the final 3D tissue comprises three crucial steps: micro-scaffold design and realization, fabrication of functional building block named micro-tissue precursors and finally their assembly and maturation to obtain the final tissue. The micro-scaffold has been obtained by double emulsion photopolymerization that allowed the realization of porous gelatin micro-spheres having average diameter of 120 micron. Glyceraldehyde (GAL) has been used as crosslink agent to stabilize the gelatin microspheres. By varying the GAL crosslink extent it was possible to obtain micro-spheres having various degradation rate to simulate degradation of tissue matrix. The spontaneous degradation of the micro-spheres led to the release of GAL. The concentration of GAL was analyzed by means of spectrophotometric analysis and correlated with the degradation rate. In a second step, the micro-tissue precursors were composed by collagen sponge which consists of a porous chitosan scaffold containing a dispersion of GNRs, which acts as an absorber of the incoming laser light, and of thermosensitive polymeric micelles, which serve as a reservoir for the drug molecules to be released. The photothermal response of the nanoparticles contained inside the sponge triggers a contraction in proximal micelles, thus promoting the expulsion of the drug that in turn is released from the sponge to the external environment. Specifically, the thermosensitive micelles, composed of poly(e-caprolactone)- poly(ethylene glycol)- poly(e-caprolactone) (PCL-PEG-PCL) copolymer, underwent a 35% reduction in their volume almost instantly when the temperature dropped slightly above the physiological value while the chitosan enwrapping both GNRs and micelles plays here only a structural role and is stable at these temperatures. We proved the possibility of regulating the temperature generated in the sponge by laser illumination with a continuous wave diode laser light through a variation in the laser intensity (in the 0.3 - 0.5 W cm-2 range) and with a linear relationship within the temperature range of interest for the activation of the release (40 – 45 °C). The peculiar physiochemical and structural properties of the nanocomposite sponges impart a number of interesting features to this drug release system, including the possibility of spatially confining the therapeutic treatment as well as of precise control of the amount of released drug as a function of duration and power of the excitation light.

References
photodamage. Further investigation was carried out in order to assess biological responsiveness of HDE to UVA exposure. After UVA treatment HDE showed higher expression of matrix metalloproteinase (MMP1 and MMP2) compared with control. Taken together these results indicated that HDE are able to recapitulate in vitro relevant phenomena occurring in the human dermis during human daily life. In conclusion the realization of 3D living tissue in vitro has been proved feasible and. The tissue realized resembled most of the native human dermis features in terms of composition, ultra structure, collagen network organization and mechanical properties. The HDE can be imaged by means of non-linear optic techniques and it responds to external stimuli in a similar fashion as the native dermis. By coupling the living nature of the HDE and non linear, non invasive a stain-free optical techniques such as SHG imaging, it will be possible to realize biological platform in vitro. In this work we have carried out studies on photaging but the concept can be applied to a board range of cases: in vitro tumor model by realizing pathologic tissue, collagen reorganization after injury, to test the efficacy of therapeutics agents.

**8792-24, Session 5**

**Topographic mapping of microscopic objects using quantitative phase microscopy coupled with optical manipulation**

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Quantitative phase microscopy (QPM) allows dynamic mapping of optical path length of microscopic samples with high temporal and axial resolution. However, the central problem of QPM, which is decoupling geometric thickness from refractive index, remains to be solved. Here, we report use of optical tweezers combined with QPM for decoupling geometric thickness from refractive index. This is accomplished by orienting the microscopic sample by optical tweezers and imaging in various orientations using QPM. Since optical tweezers can orient wide variety of micro and nanoscopic objects, this method can be employed for accurate determination of physical properties.

**8792-25, Session 5**

**A novel simultaneous method for polarization retrieval in multi-heterodyne scanning near-field optical microscopy**

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Scanning near-field optical microscopy (SNOM) is a popular tool to overcome the diffraction limit for the investigation of subwavelength-scale optical structures. For nearly 30 years, various configurations have been implemented to characterize the interactions of the electromagnetic field with nanostructures in the near field. An accurate understanding of these interactions requires a detailed knowledge of the field, including the state of polarization (SOP) in the near field. The state of polarization is easily accessible in far-field microscopy, but is challenging to measure in the near field. When the SNOM probe interacts with the near-field and scatters the signal to the far field, the near-field polarization may be considerably altered. Moreover, the near-field polarization may be oriented in all three dimensions whereas far-field propagation implies a two-dimensional (transverse) polarization.

Recently, several phase- and polarization-sensitive measurements in the near field have been reported. Each of the methods introduces a polarization-selective element to a SNOM configuration to obtain polarization-resolved information and reconstruct the vector field. For example, recently M. Schnell et al. described interferometric detection of the near-field polarization state in nano-antenna gaps using a scattering-type SNOM (s-SNOM). M. Burresi et al. observed in collection mode the polarization singularities in a 2D photonic crystal waveguide with an aperture probe. In these examples, two sequential measurements are performed to obtain information for two orthogonal polarization states, enabling reconstruction of the state of polarization observed at the sample. L. S. Goldner et al. have demonstrated SNOM using a time-varying input polarization state to mitigate some of the concerns. Nevertheless, since the polarization measurements are not performed concurrently, this may introduce some measurement uncertainties due, for example, to drift from mechanical misalignment, changing condition of the probe, or time dependent phase drift. Multi-heterodyne scanning near-field optical microscopy (MH-SNOM) enables the simultaneous detection of two vector field components associated with each of two orthogonally polarized illumination beams. This provides further information about the SOP in the near field, although still does not provide the full three-dimensional SOP. In our previous work, we extracted concurrently from a MH-SNOM measurement the state of polarization using a polarization retrieval algorithm based on criteria predicted from simulations. However, these criteria are applicable only if the near-field response of the nanostructure can be determined by another method.

In this paper, we strengthen the algorithm by freeing it from a priori knowledge of the fields. We use an isotropic region in the vicinity of the nanostructure as a calibration area, whose known polarization properties provide a global criterion to calibrate the polarization distortion induced by the detection system. Moreover, with a tunable laser source, this process could be iterated to calibrate the system characteristics over the desired wavelength operating range. This makes MH-SNOM a powerful polarization-resolved tool which can be applied to analyze any polarization-dependent nanostructure with subwavelength resolution, as long as an isotropic region is available in its vicinity. This method could contribute to the fundamental study of polarization-sensitive nanophotonic structures such as photonic crystal microcavities, waveguides, thin films, nanoparticles and other nearfield polarization-sensitive imaging applications.

Due to their simplicity in terms of the near-field distribution and strong polarization dependence, form-birefringent gratings (FBG) are optimal structures to assess the polarization-retrieval algorithm proposed here. We experimentally demonstrate this algorithm by validating it in retrieving the polarization-dependent near-field distribution on silicon FBG. Due to the symmetries inherent in this one-dimensional grating and the configuration of the illumination beam—longitudinally oriented fields with respect to the probe are not excited—the full vectorial field emitted by this structure can be detected using the MH-SNOM. A description of the experimental set-up is first presented. Next, the polarization-retrieval algorithm used in this work is explained step by step. Then, the fabrication of the FBG is described. Afterwards, the results of near-field measurements are discussed: we first demonstrate the method through the retrieval of the measured near-field confinement on the FBG in three spatial dimensions. Then, pseudo-far-field measurements are performed to verify the effective refractive index of the FBG. Finally conclusions are presented.

