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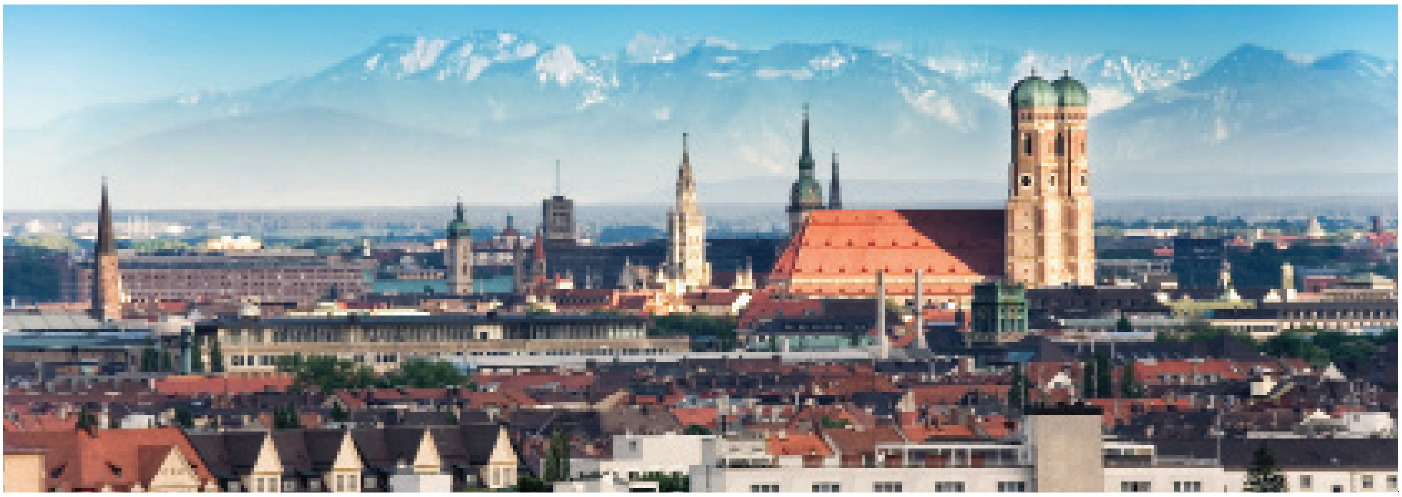

# SPIE. DIGITAL OPTICAL TECHNOLOGIES

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# Conference 10335: Digital Optical Technologies

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10335-1, Session 1

## See-through 3D technology for augmented reality *(Invited Paper)*

Byoungho Lee, Seungjae Lee, Gang Li, Changwon Jang, Jong-Young Hong, Seoul National Univ. (Korea, Republic of)

Augmented reality (AR) is recently attracting a lot of attention as one of the most spotlighted next-generation technologies. In order to achieve realization of ideal AR, we need to integrate 3D virtual information into real world. This integration should not be noticed by users, blurring the boundary between the virtual and real worlds. Thus, the ultimate device for AR should reconstruct and superimpose 3D virtual information on the real world that is not distinguishable, which is referred to as see-through 3D technology. Here, we introduce our recent researches to combine see-through displays and 3D technologies using emerging optical combiners: holographic optical elements and index matched optical elements. Holographic optical elements are volume gratings that have angular and wavelength selectivity. Index matched optical elements are partially reflective elements using a compensation element for index matching. Using these optical combiners, we could implement see-through 3D displays based on typical methodologies including integral imaging, digital holographic displays, multi-layer displays, and retinal projection. Some of these methods are expected to be optimized and customized for head-up displays, head-mounted or wearable displays. We conclude with demonstration and analysis of fundamental researches for head-mounted see-through 3D displays.

10335-2, Session 1

## OLED microdisplays in near-to-eye applications: challenges and solutions

Uwe Vogel, Fraunhofer-Institut für Organische Elektronik, Elektronenstrahl- und Plasmatechnik (Germany); Bernd Richter, Philipp Wartenberg, Peter Koenig, Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology FEP (Germany); Olaf R. Hild, Fraunhofer-Institut für Organische Elektronik, Elektronenstrahl- und Plasmatechnik FEP (Germany); Karsten Fehse, Matthias Schober, Elisabeth Bodenstein, Fraunhofer-Institut für Organische Elektronik, Elektronenstrahl- und Plasmatechnik (Germany); Beatrice Beyer, Fraunhofer-Institut für Organische Elektronik, Elektronenstrahl- und Plasmatechnik FEP (Germany)

The prominent emissive microdisplay technology on the market is OLED-on-silicon. A single-crystalline silicon CMOS chip provides the active-matrix circuitry to address and drive the millions of individual pixels (pixel cell circuitry also known as the backplane). Since the silicon substrate itself is intransparent in the visible spectrum, a top-emission OLED setup is required (emitting away from substrate). OLED microdisplays cover by far the major portion of emissive microdisplays on the market today as they are well-suited for extremely small form-factor and low-power consuming optical engines. Due to the size, power, contrast and color-space advantages, NTE applications represent the largest opportunity for OLED microdisplays. This relates to both personal viewers (PV) and electronic viewfinders (EVF). PV are either see-through data glasses used for mixed- and augmented reality (AR) applications, or non-see-through/immersive video glasses used for entertainment or virtual reality (VR) applications in gaming, training or entertainment. Due to their emissive nature OLED microdisplays are specifically suited for see-through/AR smart glasses, since they prevent a virtual grey-shaded monitor-like perception inside the user's field of view, which is caused by the insufficient backlight suppression of non-emissive microdisplays.