**8792-28, Session 5**

**In situ imaging of the mouse cochlea using two-photon microscopy** (**Invited Paper**)  

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Sensoneural hearing loss is the most common type of hearing loss worldwide, yet the underlying cause is typically unknown. This is mainly because the inner ear cannot be biopsied today without destroying hearing, and intracochlear cells have not been imaged with resolution sufficient to establish diagnosis. Intracochlear imaging has been technologically challenging because of the cochlea’s small size and encasement in bone. We report in situ imaging of the mouse cochlea using endogenous two-photon excitation fluorescence (TPEF) as the contrast mechanisms. TPEF eliminates the need for exogenous labeling, eradicating the staining-induced artifacts; one of the two natural openings of cochlea, the round window, is used as the optical access to reach the hook region of organ of corti,
The development of strategies to reproduce the functional anisotropy of living tissue remains a puzzling challenge for tissue engineers. In human body, most biological tissues are composed of different cell types, each embedded in their specific extracellular matrix (ECM), with interwoven vasculature. During the development and the remodeling of tissues, most mechanisms of pattern formation are based on spatiotemporal heterogeneity, which induces the formation of a local microenvironment, including gradients of soluble or insoluble factors, and even physical forces. This suggests a dynamic reciprocity of form and function and further underlies the importance of engineering multicellular geometries to reproduce functional histitecture of live tissue and organs and to promote proper tissue remodeling and homeostasis.

Tissue Engineering (TE) is a multidisciplinary field, which applies the principles of engineering and life sciences toward i) the development of biological substitutes that restore, maintain, or improve tissue function or a whole organ, and ii) the production of realistic tissue constructs for in vitro applications. Regarding clinical applications, TE aims at resolving shortage in tissues and organs for transplantations. In vitro, tissue engineered “realistic” human surrogates serve for drug screening, chemical toxicity testing, as well as for basic cell biology. From a manufacturing prospect, two TE strategies have been implemented. The top-down TE approach is based on the design and the fabrication of 3D scaffolds, either synthetic or natural, or a decellularized organ, onto which cells are subsequently seed. Parallel to this approach, bottom-up TE has been introduced, and relies on the paradigm of assembling building blocks mimicking native functional units into larger tissue constructs using layer stacking, random packing, and 3D bioprinting. Bioprinting can be defined as the “use of computer-aided transfer processes for patterning and assembling living and non-living materials with a prescribed 2D or 3D organization in order to produce bio-engineered structures serving in regenerative medicine, pharmacokinetic and basic cell biology studies”. As for technologies, besides ink-jet printing and bioplotting, the Laser-Assisted Bioprinting (LAB) technology has emerged as an alternative method to print cells and liquid biomaterials with a cell-level resolution, thereby overcoming some limitations of other techniques, which are the clogging of print heads or capillaries due to viscosity, cell agglomeration, or ink drying. In this paper, we will demonstrate how LAB holds promise to fabricate living tissues with physiological functionality. After having introduced the rational of applying the LAB to tissue engineering, we present exhaustively the physical parameters related to laser induced forward transfer technique (LIFT) which is implemented in the LAB. These parameters are critical to control the cell printing process and must be adjusted according to each other to print viable cell pattern with respect to cell-level histiological organization, and to high throughput manufacturing. After describing the experimental requirements that should be considered to fabricate 3D tissues by LAB, we present some of the main breakthroughs including multi-component printing, 3D printing approaches, and bioprinting in vivo that may serve in tissue engineering and regenerative medicine.
Multi-wavelength digital lensless holographic microscopy: a simple approach to color digital holographic microscopy (Invited Paper)

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The use of multiple wavelengths has brought new opportunities to digital holography (DH). In DH, namely the electronic recording of holograms with numerical reconstruction, the use of colors was introduced by Yamaguchi who implemented the hologram reconstruction by means of a phase-shifting approach [1]. Since then, multi-wavelength DH has been used to improve the performance of interferometric system for numerous applications; color dynamic measurement of flows [2, 3], optical metrology systems of high-resolution [4], study of cracks in electronic printed circuit boards [5], are some of the current uses of color DH. In order to avoid the decoding of the color recorded holograms, most of the applications utilize multiple shooting over monochromatic digital cameras. However, for many applications the multiple shooting may be inconvenient, hence color DH has been highlighted to enable one-shot or double-shot the needed chromatic channels [6, 7]. The former developments added to the correct compensation of the chromatic aberrations [8] and/or the use of spectral estimation techniques [9], have greatly improve the performance of color DH. Notwithstanding the wide use of color DH to study millimeter-sized objects, only few applications have been reported in the field of digital holographic microscopy (DHM) [10-12]. That limited use of color DHM may be due to the need of two illumination arms: reference- and object-arm for the off-axis applications. For the two-arm architecture of DHM, the main limitation arises from the sensibility of the required laser wavelengths to the chromatic aberrations that are present in the color DHM. These aberrations, which are inherited from optical set-ups and the numerical processing of the electronically recorded holograms, must be reduce to recover useful images of the micrometer sized world.

The possibility of studying colorful biological specimens powers the seeking of different approaches that simplify the use of color DHM. As an alternative to colorful life sciences studies, in this contribution is presented color digital lensless holographic microscopy (CDLHM) [13]. This multiwavelength approach to DHM, uses three lasers with wavelengths for red, green and blue in an in-line configuration. Each laser is utilized for recording monochromatic hologram each one called in-line hologram. Each hologram is reconstructed by means of the computing the diffraction that a spherical wavefront undergoes on the recorded hologram in-line hologram. For CDLHM this diffraction process is correctly described by Kirchhoff-Helmholtz transform [14].

The numerical implementation the Kirchhoff-Helmholtz transform allows for manipulating the sizes of the reconstructed pixel over the reconstruction plane [14]. The correct use of this feature permits the reduction of the chromatic aberration on the colorful reconstructed image.

CDLHM has been used to image a paraffin wax section of the head of a drosophila melanogaster fly (fruit fly). The section is about 1000 µm wide and the sample has a thickness of the order of 10µm. The CDLHM microscope has been built with a CMOS monochrome camera of 1280x1024, 6.7 m square pixels. Three solid state lasers with wavelengths 671(red), 532 (green) and 473 nm (blue) are aligned with a plan apochromat microscope objective. The use of this microscope objective minimizes the waist variation of the focused beams; hence white illumination of the sample is obtained for perfect alignment. A hologram in this work of CDLHM is based on the composition of the color reconstructed image by the proper merging of the individual red, green, and blue color channels. Each color hologram is reconstructed with the corresponding wavelength for reconstructed image planes with exactly the same dimension. This condition on the sizes is mandatory to guarantee the best possible merging of the reconstructed images for each color channel and the reduction of the chromatic aberration. The resulting merged RGB image shows details with dimensions on the micrometer range. Because the inhomogeneous absorbance of the sample for the three wavelengths, each color channel presents unique details and/or different irradiance levels for the structures of the sample. That means that the use of
a unique wavelength in digital in-line holographic microscopy could lead to misleading conclusions. The RGB image presents clearly details that are unseen or faintly visible for the individual color channels. Essentially, the merging of the information gathered by each wavelength into a single RGB image renders a better performance of the CDLHM over the monochrome digital in-line holographic microscopy [15]. This enhancement is because the RGB image collects in a unique view the separate spectral views of the sample. In this contribution further details about the implementation and performance of CDLHM are presented.

References

8792-35, Session 7
New method of 3D tracking of in vitro cells by digital holographic microscopy
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Many studies report on the ability of digital holography to track particle, microorganism and cells and there are several methodology to obtain the 3D positions. The typical strategy adopted in digital holography for the tracking of living cells consists into estimate the 3D position dividing the calculation process into two parts: the estimation of the focal plane (i.e. the Z coordinate along the optical axis of the imaging systems) on the amplitude reconstruction of the digital holograms, and the estimation of the transverse coordinates by the phase reconstruction of digital holograms computed at distance d equal to the estimated focal plane. About the estimation of the focal plane, several autofocus approaches were developed in digital holography for pure phase objects for live-cell imaging. These techniques are based on a suitable image contrast coefficients and perform a numerical scanning of the focus. Instead the localization in the plane can be computed through different image segmentation methods. We propose a new strategy for both focal plane estimation and image segmentation. In particular, we propose to use an approximation of the Tamura coefficient, as image contrast measure, for the estimation of the in-focus distance. This metric has been applied successfully for the amplitude reconstruction of digital holograms of macroscopic scattering objects. Instead, for the estimation of the transverse coordinates, we introduce a new morphological operator that we have called minimum boundary filter (MBF). This operator is robust with respect both noise and morphological variations of cells. In fact, the most popular image segmentation techniques used in the holographic tracking methods introduce position estimation errors caused by these two aforementioned issues. Instead the MBF is built specifically to take into account the morphological changes during the cells migration. We test the proposed method in a typical situation for which extensive changes in cells morphology are associated to cells motion and we perform a comparison between other popular strategies of both autofocusing and image segmentation algorithms.