OLED-on-Silicon microdisplay technology might be best suited to bi-directional microdisplay techniques too, which combine both image display and image acquisition in a single chip. That is mainly due to the fact that there is no intrinsic saturation of photodetectors embedded inside the microdisplay backplane caused by the external illumination of "modulating" displays (in contrast to the top-emission here), though, optical cross-talk inside the emissive microdisplay device should be factored in. Image sensor elements, for example, pn-junction CMOS photodiodes, are arranged in a fixed matrix/pixel pattern correlated to the image display pixel matrix/pattern. In a common case, both arrays have become intersected to each other; one photodetector pixel per one display pixel. Other design arrangements are feasible and should be adapted to the application. Moreover, optical crosstalk effects can be limited or avoided by design, driving scheme and technological means. For smart glasses application that feature can add eye-tracking capability for enabling hands-free user-interaction with the virtual display content, e.g., via gaze-controlled virtual buttons.

Luminance and lifetime are two critical performance parameters for OLED microdisplays, specifically under high-temperature conditions. For cost reasons, achieving low-pixel pitch is important, since it directly translates into die size and chip cost. For immersive environments (for example, non-see-through or EVF and NTE applications), usually luminance up to 500 cd/m? and lifetime >10,000 hours are sufficient, whereas current see-through optics and consideration of sunlight conditions easily demand >5,000 cd/m? of luminance and beyond, regularly combined with elevated temperature operation. The challenge at high luminance is to supply and modulate the forward voltage at dynamic range levels of 2V up to 7 V (or even more, depending on OLED stack architecture) toward each OLED pixel; this requires integrated driving transistors able to withstand voltage swing of 5 V or more. That's a high-voltage for advanced mixed-signal CMOS processes at minimum feature sizes (usually referenced by minimum transistor channel length), for example, in the range of 0.25 to 0.11 $\mu$m at core voltages of about 1.2 to 2.5 V. Such high-voltage transistors require more die area, whereas smaller feature size CMOS processes typically provide even fewer options for HV devices, i.e., shrinking pixel cell size remains limited.

There are plenty of NTE applications which demand long battery life above frame rate and resolution. For such applications it becomes sufficient to display simple graphics (e.g., symbols) and text. Even more, the alteration frequency of screen content is often rather low (<5Hz). Therefore image data can be stored in a static random access memory SRAM-like pixel cell architecture, and the direct pixel-wise addressing scheme enables much lower bandwidth for the display interface as well. That approach allows to drastically reduce display power consumption by minimizing the backplane consumption. Consequently, OLED power (and its efficiency) now determines the overall power consumption. At moderate display resolution and frame rate there is even a power advantage for video display.

To summarize: Advancing near-to-eye applications of microdisplays demand improved parameters and extended features, such as full-color high-brightness, low-power and embedded sensors for user interaction. OLED micro-patterning for achieving R, G, B sub-pixels appears to be an inevitable approach, though remaining unsolved for commercialization yet. That will require further technology progress - electron-beam patterning might potentially contribute to that. Moreover, low-power backplane architectures will enable significantly longer battery operation in those NTE applications, that do not require high-resolution full-frame video capability.

10335-3, Session 1

## Time multiplexing for increased FOV and resolution in virtual reality

Juan C. Minano, Pablo Benítez, Univ. Politécnica de Madrid (Spain) and Limbak (Spain); Dejan Grabovickic, Pablo Zamora, Marina Buljan, Bharathwaj A. Narasimhan, Limbak (Spain)

We introduce a time multiplexing strategy to improve the density of pixels or the Field of View (or both) of the virtual image seen in a VR or AR headset. A given virtual image is displayed by generating a succession of partial real images, each representing part of the virtual image and together representing the virtual image. Each partial real image uses the full set of physical pixels available in the display. The partial real images are imaged to form a part of the virtual image viewable from an eye position. Each one of these different parts (called sub-images) are shown during a fraction of the frame time called a sub-frame slot. The union of all sub-frame slots is the frame display time and the union of all sub-images forms the full image shown on the virtual screen. The optical system contains different channels, each one imaging the physical display in one sub-image. Every optical channel entrance sees the display. Each optical channel is only used during the sub-frame slot corresponding to its sub-image. When using displays with wide angular emission, such as OLED displays, for instance, then the system must prevent light entering the wrong channel since this light will image a portion of the virtual image in the wrong place. For the purpose of controlling the light entering the active channel, shutters are used (high-speed, high-contrast active shutters such as the ones used in 3D glasses). Alternatively to the use of shutters, LCD displays may use directional backlights such that the backlight sends light only to the active optical channel entrances. Since VR and AR applications require very compact designs, in general, at least some of the sub-images (images of the partial real images) are occupying overlapping positions. This optical overlapping diminishes slightly the resolution/FOV gains due to time multiplexing.

The sub-images, which are successively formed, combine spatially and temporally to form a virtual image viewable from the eye position so that said overlapping portions of different partial real images from different portions of the virtual image. This time multiplexing strategy needs real images be shown at high frame rates. Available display and light channeling (shutters, etc.) technologies are discussed with regard to pixel density and frame rate. Several optical designs for achieving this time multiplexing scheme in a compact format are shown.

This time multiplexing scheme allows increasing the resolution /FOV of the virtual image not only by increasing the physical pixel density but also by decreasing the pixels switching time, a feature that may be simpler to achieve in certain circumstances.

## 10335-4, Session 1

### Phase space methods in HMD systems

James Babington, Qioptiq Ltd. (United Kingdom)

Unoccluded head mounted display (HMD) systems, such as freeform prisms or pupil replicating waveguide geometries provide good examples of augmented reality technology, where digital images are overlaid onto the real world. Since the optical systems used to implement this necessarily involve a different type of complexity, it is a worthwhile venture to try and understand them using alternative methods of analysis and design. In this paper we consider using phase space techniques and methods in analysing and understanding HMD geometries. The point of view taken here is to understand the global nature of the imaging problem, where the phase space coordinates are the fundamental variables from which physical quantities and observables can be constructed. In this paper we consider firstly how phase space provides a global map of the physical ray trace data. As such, this gives a complete optical history of the entire ray trace data propagating through the system. Phase space methods originally were the domain of classical dynamics, where Hamiltonian mechanics is naturally formulated. However, classical optical imaging also provides a natural stage to employ phase space techniques, albeit as a constrained system.