8792-36, Session 7
Visualization of 3D surface acoustic waves in granular media using digital color holography
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The perspective of measurement of 3D vibration motions using digital Fresnel holography could be very important for better comprehension about the fundamental dynamics of disordered granular materials. It is established that continuum elasticity, applied to grain assembly, actually decreases significantly below a length scale of typically 30 to 50 grain sizes [1,2]. At shorter scales the response of an unconsolidated granular material even to normal compression loading is nonaffine, i.e. contains additional component of the displacement field of predominantly rotational nature, which is rather controlled not by the symmetry of loading but by the characteristic of the disorder. Consequently 3D monitoring of the dynamics of disordered granular media could provide opportunity to study 3D nonaffine motion, to characterize its spatial scale and statistic (correlation) properties. Previous experiments used a velocimetric doppler set-up in order to characterize the media [3]. In this paper, we present an experimental investigation of the 3D motion of granular medium excited by a vibrating shaker using three-color digital holography. The set-up provides a full field visualization and measurement of 3D acoustic waves propagating at the surface of the medium. Digital holography is a powerful technique to measure the mechanical amplitude and phase of an excited vibrating object. Numerical 3D sensing in digital color holography uses the relation between the 3D displacement vector of the object, U, the phase differences of two different states of the object, and the sensitivity vector S, which is related to the illumination and observation vectors: \( f \sqrt{\int f_0} = 2 f / \sqrt{\int} \), where \( f_0 \) is the current wavelength. The use of three different wavelengths, providing three different equations, permits to retrieve the 3D displacement field [4]. This basic principle gives an opportunity to measure and visualize 3D acoustic waves propagating at the surface of a granular media. The digital color holographic set-up is described in Fig. 1. Three laser wavelengths in the red, green and blue color (i.e. 660nm, 532nm, 457nm respectively) are used to illuminate the object. The laser beams are combined by dichroic plates in the reference beam, and the object beams are separated using three polarizing beam splitters. Then, the object waves illuminate the useful area along three dissociated
Optics with diatoms: towards efficient, bioinspired photonic devices at the micro-scale

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Diatoms are among the dominant phytoplankters, ubiquitously diffused in all oceans and freshwaters. They appear as monocellular algae, sometimes forming colonies, in a huge variety of species (up to 105 known and classified species), shapes and dimensions (2–500 microns in diameter) and are responsible of 20–25% of the global oxygen produced by photosynthetic processes. The protoplasm of every single cell is enclosed in an external wall made of porous hydrogenated silica, the frustule, formed by two valves interconnected by a lateral girdle. The different families of diatoms can be classified into two main orders: Centrales, characterized by a radial simmetry of the frustule, and Triceratops, which are bilaterally symmetrical. Frustule generations, whose dimensions can range from nanometer to micrometer scale (depending on species and position in the cell wall structure), interact very efficiently with light by means of diffractive processes, as it was well known by XIX century microscopists who exploited the iridescence of diatom frustule in order to assess the quality of the optics of their instruments. Frustules and their complex pores architecture could have been designed over billion years of evolution not only serving as mechanical protection and filter against external environment, but also as very efficient light collector, explaining in this way the high photosynthesis efficiency which characterizes diatoms also in very harsh environmental conditions.

In recent times, more effects related to photonic properties of diatom frustules have been discovered. Light coming both from coherent or non-coherent sources is efficiently confined and collected by a single valve of the centric diatom Coscinodiscus walesii, due to coherent superposition of the diffractive contributions of the single pores; the spatial position of the spot in which light is confined is strongly wavelength-sensitive, according to diffraction laws. Valves from diatoms of Arachnoidiscus genus are able to confine light in a train of discrete spots, exploiting a Talbot-like diffractive effect; furthermore, polarization of incident light is selectively affected by the elongated radial slits of the valve. Photoluminescence coming from Thalassiosira rotula frustules has been applied as transducing element in chemical and biochemical sensing schemes, due to the ability to functionallize the porous surface of the valves with the proper, selective biopores. Photonic-crystal-like behavior of valves and girdles has been quantitatively estimated in terms of supported modes and photonic-band structure analysis for the centric diatom Coscinodiscus granii. In present work we show several techniques, both experimental and numerical (e.g. digital holography, polarization microscopy, Wide-Angle Beam Propagation Technique algorithm, Finite-Difference Time-Domain algorithm) allowed us to retrieve information on how diatom cell walls, mainly from Coscinodiscus and Arachnoidiscus genera, manipulate light in terms of amplitude, phase and polarization, both in air and in a cytoplasmatic environment. Numerical algorithms properly designed for the propagation of amplitude and phase of the optical field starting from the acquired hologram of the valve allowed to reconstruct how light is redistributed inside the cell and how this is correlated with relocation of plastids as a function of different lighting conditions. Possible applications in optical microsystems of diatom frustules and frustule-inspired devices as active photonic elements are finally envisaged.
We describe a dual-trap force-clamp configuration that applies constant load between a binding protein and an intermittently interacting biological polymer with a measurement delay of only ~10 µs.

8792-26, Session JS2

Investigation on 3D morphological changes of in vitro cells through digital holographic microscopy

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Digital holographic microscopy is a powerful tool for the imaging of micro-objects contained into a three-dimensional (3D) volume. Cells, display a very singular behavior when seeded in 3D matrices like collagen, fibrin or cell derived matrix. In fact, cells scan the surrounding environment and highly dynamic membrane processes are continuously projected out the cell body in order to eventually forming new adhesions. Such a dynamic morphology might hamper the estimation of the cell dimensions as well as the assessment of its real position in the 3D volume. In particular, the correct estimation of the position, through a typical 3D holographic tracking, is highly influenced by morphological variations. Therefore, we proposed to use the quantitative phase-contrast map, obtained from the digital holograms of cells recorded in microscope configuration, in order to investigate 3D positions and 3D morphological changes together. In particular we are able to establish if, from one moment to the next one, the cell really changes its position, or simply is probing the surrounding environment or both. This aspect is investigated by introducing a morphological parameter that we have called Minimum Boundary Region (MBR). The MBR extracts the two dimensional (2D) minimum region of interest that the cell occupies from one moment to the next one providing both the real movement, quantified by the center of mass, and the morphological changes, by extraction of the membrane processes used for new adhesions. Obviously, we assume that the variation along the third dimension between two subsequent quantitative phase maps is negligible. In addition, the other classic 2D and 3D morphological parameters are calculated and the analysis of the of the variable 3D shape is supplied.

8792-27, Session JS2

A new 3D tracking method exploiting the capabilities of digital holography in microscopy

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A method for 3D tracking has been developed exploiting Digital Holographic Microscopy (DHM) features. In the framework of self-consistent platform for manipulation and measurement of biological specimen we use DHM for quantitative and completely label free analysis of specimen with low amplitude contrast. Tracking capability extend the potentiality of DHM allowing to monitor the motion of appropriate probes and correlate it with sample properties. Complete 3D tracking has been obtained for the probes avoiding the issue of amplitude refocusing in traditional tracking processing. Our technique belongs to the video tracking methods that, conversely from Quadrant Photo-Diode method, opens the possibility to track multiples probes. All the common used video tracking algorithms are based on the numerical analysis of amplitude images in the focus plane and the shift of the maxima in the image plane are measured after the application of an appropriate threshold. Our approach for video tracking uses different theoretical basis. A set of interferograms is recorded and the complex wavefields are managed numerically to obtain three dimensional displacements of the probes. The procedure works properly on an higher number of probes and independently from their size. This method overcomes the traditional video tracking issues and the inability to measure the axial movement and the choice of a suitable threshold mask. The novel configuration allows 3D tracking of micro-particles and simultaneously can furnish Quantitative Phase-contrast maps of tracked micro-objects by interference microscopy, without changing the configuration. In this paper, we show a new concept for a compact interferometric microscope that can ensure the multifunctionality, accomplishing accurate 3D tracking and quantitative phase-contrast analysis. Experimental results are presented and discussed for in vitro cells. Through a very simple and compact optical arrangement we showed how two different functionalities can be accomplished by the same optical setup, i.e. 3D tracking of micro-object and quantitative phase contrast imaging.

8792-43, Session 9

Optical elastography: progress in medical micro-imaging of tissue mechanics (Invited Paper)

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Examination of patients by palpation, the sensing of tissue stiffness (elasticity) through touch, is one of the physician’s most basic tools to identify abnormal or diseased tissues and organs. It also features prominently in surgery in general and in cancer surgery in particular: surgeons commonly palpate tissues in an attempt to identify tumour margins during excision. However, palpation is limited by its subjectivity and low resolution, making it challenging to detect small or indistinct regions of malignant tissue. Assessing the small-scale changes in tissue elastic properties that can indicate precisely the extent of a cancer using imaging may offer new surgical tools that enable improved differentiation of tissue pathologies.

In elastography, tissue elastic properties are estimated by subjecting a tissue to a load (stress), measuring the resulting displacement throughout the tissue under study using an imaging modality, and using the results to estimate the elasticity at each position. The resulting image of tissue elasticity is known as an elastogram.

Elastography methods date back to the early 1990s, and since then the field has undergone rapid development, with ultrasound and the most commonly employed modality, and magnetic resonance elastography, rapidly following. According to simple searches conducted on the ISI Web of Science, ultrasound elastography alone currently produces more than 300 papers and more than 5,000 citations per year, and both modalities are commercially available. The current spatial resolution and sensitivity of such elastography techniques are suboptimal for many applications, especially in the guidance of cancer surgery.

Since the first demonstration in 1998, 3 methods based on optical coherence tomography have shown promise for increasing the resolution and sensitivity of elastography. Apart from the inherent limitation of penetration depth faced by all optical techniques, several other factors have impeded the progress of optical elastography.

Firstly, as the elasticity is derived from the measured displacement, very sensitive displacement measures are required to achieve high sensitivity to changes in tissue elasticity; methods with such sub-micrometer sensitivity, spanning a range of 4 seconds to 0.02 seconds, are needed to apply a load to tissues are still evolving and present difficulties yet to be overcome. Quasi-static loading, such as compression, results in a non-uniform stress field when the target tissue is heterogeneous, as is often the case of interest. Accurate determination of tissue elasticity from the resulting deformation requires determination of the stress field, which has yet to be demonstrated. An alternative to surface loading is spatially localized internal loading, using focused ultrasound for example, and such methods are being actively investigated. 5, 6

Optical elastography has previously been largely based on schemes that use small tissue samples, but not intact tissues, and have not had the sensitivity or range to produce high-fidelity images of mechanical properties. We have targeted both these issues in our recent work, 7-14 developing means of access to in vivo tissues and improving the sensitivity and range of optical elastography by using phase-sensitive optical coherence tomography to measure...
displacement. The use of optical coherence tomography to perform elastography has come to be referred to as optical coherence elastography.3

We began by developing a practical in vivo imaging system based on a ring actuator capable of dynamic loading in the kilohertz range.7, 8 We extended this to three-dimensional in vivo operation10 and explored varying the load frequency.9 Latterly, we have substantially refined our approach to achieve 200 pm displacement sensitivity11, 12 and have implemented biomechanical models of deformation that demonstrate excellent agreement with experiment. In addition, we have demonstrated the first implementation in a needle probe, enabling optical elastography to be performed deep in tissues.13

In this talk, I will describe our advances, including examples of the current state-of-the-art in elastography imaging of tissues, in both animal models and in humans.

References:
needed for the characterization of tissue-like biomaterial specimens. For demonstration we show the performance of our setup for the investigation of fiber-reinforced polymer structures during tensile mechanical testing (as depicted in Figure 1), or for observing movements and displacements within biological micro-samples. We show that miniaturized details such as fiber end delaminations, evolving cracks or arising micro-defects can be revealed within the material during the testing process. By subsequent mathematical image processing the visualized structures can be analyzed and evaluated with respect to their localizations and distributions. The change of fiber orientations, the displacement of inner structures, and the temporal development of the micro-defects during the testing process may provide valuable insights into material properties under dynamic process conditions. In addition, a polarization sensitive version of our FF-OCM configuration may deliver additional information about the probed materials, like birefringence and internal strain.

In our presentation we will further discuss the multiple use of Riesz-transform based (monogenic) approaches: on one hand using spiral phase filtering in optics for the isotropic contrast enhancement in microscopic or interferometric imaging [3, 4], on the other hand in signal processing being applied as mathematical basis for a demodulation scheme of two-dimensional amplitude-frequency signals [5, 6]. These demodulation methods are in particular of advantage and even a requirement for the analysis of dynamic processes observed by FF-OCM imaging. Additionally, we will describe anisotropic contrast modification based on optical Fourier filtering with filters mathematically describable by either fractional Riesz transform kernels, monogenic curvelet-like kernels, or 2D analytic kernels [7, 8]. The mutual advantages of isotropic and anisotropic contrast modifications are regarded for organic coatings and layered structures with respect to microscopic and FF-OCM imaging.

Summarizing, we will demonstrate how the combination of mathematical, optical and technical improvements can increase the strength of the FF-OCM imaging towards advanced material characterization in the micron-range. We expect that our methods can also be adapted for applications in the field of micro-fluidics in the future.

References:

8792-46, Session 9

Variable-focus diffractive Moiré-lenses

Walter H. Harm, Stefan Bernet, Monika Ritsch-Marte, Innsbruck Medical Univ. (Austria)

1. Introduction:

Optical lenses of variable focus are desirable for various applications such as imaging [1] and beam steering [2]. We demonstrate the experimental realization of high efficiency variable-focus lenses consisting of a pair of diffractive optical elements (DOEs) fabricated in (0.75 mm) glass slides. The adjustable diffractive power of the optical elements is highly reproducible and remains fixed without applying any external thrust force by pressure or voltage.

2. Diffractive Moiré-lenses:
The DOEs are designed such that the optical thickness of two axially stacked elements corresponds to that of a Fresnel zone lens [3]. The basic principle is similar to the Moiré-effect, where a superposition of two gratings with similar grating constants enhances a structure with a much larger spatial beating period. The refractive power of the combined optical system can be continuously adjusted by rotation around the central axis of one element with respect to the other. Each element contains a two-dimensional 4 bit (16 level) phase structure ranging from 0 to 2 with a pixel size of 2 μm designed for 633 nm illumination fabricated by lithography and subsequent etching. Geometric lens aberrations can be excluded by design. Furthermore, the structure of the DOEs could in principle be tailored to correct spherical aberrations of a standard lens or to compensate chromatic aberrations in a compound refractive/diffractive optical system [4].

3. Experimental results:

We measured a peak diffraction efficiency of assembled Moiré-lenses of 86 % which theoretically can be increased by a higher bit depth of the phase structure. The imaging quality was characterized by a diffraction limited point-spread-function for quasi-monochromatic illumination. The key advantage of diffractive Moiré-lenses is that focusing requires no axial shift of the lens, as necessary in a conventional lens. We assembled a zoom telescope where the ability of tuning the refractive power D in the range of ±40 diopters enables the crossover between a Kepler telescope (D1,D2 > 0) and a Galilei telescope (D1 > 0, D2 < 0) with two Moiré-lenses at fixed positions. Diffractive optical elements, however, are strongly dispersive, which leads to chromatic aberrations in broadband applications. Nevertheless, depending on the requirements diffractive Moiré-lenses can even be used for white light imaging. The compact design of the proposed lenses makes them especially useful for situations with strict space or weight limitations. We have experimentally investigated the performance of four designs of Moiré-lenses with different diffractive properties for imaging and beam steering applications.