Two example geometries are considered in some detail in this paper. Firstly, the well known shark tooth freeform geometry is presented that embodies much more complexity in its optical surfaces. A second example of a waveguide geometry that replicates a pupil in one dimension is also shown. The complexity here lies in the multiple copies of the exit pupil that propagate out to an external eye box. In both examples, ray trace data is recorded on a number of well defined surfaces that capture both the parabasal and the global regions. Using this data, one can subsequently look at how ray aberrations can be extracted numerically from the phase space diagrams. This is of particular relevance for the example of a freeform imaging prism. An important point to note here is that this gives direct access to the second order aberrations that arise due to the system only having one plane of symmetry. Standard third order aberration theory is insufficient in capturing the ray aberrations of the freeform surfaces. This is consistent with the nodal aberration theory approach, where titled optical surfaces can introduce different nodal structure at the image plane. In the example of the waveguide geometry, phase space diagrams provide a way of illustrating how replicated pupils behave at the eyebox and what these imply for design considerations. In particular, one can see with this approach how the field of view is limited by the spectral bandwidth and field of view of the system. Ray aberrations are manifest in the phase space diagrams of the replicated pupils, for example, due to imperfect optical tolerances of the waveguide structure itself.

## 10335-5, Session 1

### Comparison of different designs of head mounted displays with large field of view

Bo Chen, Alois M. Herkommer, Univ. Stuttgart (Germany)

Head mounted displays (HMD), as one type of wearable virtual reality device, are nowadays rather popular in aviation, 3D gaming, training, and many other applications. There are already many optical design concepts for these systems in the literature. Takahashi (1997) [1] presented one prism HMD optics which is small in size and light in weight with one total internal reflection (TIR) surface. In contrast A. Bauer and J. P. Rolland (2014) [2] depicted two freefrom HMDs, which contain only mirrors.

The HMDs are required to be light in weight, small in size, offering a wide field of view and high imaging quality. In nearly all the designs, freeform surfaces are employed with the advantage to effectively correct aberrations while reducing the number of lenses. Also in this paper, anamorphic aspheric surfaces are used for the description of the freeform.

The TIR prism type described by Takahashi [1] represents a basic design type of HMD optics, which is widely applied by others. This patent and one similar TIR prism HMD designed by our own will be employed as a reference in this paper. The goal of our investigation is to find alternate design form with potentially better performance. Therefore we have designed one catadioptric HMD (consisting of a lens and two mirrors), and one prism with different folding geometry for comparison. These two types of HMDs are seldom studied and may have mechanical disadvantages, however the optical performance of these two alternate types are quite good.

SPECIFICATIONS AND DESIGN PROCESS:

For fair comparison, the specifications of all the systems designed are the same as the patent lens [1]. The specifications are depicted in Table 1 and the layout of the patent lens is presented in Fig. 1.

FOV vertical 30º, horizontal 40º In order to find competitive design forms a specific process has been developed, stating from on-axis systems which are modified to form valid off-axis geometries. During design the paraxial focal length calculation is non-trivial and cannot be used during optimization. As a substitute the numerical aperture at the image is applied to constrain the size of the systems. In addition obscuration and escaping of rays needs to be avoided during design. To correct the serious aberrations, anamorphic freeform surfaces (Eq. (1)) are applied for these tilted and decentered systems. Additionally, up to 15 fields of angle are applied during the optimization to minimize the distortion since the off-axis system allows for large distortion.

where z is the sag, cx and cy represent the curvatures in the orthogonal directions x and y, respectively, kx and ky denote the conic constants, and Ai and Bi are the higher order symmetric and asymmetric terms, respectively.

RESULTS:

Several forms of head mounted display optics are designed and compared. One is a prism HMD, which is similar to the patent lens shown in Fig. 1. Another is a catadioptric system with one lens and two mirrors shown in Fig. 2. Besides, an alternate prism without TIR surface and different folding geometry is depicted in Fig. 3.

1) TIR head mounted display

2) Catadioptric head mounted display

3) Prism head mounted display without TIR surface

References:

[1] K. Takahashi, "Head or face mounted image display apparatus." U.S. Patent No. 5,701,202. 23 Dec. 1997.

[2] A. Bauer and J. P. Rolland, "Visual space assessment of two all-reflective, freeform, optical see-through head-worn displays." Opt. Express 22, 13155-13163 (2014).

## 10335-6, Session 2

### Designing optics to reduce digital processing and communication in computational sensors and imagers: a new approach to low-power sensing *(Invited Paper)*

David G. Stork, Rambus Inc. (United States)

No Abstract Available

## 10335-7, Session 2

### Computational wavelength resolution for in-line lensless holography: phase-coded difraction patterns and wavefront group-sparsity

Vladimir Y. Katkovnik, Tampere Univ. of Technology (Finland); Igor A. Shevkunov, Nikolay V. Petrov, ITMO Univ. (Russian Federation); Karen O. Egiazarian, Tampere Univ. of Technology (Finland)

In-line lensless holography is considered with a random phase modulation at the object plane. The forward wavefront propagation is modelled using the Fourie transform with the angular spectrum transfer function. The multiple intensities (holograms) recorded by the sensor are random due to the random phase modulation and noisy with Poissonian noise distribution. In computational imaging sparse and redundant representations have been successfully developed the last years as a general concept. It is based on the assumption that there exists a small number of items such that image can be represented exactly or approximately with a good accuracy. In term of statistics, a sparse representation can be thought as a low-order parametric approximation. The group (or structured) sparsity has appeared artificially by special grouping of observations. In particular, for 2D images a small similar 2D patches are grouped in 3D array processed independently. The similarity of the grouped patches enables a high-level sparsity of the grouped data and high efficiency of small size their approximations. The main features of these techniques are originated from the work on Block Matching 3D (BM3D) filtering, which is a well established technique enabling the state of the art performance for various imaging problems.