Specifically, SICM is a powerful means to obtain topographic 3D images of living cells with high resolution and without perturbing them (far-scanning mode). Since its inception, several research groups have devised and developed other operational modes. Among the possible applications, one of particular interest permits the application of an external pressure to the specimen via a solution flux coming out from the pipette aperture. This method has been employed to measure cell membrane elasticity. Another approach is based on placing the pipette closer to the cell and recurrently scanning along a defined line (near-scanning mode). In this way, it has been demonstrated that one can guide the cone growth cones of neurons for tens of micrometers.

In both cases reported, accurate measurements of the mechanical forces acting on the cell membrane are essential. Herein, we describe our work on the past few years devoted to calibration of the pressure force present at the pipette aperture, essential to measuring the elastic properties of cell membranes and also to guiding neuron growth. Our experimental setup combines together SICM, Atomic force microscopy (AFM) and inverted optical microscopy. In this configuration, a SICM pipette can be approached to an AFM cantilever while monitoring the cantilever deflection as a function of the pressure applied to the pipette and the relative distance. In this way we can directly measure mechanical forces down to 20 pN. Operating in AFM mode, we can also directly image the pipette aperture in situ. The same apparatus is thus sufficient to completely calibrate a given pipette and immediately use it to study the pressure effects on living cells.

Regarding the measurement of cell membrane elasticity, we have demonstrated that the sample deformation induced by an external pressure applied to the pipette can be indirectly and reliably evaluated from the analysis of the current-displacement curves. This method allows us to measure the linear relationship between indentation and applied pressure on uniformly deformable elastomers of known Young’s modulus. Finally, we have applied the same method to murine fibroblasts in order to show that it is sensitive to local and temporally-induced variations of the cell surface elasticity.

In addition, we have been able to measure the force induced by a constant hydrostatic pressure applied via the pipette. A filling level of the pipette different from the capillary tension value determines a hydrostatic pressure, a flux through the pipette tip and detectable forces, even in far-scanning mode. The absolute value of these forces depends on the pipette tip size. Our data indicate that, operating in far-scanning mode with current decrease values below 2%, no force can be detected provided that the level of the electrolyte filling the pipette is equal to that determined by the capillary tension. A filling level different from this value determines a hydrostatic pressure, which can be either positive or negative. Therefore, we have found a possible pitfall when using SICM for cell imaging: far-scanning does not always imply zero-force working conditions. Nevertheless these hydrostatic forces can be exploited in order to deliver weak mechanical stimuli and guide neuronal growth cones. Evidences of the effectiveness of this approach are finally given.

References

8792-48, Session 9
Lensfree computational imaging (Invited Paper)
Aydogan Ozcan, Univ. of California, Los Angeles (United States)

Today there are around 6 billion cell-phone users in the world, and the majority of these cellphones are being used in the developing parts of the world. This massive volume of wireless phone communication brings an enormous cost-reduction to cellphones despite their sophisticated hardware and software capabilities. Utilizing this advanced state of the art of the cell phone technology towards point-of-care diagnostics and/or microscopic imaging applications can offer numerous opportunities to improve health care especially in the developing world where medical facilities and infrastructure are extremely limited or even do not exist.

Centered on this vision, in this talk I will introduce new imaging and detection architectures that can compensate in the digital domain for the lack of complexity of optical components by use of novel theories and numerical algorithms to address the immediate needs and requirements of Telemedicine for Global Health Problems. Specifically, I will present an on-chip cytometry and microscopy platform that utilizes cost-effective and compact components to enable digital recognition and 3D microscopic imaging of cells with sub-cellular resolution over a large field of view without the need for any lenses, bulky optical components or coherent sources such as lasers. This coherent holographic imaging and diagnostic modality has orders of magnitude improved light collection efficiency and is robust to misalignments which eliminates potential imaging artifacts or the need for realignment, making it highly suitable for field use. Applications of this lensfree on-chip microscopy platform to high-throughput imaging and automated counting of whole blood cells, monitoring of HIV+ patients (through CD4 and CD8 T cell counting) and detection of waterborne parasites towards rapid screening of water quality will also be demonstrated. Further, I will discuss lensfree implementations of various other computational imaging modalities on the same platform such as pixel super-resolution imaging, lensfree on-chip tomography, holographic opto-fluidic microscopy/tomography. Finally, I will demonstrate lensfree on-chip imaging of fluorescently labeled cells over an ultra wide field of view of >8 cm2, which could be especially important for rare cell analysis (e.g., detection of circulating tumor cells), as well as for high-throughput screening of DNA/protein micro-arrays.

8792-72, Session JS2
Nano gold markers tracked and localized in cell
Michel Gross, Univ. Montpellier 2 (France); Frederic Verpillat, Lab. Kastler Brossel (France); Pierre Desbiolles, Ecole Normale Supérieure (France)

By using the dark field holographic microscopy technique described in Opt. Express, 19 pp 26044–26055 (2011) we have track gold particles in brownian motion in living cells. First results are presented. The particles remain confined to a region a few microns in size.

8792-37, Session 8
Rheology at the micro-scale: new tools for bio-analysis (Invited Paper)
Rebecca L. Warren, Manlio Tassieri, Xiang Li, Andrew Gidle, David J. Paterson, Allan Carlsson, Jonathan M. Cooper, Univ. of Glasgow (United Kingdom)

The study of physical and biological phenomena at very small scales has been made possible thanks to developments in micro- and
nano-scale science, coupled with the commercialization of new instrumentation and equipment, available at relatively low prices. For example, the progressive improvements in imaging technologies associated with CCD and CMOS cameras, providing increased sensitivities and speed at relatively modest prices, have opened up new fields in biophysics and medicine. These trends have also been seen in Lab-on-a-Chip, where the rapid analysis of complex biological solutions has enabled new technologies in medical diagnostics and drug delivery.

Sitting between the two areas of instrumentation and microfluidics is the field of rheology, which is the study of materials’ viscoelastic properties, exploring the interactions between macromolecules, such as polymers, and their solvents. Microrheology is a branch of rheology, which is underpinned by the same principles as conventional bulk rheology, although experiments and information are obtained on micrometer-length scales. The development of techniques in microrheology has dramatically reduced the sample volume that can be analysed (down to ~1 µl) compared with the sample volume used for conventional rheology (more than 1 ml); making it particularly suitable for use with rare and expensive materials, including biological samples. As a consequence of these small scales, microrheology measurements have the potential to be performed in situ in an environment that could not be reached by bulk experiments; e.g. inside a living cell.

The mechanical properties of the cell’s cytoskeleton can influence factors such as growth, apoptosis, motility, signal transduction and gene expression. To this end, there is a desire to be able to provide a rheological interpretation of the cell’s viscoelastic properties that has the potential to yield quantitative information on the cell’s cytoskeletal structure and dynamics. The interpretation of rheology measurements performed on living systems such as cells is not trivial and represents a lively point of discussion in literature.

A fundamental reason for the recent interest in the development of microrheology techniques has been that these techniques operate with the appropriate range of sensitivity, in terms of force (pN), position (nm) and time (s), required to study a wide range of biological processes. Indeed, biophysical studies were initially very quick to take advantage of microrheology techniques for such purposes as measuring the compliance of bacterial tails, the forces exerted by single motor proteins and the stretching of a single DNA molecule. Since this initial activity, a wide variety of microrheology techniques have been developed so far and the area continues to advance with a series of technical and theoretical barriers being overcome.

The microrheology techniques most commonly used are: passive video particle tracking, magnetic tweezers, optical tweezers, diffusing wave spectroscopy and atomic force microscopy. With the exception of the latter, these techniques are all based on the observation of either the free or driven motion of micron-sized beads suspended in the solution under analysis. The time trajectories can be directly related to the mechanical (viscoelastic) properties of the molecules and their solvents. The material’s viscoelastic properties can then be related to the topological structure of the sample with the potential of revealing information down to the molecular level (e.g. intra-membrane).