The sparsity and group sparsity for optics is a nontrivial development of the standard concepts because of the complex-valued objects of interest with phase and amplitude. The Sparse Phase and Amplitude Reconstruction (SPAR) algorithm is proposed in this paper using the group sparsity (BM3D) as the main tool for noise suppression and super-resolution imaging. The algorithm is designed for optimal phase/amplitude reconstruction from Poissonian data. It is shown by computational experiments that high-accuracy reconstructions can be achieved with resolution going up to the quarter of the wavelength, ?/4. With respect to the sensor pixel size it is a 32? super-resolution.

Some qualitative effects of the basic ingredients (modulation phase masks and group sparsity) used in the algorithm are demonstrated in Fig. 1. The first left image shows the true phase. The next completely destroyed image is obtained by the Gerchberg-Saxton algorithm from the experiment with no phase modulation and without the sparse modeling for phase and amplitude. The next third image is obtained from a single experiment where the phase modulation is employed but no sparse filtering. This modulation makes the main features of the phase distribution at least visible but quite noisy. This noise is a result of the used phase modulation. The last fourth image in this set of experiments is obtained by the SPAR algorithm, i.e. for the data with the phase modulation and sparse imaging for the phase and amplitude. It shows near perfect reconstruction of the object phase. These 512?512 images are obtained for the very low noise level. For a larger number of experiments the accuracy of the phase reconstruction with the phase modulation is improving quickly both for processing with (SPAR) and without sparse filtering (GS).

## 10335-8, Session 2

### Fast physical optics-based simulation of waveguide displays for mixed and virtual reality applications

Daniel Asoubar, LightTrans International UG (Germany); Christian Hellmann, Wyrowski Photonics UG (Germany); Frank Wyrowski, Friedrich-Schiller-Univ. Jena (Germany)

Various displays for mixed or virtual reality applications consist of one or several waveguides for guiding light from an image generation unit to the human eye. On the waveguides holographic or surface gratings are located for coupling light into, between and out of the waveguides as well as expanding the exit pupil of the imaging system. For the realistic simulation of such waveguide displays the propagation of entire wavefronts through the macroscopic waveguide as well as stray light caused by zero and higher diffraction orders at the microscopic grating structures must be analyzed. Thus in this presentation we introduce a non-sequential field tracing approach, which enables a physical optics based system analysis. It is shown that this field tracing computation includes all relevant physical effects like refraction, speckle, interferences, spatial and temporal coherence as well as polarization. Furthermore field tracing provides a calculation speed advantage compared to conventional Monte-Carlo ray tracing. To ensure that diffraction efficiency and polarization effects can be taken into account correctly even for grating periods in the region of the wavelength of light, a rigorous Fourier modal method (FMM) is applied. Simulation results of several simple waveguide displays are shown to demonstrate the flexibility and performance of the discussed modeling concepts.

## 10335-9, Session 2

### Real-time augmented reality overlay for an energy-efficient car study

Peter Wozniak, Hochschule Offenburg (Germany); Nicolas Javahiraly, ICUBE (France); Dan S. Curticapean, Hochschule Offenburg (Germany)

Our university carries out various research projects. Among others the project "Schluckspecht" is an interdisciplinary work on different ultra-efficient car concepts for different international contests. Besides the engineering work, one part of the project deals with real-time data visualization. In order to increase the efficiency of the vehicle, an online monitoring of the runtime parameters is necessary.

The driving parameters of the vehicle are transmitted to a processing station via a wireless network connection. We plan to use an augmented reality (AR) application to visualize different data on top of the view of the real car.

By utilizing a mobile Android or iOS device a user can interactively view various real-time and gathered statistical data. The car and its components are meant to be augmented by various additional information, whereby that information should appear at the correct position. An engine e.g. could show the current rpm and consumption values. A battery on the other hand could show the current charge level.

The goal of this paper is to evaluate different possible approaches, their suitability and to expand our application to other projects of our university.

10335-10, Session 3

## The ideal imaging AR waveguide

David Grey, WaveOptics (United Kingdom)

From 2016 onwards we have seen an unprecedented pull for near-to-eye AR displays declared by leaders of major consumer companies. WaveOptics believe that imaging waveguides will provide the key component as a solution to achieve this mass market adoption. The whole field of imaging waveguides is a very challenging technical area with worldwide interest in AR continuing to grow and a constant search for new IP that will secure a commercial route forward. Our experience of working in this area for much longer than the subject has been of general interest has given us a real insight into the problems and requirements for a scalable solution. This paper first considers the ideal imaging waveguide device then looks at what we and others have achieved towards this goal.

The ideal imaging AR waveguide description will vary for a given application, implementation and cost requirement however in our view, the solution has to have the following aims:

1. Highly scalable manufacturing process

2. Maintain high angular (over say 90+ degrees field of view) and chromatic (full visible spectrum) image information from a display projector without introducing any optical aberrations.

3. No tinting of outside world image ( 100% transmission)

4. Create a large eyebox from a small input projector aperture to allow best form factor for a given eye relief to allow different size head/IPD use and movement of AR headset

5. Introduce no distractions for the user, for example diffractive colour effects.

6. Maximize the use of light to ensure optimum battery life.

7. Low weight – minimize thickness and area of waveguide

Current real solutions suffer from not being able to solve all of these requirements. These solutions are restricting the adoption of the technology in enterprise applications and cannot approach low-cost consumer applications which require a readily scalable solution.

Imaging waveguides are a key development that are helping to create this Augmented Reality revolution. WaveOptics are at the forefront of this AR technology and have developed and demonstrated a radically new approach based on photonic crystal 2D pupil expansion.

One of our key PCT patent applications covers our design concept of an imaging waveguide which has a single input diffraction grating and a single output area photonic crystal lattice. We have a regular array of nanostructures in the output which in conjunction with the input grating design provide full angular and chromatic correction as well as provide pupil expansion. We have developed this concept through prototype stages and it now gives a field of view beyond 40 degrees, large eyebox, full colour, outside world transmission >80%, and a HD+ resolution display.