An example of such studies is the denaturation of amyloid proteins leading to the formation of fibrils and plaques, associated with many pathologies including Alzheimer’s diseases. There is the clear potential of using these techniques as new bio-analytical methods for observing the dynamics of protein interactions during amyloid formation, and testing the efficacy of drugs in disrupting or reversing these processes. This could be performed either in a high throughput microfluidic format, in vitro, for new drug screening, or excitingly, within cells and tissues showing symptoms of these chronic degenerative diseases.

Recently we have introduced a data analysis procedure for determining the linear viscoelastic properties of complex fluids via microrheology measurements with optical tweezers [Tassieri et al. (2012) New J. Phys. 14, 115032]. In particular, the improved data analysis procedure provides the solution to a long-standing issue in microrheology studies, i.e. the evaluation of the fluids’ linear viscoelastic properties from the analysis of a finite set of experimental data. By properly designing the micro-channel and by using a viscoelastic liquid (a solution at 0.4% polyethylene oxide in water by weight) as the suspending medium we were able to determine particle migration towards the center of the channel [3] and hence to realize a precise 3D focusing of the target particle. The forward scattering of the emitted particle was collected by an aspheric lens with high numerical aperture. Further at the focal point of that lens a homemade beam splitter was reflecting the incident laser light out of the collecting system. Concluding the collection phase, a plano-convex lens mapped the scattered light on the CCD sensor of the camera. This two lens system allowed to obtain far field images on short distances. [2] Each speckle corresponded to the same magnitude of the scattering wave vector q (but different azimuthal orientations were collected by one ring, where the wave vector q = 4πsinθ/2, with the scattering angle, and the laser wavelength. [2]

Pinholes with well known size of 10 and 20µm placed at the sample position were used to align and calibrate the system. Measurements of the particles were performed on mono-disperse polystyrene (PS) latexes having diameters of 2, 4, 6 and 8µm, both in quiescent (multi-particle signal) and in flow (single-particle signal) conditions. The complex refractive index of PS was assumed to be 1.58722 ± 0.000001 for the wavelength used (λ = 632.8nm). [5] For the medium, a refractive index of n = 1.33168 was assumed. [4] Measurements in quiescent conditions were implemented with rectangular glass capillaries placed at the same position of the micro-channel. The solution was strongly diluted to minimize multiple-scattering, and 50 successive frames with an exposure time of 1µs were collected. The intensity of each pixel was first averaged over 50 frames and then the radial averaged intensity was calculated. Finally, a background intensity subtraction (glass capillary filled with water measured over 50 frames) was performed. Results were validated by comparison with calculations based on the Lorenz-Mie theory. [1]

For the in-flow measurements a homemade microfluidic device was used. In particular, a syringe pump supplied a flow rate of about 2.5µl/ min which was needed to focus the particle on the top of the capillary with inner diameter of 75µm. The round capillary was connected to a homemade microfluidic device, where the particles kept on track in
the center until the end of the 50mm long and 1mm wide rectangular channel used for the measurements. Scattering profiles from streams of both mono-disperse and mixed particles were recorded for 150 frames at exposure times of 3µs. The resulting quality of the intensity profiles was comparable to the quiescent measurements corroborating the possibility to use this apparatus in real multiplex applications. Moreover we expect that more complex systems, like multi-shell, or non spherical particles can now be characterized in terms of single particle features.

References:

8792-39, Session 8

Photo-pyro-electrohydrodynamic dispensing by using gold nanorods

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Displacing and manipulating small amounts of liquids are crucial maneuvers in microfluidic systems. Here a reduction in size to the micrometric length scale may improve controlled mixing, expedite chemical reactions and reduce the consumption of expensive reagents. This brings microfluidic technologies to be applied in many fields, with medical diagnostics and bio-sensing being important application areas. Fine control over liquid dispensing and motion on a micrometric length scale is typically obtained through mechanical, electric or magnetic forces. The activation of these forces relies on the geometry the laser light which triggers the pyroelectric effect.

Recently, a novel technique based on the pyro-electrohydrodynamic effect from lithium niobate (LN) has been proposed to draw attoliter liquid droplets, to plot solid photonic microstructures or to manipulate dielectric micro-targets [1-3].

On the other hand gold nanorods (GNR) have been extensively used in a broad range of applications because of their unique optical and photothermal properties. The optical response of GNR originates from sharp plasmonic resonances. Their prolate shape gives two intense sharp plasmonic resonances. Their prolate shape gives two intense
drawn from a reservoir in an all-optical device. Without mechanical and electrical parts this setup can be very compact and versatile thanks to the possibility of structuring at high spatial resolution and complex geometry the laser light which triggers the pyroelectric effect.

This method is applicable to different kinds of liquids, including oil and water with a rather fast response since the ejection of droplets begins in seconds after the laser light is switched on. The possibility to use NIR laser diode light to induce pyro-EHD pressures opens the way for compact, low-cost and integrated systems with minimal interference with the solvents and reagents constituting the liquid droplets.

Moreover this system can be very precise in terms of the spatial resolution, which may be limited by the optical resolution only.


8792-40, Session 8

Non-invasive continuous imaging of drug release from soy-based skin equivalent using wide-field interferometry

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Over the past decades, biodegradable polymer based devices have attracted the attention of many researchers and clinicians as implantable drug-delivery devices. However the underlying mechanism of drug release from biodegradable polymer devices is not fully understood. This mechanism cannot be related to diffusion only due to the fact that it involves chemical and physical reactions (e.g., polymer degradation). In general, many factors may influence degradation and drug release processes. For example, the geometry of the biodegradable device (e.g., porosity), polymer and drug type (i.e. composition), immersion media type, all, individually and mutually, have great effect on the degradation and drug release process. These factors make the mathematical modeling of drug release process a challenging task. Moreover, the extrapolation of the in-vitro results into characterization of in-vivo devices is even more difficult and hence hardens the developmental process of such devices.

Current techniques for drug release assessments, such as infrared spectroscopy and chromatography are intrusive due to the fact that they require the extraction of some of the immersion media in each measurement. In addition, this kind of measurement cannot provide whole-environment analysis which can be useful in understanding the drug release mechanism. Moreover, it cannot provide vital information on the different degradation stages of the biodegradable device, which is a crucial factor in the drug release process.

In this work, we suggest to use wide-field off-axis interferometry as a unique quantitative imaging method for characterization of drug release and polymer degradation. Moreover, we suggest to use phase imaging carried out by interferometry as a tool that quantifies drug release.

By using interferometry, we can continuously and noninvasively capture the drug release from the polymer in its immersion media, and provide whole-environment analysis without the need for scanning. Our underlying assumption is that drug release will result in an immediate local change in the refractive index of the immersion media and consequently a local change in the quantitative phase profile.
of the sample, and thus provides volumetric profile measurements. In addition to the phase information induced by drug release, the wide-field imaging and the ability to perform continuous measurement have the potential to improve the current drug-release mathematical models.

For this purpose, we have constructed a noise reduced, wide-field interferometric imaging system, which is based on single element common-path interferometer. The imaging system is coupled to a low-coherence light source (Fanium SC400 + acousto-optical tunable filter, FWHM = 6 nm). Due to the common-path property of the setup, no beam-path matching is required in order to obtain interference with low-coherence light source. Moreover, a dual-channel imaging of two 180°-degree phase-shifted interferograms can be obtained and used in achieving a single, noise-reduced and DC-suppressed interferogram.

For drug-release analysis, we have used a soy-based skin equivalent which contains a drug.

The skin equivalent was immersed in phosphate-buffered-saline (PBS) for 4 hours, where no enzymes were introduced to the medium in order to avoid degradation. Every half an hour, the immersion media was captured by the interferometric system.