We will demonstrate our latest display and roadmap to take our technology forward in 2017 where we are looking to increase the field of view towards 60 degrees whilst maintaining or improving all of the other specifications. We will present our view of the ideal imaging AR waveguide, the current status (June 17) of our technology and review existing imaging waveguide technologies against the ideal component.

The future of AR with the potential for mass market adoption for the first time is here.

10335-11, Session 3

## Thin combiner optics utilizing volume holographic optical elements (vHOEs) using Bayfol® HX photopolymer film

Friedrich-Karl Bruder, Thomas Faecke, Rainer Hagen, Sven Hansen, Christel Manecke, Enrico Orselli, Christian Rewitz, Thomas Rölle, Günther Walze, Covestro AG (Germany)

The main function of any augmented reality system is to seamlessly merge the real world perception of a viewer with computer generated images and information. Besides real-time head-tracking and room-scanning capabilities the combiner optics, which optically merge the natural with the artificial visual information, represent a key component for those systems. Various types of combiner optics are known to the industry, all with their specific advantages and disadvantages. Beside the well-established solutions based on refractive optics or surface gratings, Volume Holographic Optical Elements (vHOEs) are a very attractive alternative in this field. The unique characteristics of these diffractive grating structures – being lightweight, thin and flat – make them perfectly suitable for use in integrated and compact combiners. For any consumer application it is paramount to build unobtrusive and lightweight augmented reality displays, for which those holographic combiners are ideally suited.

In contrast to other diffractive solutions, like surface gratings, rainbow effects can be suppressed and vHOEs are also completely transparent in off-Bragg condition. Due to processing challenges of (historic) holographic recording materials, that did not allow mass production of vHOE holographic combiners, they only found use in military applications by now. The new Bayfol® HX instant developing holographic photopolymer films provide an ideal technology platform to optimize the performance of vHOEs in a wide range of applications. Bayfol® HX provides full color capability and adjustable diffraction efficiency as well as an unprecedented optical clarity when compared to classical holographic recording materials like Silver Halide emulsions or Dichromate Gelatin.

Bayfol® HX is an industrially available product, with optional tailored properties for various diffractive performance and integration methods. Those films are easy to process without the need for chemical or thermal development steps offering simplified contact-copy mass production schemes.

10335-12, Session 3

## Folded optics with birefringent reflective polarizers

Timothy Wong, Zhisheng Yun, Gregg Ambur, Jo Etter, 3M Co. (United States)

Folded optics with curved reflective polarizers provide optical design freedom and enable important capabilities for head-mounted and near-to-eye displays.

Polymeric, birefringent reflective polarizers have been used to produce compact, mid-FOV eyepieces and wide field-of-view optics for virtual reality (VR) head-mounted displays using the "pancake" lens configuration. In these folded systems a quarter-wave retarder is disposed between a 50:50 beamsplitter and the reflective polarizer. The retarder enables polarization conversion such that the imaging light is first reflected by the polarizer and subsequently transmitted, or vice-versa. The beamsplitter also is used in both reflection and transmission in the imaging system.

Catadioptric imaging systems have well known advantages over solely refractive systems including a more compact form, lighter weight and improved aberration control. Using partial reflectors in catadioptric systems eliminates obscurations and enables the optics to be useful for eye-pieces and head-mounted displays.

Deploying a birefringent reflective polarizer in this scheme has advantages. Current research and development includes forming polymeric films to have reflective optical power and integrating them onto the curved surface of lenses. Polymeric reflective polarizers have high transmission efficiency critical to visual contrast. Additionally, the polymeric reflective polarizers have good environmental stability and do not need to be protected from corrosion.

Multiple configurations for pancake lens systems are discussed as are their advantages and disadvantages relative to refractive systems. Polarization control is an important consideration and the polarizing effects of different components are discussed. Designs for mid-FOV, wide-FOV and ultra-wide FOV are presented and additional benefits of using folded optics for virtual reality systems are explored.

10335-13, Session 3

## Subwavelength optics for new optical combiners: beyond diffractive optics' limitations

Guillaume Basset, Giorgio Quaranta, Frédéric Zanella, Angélique Luu-Dinh, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland)

Until recently, resonant subwavelength gratings have been successfully industrialized only in the field of optical document security and biochemical sensing. Due to their subwavelength structure, resonant waveguide-gratings (RWG) support only very few diffraction modes, and present eventually no diffraction except Zero-order transmission/reflection filtering. Recent developments have demonstrated their ability to redirect light with a very high selectivity and tunability, opening great promises to use them as optical combiners for augmented and mixed reality systems. Due to their subwavelength structures, the typical limitations of Diffractive Optical elements can be overcome, especially their chromatic aberrations, limited transparency and "rainbow" effect.

The proposed presentation will introduce resonant/subwavelength gratings and present their strength and weaknesses.

A short word will be given about their application today in different products and their successful industrialization and production of hundreds millions of units per year.

Finally example of use of see-through optical combiners based on RWG will be presented in different configurations. A first example will show very thin and highly transparent optical combiners providing high resolution, and large field-of-view RGB images. A second one will present opportunities for light-field display see-through optical combining.

10335-14, Session 3

## Super-resolution optics for virtual reality

Dejan Grabovickic, Limbak (Spain); Pablo Benítez, Juan C. Minano, Limbak (Spain) and Univ. Politécnica de Madrid (Spain); Pablo Zamora, Marina Buljan, Bharathwaj A. Narasimhan, Limbak (Spain); Milena I. Nikolic, CeDInt-UPM (Spain); Jesus Lopez, Limbak (Spain); Eduardo Sanchez, CeDInt-UPM (Spain)

Resolution perceived in VR is still limited, since the Nyquist frequency of the VR pixels (typically 10-15 pixels/deg) is well below the angular frequencies the human eye can resolve (60 pixels/deg). We present here a novel optics that approach to dramatically increase the perceived resolution of the VR keeping the large FOV required for VR.

Our optical design approach is based on two main features. First, we take into account the eye rotations in order to pay special attention to the rays that will be focused on the fovea (where the human vision acuity is maximum). This permits us to optimized for the sharpest image of a VR pixel to be obtained when it is directly gazed (so the eye images it on the fovea), and relax the resolvable angular frequency when the eye is positioned so that VR pixel is seen obliquely (imaged outside the fovea). This allows the best use of the limited degrees of freedom in the design. Note that all this is done at the optical design stage, and no eye tracker is needed in the headset.

Secondly, we design with variable magnification to make VR pixels denser where they can be gazed, and coarser in the highly peripheral regions. This variable magnification implies that the lens will present a strong distortion, which must be compensated for the displayed contents by software (in the same way as it is done for conventional lenses too). The variable magnification is precisely adapted to the resolution and movements of the human eye, so the user does not detect that the VR pixels in the periphery are not as small as those in the central region. This strategy is effective because the aperture stop of VR optics is also the exit pupil and is located only 15-20 mm from the eye pupil, which implies that, for a FOV=100 lens measured with the eye is looking forwards, the user can gaze only up 30-35 degs from the frontward direction, so the VR pixels from that angle to the rim of the FOV (50 deg) will never be focused on the fovea. Additionally, 90% of all eye movements occur within less than 15 degs from the normal direction.

We apply this design approach to multiple architectures, and three design examples will be presented: an axisymmetric diffractive singlet, an axisymmetric two-element lens, and a multichannel freeform lens that perform a squeezed segmented mapping between display pixels and VR pixels. Compared to a conventional lens design for a QHD (2560x1440) display (for both eyes) and FOV = 100 degs, those examples achieve the same FOV but a resolution gain in pixels/deg of 1.35, 1.50 and 1.75 at the center of the central area of the FOV. Alternatively, for a given resolution of the VR pixels, our novel optics can provide a much larger field of view than a conventional lens. A design example of this type achieves a FOV=130 degs with the same resolution of a conventional lens of FOV=100 degs.

We have also developed a prototype, whose experimentally measured performance will be shown too. It is a two-element design, manufactured in PMMA and PS by direct cut with a single-point diamond tool, which does not only produce 1.50 times the resolution of a conventional design, but also a good correction of chromatic aberration. This prototype lens, if used with a mobile-based headset with a QHD (2560x1440) display and using our lenswill show 19 pixels/deg, the same VR resolution obtained with a 4K UHD (3840x2160) display and the conventional lens. Experimental measurements (EFL, FOV, distortion, MTF) of the lens show a good agreement with the expected design values.

10335-15, Session 4

## Mass production of holographic transparent components for augmented and virtual reality applications

Juan Manuel Russo, Fedor Dimov, Joy Padiyar, Seth A. Coe-Sullivan, Luminit LLC (United States)

Diffractive optics such as holographic optical elements (HOE) can provide transparent, and narrow band components with arbitrary incident and diffracted angles for near to eye commercial electronic products for augmented (AR), virtual reality (VR), and smart glass applications. In this paper, we will summarize the operational parameters and general optical geometries relevant for near to eye displays, the holographic substrates available for these applications, their performance characteristics and ease of manufacture.

Compared to HOEs, conventional optics present several disadvantages for these applications, including refractive optical materials that are heavy or bulky reflective optical train designs. Since traditional optical elements are limited to the laws of refraction and reflection, cumbersome custom optical elements that are difficult to fabricate are required to form a usable image in the wearer's visual field. These limitations result in a device that fails to be ergonomic and lightweight and hence, unacceptable. HOEs are thin and can be custom fabricated for ergonomic input and output angles with relative ease. The flexibility provided by HOE fabrication allows production of an attractive, conformable, useful and easy to use consumer electronic product.

In this application space, narrow angular and spectral performance is often referred to as transparency. In other words, the wearer has an unobstructed view of the environment (AR) or of another display (VR) while the optical system overlays specific images and information. Volume HOEs operating in the thick regime are especially suited to provide the required transparency while overlaying the images with high efficiency. Although surface relief diffractive optical elements are easy to manufacture by embossed replication, they add scattering and multiple diffraction orders, causing ghosting, reducing efficiency and compromising see through operation. Conversely, thick volumetric HOEs can be designed to diffract in only one order with minimal scattering, eliminating ghosting, and maximizing efficiency and see through transparent performance.

We will compare the holographic substrates available in terms of fabrication, manufacturability and end-user performance characteristics. Like surface relief structures, volume HOEs can be manufactured in a master and replication schemes. These applications provide an important avenue for diffractive optical element penetration into the consumer electronics markets with high part volume and reliability requirements. This is because, based on recent market research reports, combined revenues of up to $120B by 2020 have been forecast. The projected revenue is divided into 70% for AR, 18% for VR, 5% for HUD. Volume HOEs are particularly crucial for the AR and HUD segments where transparency is necessary in terms of performance and cosmetic appearance.

Luminit is currently emplacing the manufacturing capacity to serve this market, and this talk will discuss the capabilities and limitations of this unique facility. Three-color, tunable, holographic grade lasers for mastering and roll-to-roll replication will be emplaced, with throughput and capacity to well-serve the AR, smart glass, and HUD markets.

10335-16, Session 4

## Advanced freeform optics enabling ultra-compact VR headsets

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At present commercial VR headsets are rather bulky and heavy, which may be not comfortable enough to use for long periods of time. The main reason for their volume is the distance required between their conventional lenses and the displays.

We present novel advanced optical designs with a dramatically smaller display to eye distance, excellent image quality and a large field of view (FOV). This enables headsets to be much more compact, typically occupying about a fourth of the volume of a conventional headset with the same FOV.

The design strategy of these optics is based on a multichannel approach, which reduces the distance from the eye to the display and the display size itself. The optical system splits the incoming bundle of rays in different sub-bundles that are optically processed (independently) and then recombined in a single outgoing bundle. This is obtained by means of dividing a conventional optical system into several lenslets, each one of which handles one sub-bundle of rays (and its corresponding part of the total field of view). Each one of the sub-bundles is emitted by certain sector of the display, then goes through one of the lenslet in the optics, and then redirected towards the user's eye. The addition of all the ray sub-bundles arriving to the eye composes the virtual image that the user perceives, with a total field of view equal to the addition of all the partial fields of view provided by each of the sub-bundle. Unlike conventional microlens arrays, which are also multichannel devices, our designs use freeform optical surfaces to produce excellent imaging equality in the entire field of view, even operating in oblique incidences. Additionally, we take into account the eye rotations, we optimized for the sharpest image of the VR pixels to be obtained when they are directly gazed (so the eye images them on the fovea).