From the captured interferograms, we have extracted the quantitative phase profiles, from which we were able to observe significant changes over time due to drug release. These preliminary results demonstrate the high potential of our method in wide-field imaging of drug release from polymers and the application of interferometric microscopy for tissue engineering applications.

8792-41, Session 8

Laser microfabrication of biomedical devices: time-resolved microscopy of the printing process (Invited Paper)

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Laser printing constitutes an interesting alternative to other more conventional printing techniques in the microfabrication of biomedical devices. It allows generating micrometric patterns from a digital file through the action of a laser in an additive way. In contrast to inkjet printing, its main competitor, laser printing is free from clogging issues, and presents practically no constraints concerning the printable solutions: almost any liquid can be successfully printed with minimal engineering of its physical and chemical properties.

The principle of operation of most laser printing techniques relies on the highly localized absorption of strongly focused laser pulses in the close proximity of the free surface of the liquid to be printed. This results in the generation of a cavitation bubble underneath the free surface; once generated, the bubble expands, displacing the liquid around it. Then, a fraction of the liquid is propelled away, and collected onto a substrate. Provided that both the depth of the bubble and its pressure are the adequate ones, it can be expected that the liquid will be deposited on the substrate in the form of a well-defined droplet. For this to occur, both the laser pulse energy and focusing depth should be properly adjusted in order to allow liquid transfer devoid of splashing. In these techniques, each droplet results from a single laser pulse, and the generation of micropatterns is achieved through the translation of the substrate respect to the laser beam.

Laser printing has been proved feasible for printing a wide range of complex materials; in spite of making use of tightly focused laser pulses, it is possible to transfer really sensitive materials in solution without harm. Thus, laser printing can be employed for biological applications, such as the fabrication of biological microdevices, such as DNA and protein pulses, it is possible to transfer really sensitive materials in solution without harm. Thus, laser printing can be employed for biological applications, such as the fabrication of biological microdevices, such as DNA and protein.

In consequence, laser printing appears to be an excellent candidate for the fabrication of biological microdevices, such as DNA and protein.

The optimization of the performances of laser printing techniques requires, however, a detailed knowledge of the dynamics of liquid transfer. The final morphology of the printed material strongly depends on the particular mechanisms involved during liquid ejection and deposition. Time-resolved microscopy techniques can play a crucial role in this concern, since they should allow tracking the evolution of the ejected material with excellent time and spatial resolution. Investigations carried out up to date have shown that the liquid ejection dynamics, which is driven by the expansion of the generated high-pressure cavitation bubble, proceeds through the formation of long, thin and stable liquid jets that propagate away the free surface of the liquid. Such jets have diameters between 5 and 50 microns, and can attain lengths up to a few millimeters before breakup, propagating at speeds of the order of tens or hundreds of meters per second. In order to properly track their evolution microscopy techniques allowing for time resolutions better than the microsecond are required. In this work the different approaches used so far for monitoring liquid ejection during laser printing are considered, and it is shown how these techniques make possible a firm understanding of the complex dynamics involved in the process, as well as the mechanisms responsible for it.

8792-42, Session 8

Optical assembly of bio-hybrid machines

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The exploitation of biomolecular motors as mechanical actuators for the implementation of microsystems and microrobots prospect exciting applications and bio-mimicking in the field of nano engineering and nanotechnology.

In comparison to the smallest man-made actuators which are tens of micrometers in size, biomotors are much smaller, ranging from the micro to the nano range. In addition, they overcome the problem of the miniaturization of the power source required for mobility since they are self-powered through the conversion of chemical energy obtained from a high-nutrient surrounding medium to mechanical energy very efficiently. Particularly, biomotors that propel swimming cells, as e.g. the rotary nanomotors that rotate the flagella filaments of prokaryotic bacteria, allow a more sophisticated motion on the nanometer scale [1]. This feature allow to power micro- and nanodevices in bacteria baths through the collective motion of several bacteria or to transport microspheres attached to a few bacteria, to mention some applications [2]. However, the interaction and attachment between a biological specimen and an abiotic object that make up the so-called bio-hybrid machines is difficult to control and established schemes are still limited to reaction in solutions, while the attachment of only one bacterium propelling a specific payload is even a more challenging task.

Dynamic holographic optical tweezers (HOT) can elegantly address these issues. The holographic approach of conventional optical tweezers extends the concept of confining transparent microparticles near the focal spot of a tightly focused laser beam to multiple optical traps by holographically tailoring the trapping light field using a spatial light modulator (SLM). The calculation of the holograms displayed in the SLM is performed with video repetition rate by using adequate computer hardware and thus providing dynamic on-line manipulation of trapped objects. These capabilities make HOT especially suitable to precisely translate and rotate tens of non-spherical particles and allow arranging the different parts of the assembly in any desired configuration [3,4].

The aim of the presented contribution is therefore to develop a method based on HOT which enables the assembly of bio-hybrid machines consisting of only one bacterium and a single micrometer payload particle. To demonstrate the feasibility of our approach we used a wild type strain of rod-shaped Bacillus subtilis as model bacterium. They have approximately a diameter of 1 μm and a length of 2.5 μm. As a model for abiotic objects, we employed zeolite L which are porous microparticulates crystals featuring one-dimensional channels across the whole crystal axis. The surface of the zeolite L crystals was chemically modified with a biocompatible functionalization to allow attachment of only one bacterium to reaction in solutions, while the attachment of only one bacterium propelling a specific payload is even a more challenging task.

In biomedicine as e.g. the use of functional bio-hybrid assemblies by loading the zeolite L crystals with specific molecules as drugs or fluorescence dyes within the one-dimensional nanochannels.

The main effect on light propagating in such objects is in phase, indeed it is altered respect to the phase of the beam propagating in the surrounding medium. This is known as phase-retardation or phase-shift. Objects are visible by Phase Contrast Imaging (PCI) due to interferometric processes able to transform tiny phase differences into amplitude modulation so that any small differences in the beam optical path can be visualized. Common PCI methods are qualitative as they enhance the phase gradients but they cannot be connected to quantitative optical path variations. Digital Holography (DH) in microscopy present as a powerful tool to overcome all these issues. DH presents many advantages as high transversal and axial resolution and allows numerical aberration compensation and focus flexibility. The main characteristic is the possibility to discern between intensity and phase information performing quantitative mapping of the Optical Path Length (OPL). Up to now, DH has been considered as an innovative and alternative approach in microscopy and it’s a good candidate for complete specimen analysis in the framework of non invasive microscopy. In this paper, the flexibility of DH is employed to analyze in a completely and non-invasive way the cell mechanics of live and unstained cells subjected to appropriate stimuli. The potentialities of DH are employed to measure all the parameters useful to understand the deformations induced by external and controlled stress in living cells.

8792-51, Session 10

Optical-mechanical properties of diseased cells measured by interferometry

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Interferometric phase microscopy (IPM) enables to obtain quantitative optical thickness profiles of transparent samples, including live cells in-vitro, and track them in time without sub-wavelength accuracy without any external labelling, chemical or force application on the sample. The optical thickness measured by IPM is a multiplication between thealf integral refractive index differences and its physical thickness. Based on the time-dependent optical thickness profile, one can generate the optical thickness fluctuation map. For biological cells that are adhered to the surface, the average physical thickness fluctuation is inversely proportional to the spring factor indicating on cell stiffness. Thus, tracking the optical thickness profile over a short period of time gives us an indication on the cell rigidity, where softer cells are expected fluctuating more than more rigid cells. This parameter is relevant as is for homogeneous refractive index cells such as red blood cells. In this case, we can calculate a map indicating on the cell stiffness per each spatial point on the cell. Therefore, it is possible to measure mechanical and morphological properties of red blood cells and obtain novel dimensional and monitoring tools for the detection changing the morphology and the mechanical properties of these cells such as malaria, certain types of anaemia and thalassemia. For cells with a complex refractive-index structure, such as cancer cells that have a nucleus and other organelles with various refractive indices, decoupling refractive and physical thickness is not possible in single-exposure mode. In these cases, we measure a closely related parameter, under the assumption that the refractive index does not change much within less than a second of the measurement. Using these techniques, we lately found that cancer cells are less stiff compared to their healthy counterparts (healthy cells taken from the same organ of the same individual), and that primary cancer cells are stiffer than metastatic cancer cells, which spread themselves over the body. Although the contribution of the mechanical properties of cancer cells in invasion is not completely clear, it is possible that greater elasticity of cancer cells helps them metastasize by more easily squeezing through the body tissues and capillaries. Stiffness as a cancer biomarker is important for preventing false diagnosis using the conventional and subjective cancer identification that is currently performed under a regular optical microscope. We thus propose to establish a quantitative cancer biomarker based on the unique optical-mechanical signatures of cancer cells measured in a noncontact, label-free manner by optical interferometry. Our study shows the potential of IPM as a simple clinical tool for aiding in diagnosis and monitoring of cancer and other diseases that change the mechanical properties of cells. These methods are expected to eventually take the place of atomic force microscopy (AFM), which is cell intrusive, hard to implement and expensive.