We present two families of compact solutions that use different type of lenslets:

(1) Refractive designs, whose lenslets are composed typically of two refractive surfaces each (i.e. rays undergo a total of two refractions while travelling from the display to the eye)

(2) Light-folding designs that use prism-type three-surface lenslets, in which rays undergo four successive deflections when travelling from the display to the eye: refraction, reflection, total internal reflection and refraction.

For both families of designs, the number of lenslets is not fixed, so different configurations may arise, adaptable for flat or curved displays with different aspect ratios. In the refractive designs the distance between the optics and the display decreases with the number of lenslets, allowing for displaying a light-field when the lenslet becomes significantly small than the eye pupil. On the other hand, the correlation between number of lenslets and the optics to display distance is broken in light-folding designs, since their geometry permits achieving a very short display to eye distance with even a very small number of lenslets.

We have built two complete headset prototypes using two different compact optics: one refractive-type and the other light-folding type. Both have only two lenslets and use (for each eye) a 2" 16:9 display. Their respective eye pupil to display distance is only 30 mm and 36 mm (to be compared to 65-80 mm in most conventional headsets), while displaying 12 pixels/deg resolution of the VR and FOV = 94x75 degs.

Additionally, two other designs (whose prototypes are under construction) will be presented. One has with 4 light-folding lenslets for a 2" 1:1 display per eye which will show 13 pixels/deg and a round FOV = 100 degs, similar or better than the main commercial VR headsets, but whose eye pupil to display distance is only 26 mm. The other design, which has been developed under the EU project LOMID, uses two 0.93" microdisplays per eye, and has been designed to achieve 22 pixels/deg with FOV =100x85 degs, targeting high end applications.

10335-17, Session 4

## High collimated coherent illumination for reconstruction of digitally calculated holograms: design and experimental realization

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Future commercialization of glasses-free holographic real 3D displays requires not only appropriate image quality but also slim design of backlight unit and whole display device.

In this paper we report coherent backlight unit (C-BLU) for 3D holographic display with thickness comparable to commercially available 2D displays (cell phones, tablets, laptops, etc.). C-BLU forms uniform, high-collimated and effective illumination of Complex Spatial Light Modulator, which consists from two parts for simultaneous and independent amplitude and phase modulation of an input wave field. Active optical element then is used to form viewing zones.

Designed C-BLU consists from two light sources and two concave lenses, one of each per eye, light guide plate (LGP), collimating hologram for light collimating and redirecting (H1), which is placed on the back surface of light guide plate, and outcoupling hologram (H2) for light redirecting out of light guide plate towards viewer, this hologram is placed on bottom surface of light guide plate.

Optical channels operate independently from each other. Light emitted by coherent light source is transformed to diverging beam by concave lens and incoupled into LGP through side surface. Beam propagates in LGP without reflection straight to opposite side surface. There it illuminates H1 and diffracts on it. Collimated first order of diffraction propagates inside of LGP without reflection straight to the bottom surface. There beam illuminates H2 and diffracts on it. Depending on H2 design first order of diffraction can stay collimated or become convergent beam. It goes normally from H2 and outcouples from LGP through top surface. Outcoupled light is uniform and coherent. It illuminates holographic display with plane or convergent wavefront depending on outcoupling hologram design.

H1 and both designs of H2 are produced by analog method that allows recording them with high uniformity and high efficiency. Holograms are reflective volume type and were recorded on Bayer photopolymer. Such material was chosen because of dry post-processing with UV light.

First was carried out design preliminary numerical simulation of C-BLU volume holograms. Simulations of diffraction efficiency and range of possible working angles were based on Kogelnik coupled wave theory. Then schemes for holograms recording were elaborated. Schemes are based on intersecting beams technique. Main challenge of such scheme, which is elimination of ghost light due to multiple Fresnel reflections near hologram plate, was successfully completed by optical elements arrangement. After that experiments on holograms recording were conducted. Goal was to find such combination of exposure time and incident power that provides maximal diffraction efficiency while recording as low noise as possible.

In result of this project several fully functional prototypes were assembled and measured. Experimental prototypes have following parameters: illumination area up to 130x80 mm2 (diagonal size 5.5"); thickness of C-BLU is 10 mm; illumination uniformity 90% (measured by VESA standard v2.0); collimation angle for backlight unit with plane wavefront output is ±0.038°; for backlighting unit with converging wavefront viewing zones are formed at distance 600mm with stereoscopic base is 62mm; angle of divergence between two optical channels is 6°. Main results were obtained for monochromic C-BLU realization, yet multi-color holograms were recorded too and stay under our continuous research.

Experimental results prove that described design of backlight unit is feasible for real-time slim holographic display.

10335-19, Session 4

## Optical architecture of HoloLens mixed reality headset

Bernard C. Kress, William J. Cummings, Microsoft Corp. (United States)

The ultimate wearable AR system would address all aspects of a truly forgettable device, to be worn throughout the entire day, such as prescription glasses or a smart watch. Comfort is king: therefore, dramatic reductions in size, weight and power requirements and at the same time increase in field of view, angular resolution, and reduction of visual induced nausea are all required. Among these challenging hardware requirements, optics is a critical one.

The human visual system is complex and dynamic, and has specifics and limitations which scale differently when the system is a near to eye display rather than a standard projection display or screen display. In order to avoid over-designing optics for next generation AR and VR systems, it is crucial to consider carefully such specifics and limitations in the optical design process itself, and adapt existing or novel display technologies to create the experience and comfort needed for the user.