8792-49, Session 10

Speckle based configuration for simultaneous in vitro inspection of mechanical contractions of cardiac myocyte cells (Invited Paper)

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In this manuscript we discuss an optical lensless configuration for a remote non-contact measurement of mechanical contractions of vast number of cardiac myocytes. All the myocytes were taken from rats, and the measurements were done in an in vitro mode. The optical method is based on temporal analysis of secondary reflected speckle patterns generated in a lensless microscope configuration. The processing involves analyzing the movement and the change in the statistics of the generated secondary speckle patterns that are created on top of the cell culture when it is illuminated by a spot of laser beam. The main advantage of the proposed system is the ability to measure many cells simultaneously (approximately one thousand cells) and to extract the statistical data of their movement at once. The presented experimental results also include investigation the effect of isopropyl noradrenalin at different concentrations on cells contraction process. An approximate factor of two in the contraction magnitude is shown between cultures with isopropyl noradrenalin and without. The experimental setup consisted of electrical shock stimuli, inverted microscope, cells culture, laser at 532nm and a CMOS camera. Reference data was recorded from cultures of cells without applying any electrical stimuli. A differentiation is made between synchronized cells contraction, when stimulii is applied, versus non synchronized cells contraction when stimulii is not applied. All the data (videos of a five seconds, recorded with 30 frames per second sampling rate), was recorded and then processed with unique Matlab algorithm. In the proposed paper we also present an algorithm in which the locations of the cells in the culture are found and experimentally demonstrated.

8792-50, Session 10

Cell mechanics investigation by digital holographic microscopy

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In biology and biomedical research fields one of the main topic is the understanding of morphology and mechanics of cells and microorganisms. Biological samples present low amplitude contrast such well-established methods present the issue to be invasive and by holographic optical tweezers,” Adv. Mater. 22, 4176 (2010).
8792-52, Session 10

Optomechanical phenotyping of biological cells (Invited Paper)

Jochen R. Guck, Univ. of Cambridge (United Kingdom)

Light has been central in biological sciences to visually investigate cells by microscopy. In recent years it has increasingly been used to also manipulate biological samples by optically induced forces. Besides trapping, moving, and rotating cells, optical traps can even be used to deform cells in a controlled and nondestructive way [1]. The deformation of cells with such an optical stretcher can be used to gain insight into the internal structure of cells, specifically the so-called cytoskeleton. In addition, the deformability of cells has turned out to be a very sensitive inherent cell marker for any physiological or pathological change in cells that is mirrored in the cytoskeleton. For example, cancer cells are much more deformable than normal cells because they need to be able to squeeze through small gaps in the tissue to form metastases [2]. An optical stretcher can, thus, be used to diagnose cancer [3], to detect malaria-infected cells [4], or to identify stem cells in heterogeneous populations [5,6]. Also dividing cells [7], or the nucleus inside living cells can be mechanically characterized [8]. In this way, we now cannot only look for changes in cell function, but feel for such changes. Integrated into an appropriate micro-fluidic system for cell delivery [9] this enables a new kind of marker-free flow cytometry.

References:


8792-54, Session 11

Optical imaging through strongly scattering layers (Invited Paper)

Allard P. Mosk, Univ. Twente (Netherlands)

No abstract available.

8792-53, Session 11

Biomechanical imaging with Brillouin microscopy (Invited Paper)

Giuliano Scarcelli, Harvard Medical School (United States)

As the mechanical properties of biological tissues and biomaterials are closely related to their functional abilities, measuring such properties in vivo would have a significant impact in many areas of biomedical research and clinical application. However, measuring the biomechanical properties of material remains a significant challenge due to a dearth of non-invasive technologies. Our research aims at developing a novel characterization technique, Brillouin confocal microscopy[1], to probe the elastic properties of tissue in vivo without contact, quantitatively, and with high spatial resolution.

The technology is based on spontaneous Brillouin light scattering. Brillouin scattering arises from the interaction between an incident optical wave and acoustic waves naturally present within a sample due to thermal fluctuations. Such interaction induces a small frequency shift in the scattered light that is directly related to the viscosity and elasticity of the sample. The typical Brillouin shift is, however, very small, in the order of 10 GHz. This poses a significant challenge to detect such a small shift in the presence of often-dominant elastic scattering or back-reflections. To address this problem, in the past years, we have developed a multistage VIPA spectrometer featuring sub-GHz spectral resolution, 80dB extinction and several orders of magnitude improvements in acquisition speed. We then integrated the spectrometer with a home-built confocal microscope to enable 3D biomechanical imaging.

The first areas of biomedical applications we are exploring are in ophthalmology. Changes in the elasticity of crystalline lens and cornea are central in the development of ocular disorders such as cataracts, presbyopia and corneal ectasia. In the crystalline lens, we found that the elastic modulus increases from the cortex to the nucleus; in vivo we found that the overall stiffness of the lens increases with age [2]. The age-related stiffening of lens has long been associated with presbyopia, but has never been measured in situ. In the cornea, we found a depth-dependent variation of stromal elasticity that varies with disease states (e.g. keratoconus) and ocular procedures (e.g. corneal collagen crosslinking)[3]. Most importantly, we recently developed a clinical prototype of the Brillouin instrumentation and demonstrated the first Brillouin characterization of the human eye in vivo [4].

In summary, Brillouin confocal microscopy can characterize in vivo the biomechanics of tissue and biomaterials non-invasively and with micron-scale spatial resolution. Given the demonstrated sensitivity to detect mechanical changes, both physiological, pathological and due to ocular procedures, Brillouin microscopy promises to be a useful clinical tool to reveal onset and progression of prominent ocular diseases as well as response to treatment and drugs. Beyond ophthalmology, our results demonstrate the broad applicability of this noninvasive mechanical imaging technique.

Optical Metrology 2013 Plenary Session

Challenges in Optical Metrology for Photo-Lithography

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The technology in photo-lithography is highly driven by the ITRS roadmap, leading to a continuous shrink of the features on ICs as used in the smart devices of today’s connected society. Consequently, the lithographic scanner needs to operate as close as possible to its physical limits dictated by its wavelength and numerical aperture (which is known as low-k1 imaging); this implies increasingly tighter process windows, and thus an increased need for advanced lithographic process control and metrology. Optical metrology is well qualified as a valuable metrology technique for the photo-lithographic industry, since it is fast and non-destructive with respect to the patterns written in the photo-resist layer, and since it offers a high precision. Moreover, optical metrology applied on periodic gratings can be used both for the purpose of overlay metrology as well as for critical-dimension (CD) metrology. For the latter, a model-based approach is implemented, in which grating profile parameters are retrieved which relate to the relevant scanner control knobs, like scanner focus. In the presentation, apart from the core technology of optical scatterometry, a range of applications in photo-lithography will be addressed together with a number of new challenges, like reduction of target size for overlay metrology and metrology of scanner aberrations.