Human-centric optical design is therefore emerging as a key to address such stringent requirements for the ultimate AR/VR experience.

10335-20, Session 5

## Metasurface polarization optics: chiral holograms and elliptical polarization beam splitters *(Invited Paper)*

Federico Capasso, Jan Philipp Balthasar Mueller, Robert Charles Devlin, Noah A. Rubin, Benedict Groever, Harvard School of Engineering and Applied Sciences (United States)

We present a method allowing for the imposition of two independent and arbitrary phase profiles on any pair of orthogonal states of polarization—linear, circular, or elliptical—relying only on simple, linearly birefringent wave plate elements arranged into metasurfaces. This stands in contrast to previous designs which could only address orthogonal linear, and to a limited extent, circular polarizations. Using this approach, we demonstrate chiral holograms characterized by fully independent far fields for each circular polarization and elliptical polarization beam splitters, both in the visible. This approach significantly expands the scope of metasurface polarization optics.

10335-21, Session 5

## Novel fabrication methods for nanophotonics

Stephan Kress, Harvard Univ. (United States)

Light rarely interacts. Fortunately, light-matter-interaction may be increased when light is confined to sub-wavelength scales. However, a prerequisite to gain control over light at such small scales is that fabrication technologies exist for sub-wavelength features with even lower surface roughness. To meet such requirements, we developed two novel fabrication technologies: The first is a molding-technique to structure thin films with nanoscale features and Angstrom-roughness. The second is an ultra-high-resolution printing-technique to place functional nanomaterials with nanometer-precision and sub-wavelength resolution.

For the patterning of thin films, we employ a technique termed 'template-stripping'. This technique enables the structuring of polycrystalline thin films that typically show large roughness when processed using standard techniques (such as lithography and etching). In template-stripping, a structured silicon-wafer is used as an ultrasmooth template onto which a thin film (such as a metal) is deposited and then peeled off using an epoxy-backing-layer. This reveals a surface that inherits the ultra-smooth and well-defined features of the silicon-wafer-template. Since the silicon-template remains unharmed, reproducible fabrication of high-fidelity nanostructures is possible.

Another challenge for nanophotonic devices is the precise placement of functional nanomaterials (such as colloidal quantum dots) into well-defined locations. Typically, multiple solvent- and lithography-steps are involved to place nanocrystals. In contrast, we achieve the placement of nanocrystals in a single-step involving an on-demand printing technique. In this process, atto-liter-sized ink droplets containing nanocrystals are ejected from an electrified printing nozzle. As for a desktop printer, this allows to build up arbitrary patterns of colloidal quantum dots. However, far beyond desktop printers this technique can produce feature sizes below Der h100 nm. This exceeds the resolution of a desktop printer by three orders of magnitude and is equivalent to more than 200,000 dots-per-inch.

In a demonstration of our newly-acquired capabilities, we develop quantum-dot plasmonic waveguides, resonators and spasers to gain control over light at scales smaller than the diffraction limit. These waveguides and resonators constitute state-of-the-art plasmonic circuitry that routes and stores light in the form of surface plasmon polaritons (SPPs). Further, we show that by exploiting quantum dots as a gain medium plasmonic losses may be fully compensated. As a result of this plasmonic gain and feedback (by a plasmonic cavity), we observe the stimulated emission of SPPs – also known as spasing – at low pumping thresholds and under ambient conditions. In sum, our results confirm the promise of template-stripping and electro-hydrodynamic printing for creating nanoscale circuits for light. More importantly, the capability of these techniques to define nanoscale features over wafer-scales should impact technologies in digital optics that rely on sub-wavelength features patterned over large areas.

10335-22, Session 5

## Digital metasurface for wavefront modulation

Yan Zhang, Capital Normal Univ. (China)

Metasurface is a kind of matematerials with only two-dimensional distribution. By carefully arranging the shape and size of each subwavelength antenna, the amplitude, phase, and polarization of reemitted light from the antenna can be artificially control. Eight antennas with same amplitude modulation and different phase modulation are selected to construct different devices. The phase modulations are selected as in the range of 0 to 2ϖ with a step of ϖ/4. Several devices, such as lens, holograms, pure phase elements, are designed, fabricated, and characterized in the terahertz range. Experiment results demonstrate the validity of this new approach. The insert loss can be reduced to 20% with two layer metasurface devices.

## 10335-23, Session 5

# Global optimization of complex optical structures using Baysian optimization based on Gaussian processes

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Advanced devices in micro- and nano-optics and -photonics include structures on micron or nanometer scales.

Most of their relevant optical properties can be projected by solving the time-harmonic, macroscopic Maxwell's equations rigorously, i.e. without simplifying the geometrical, material and source models.

We discuss how to approach challenging design tasks in this field with finite element methods (FEM).

The general framework of FEM allows to employ adaptive, error-controlled numerical resolution and accurate geometry modelling for arbitrary shapes [1].

We also briefly report on application of these methods to recent simulation and optimization tasks ranging from industrial applications (optical metrology, microcavity design, photovoltaics [2,3,4]) to academic research (plasmonics, chiral metamaterials [5,6,7]).

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## 10335-78, Session 5

# Slot silicon-gallium nitride waveguide in MMI structures based 1x8 wavelength demultiplexer

Bar Baruch Ben Zaken, Tal Zanzury, Dror Malka, Holon Institute of Technology (Israel)

A slot-waveguide is a structure that allows light to be propagated inside a narrow region (nanometer-scale) of low index material that is surrounded by two layers with high index material and also leads to a strong light confinement. The fabrication of 1x4 intensity splitter based on MMI in Silicon (Si)-Galliun Nitride (GaN) slot waveguide structures has been demonstrated [1].

Multimode interference (MMI) demultiplexer devices based on slot waveguide structures have been demonstrated the ability to separate two channels (spacing of 250nm) [2] and four channels (spacing of 50nm) [3].

Choosing a slot material with lower-index value lead to a stronger confinement inside the slot region. However, an MMI demultiplexer component with closer spacing between ports is very sensitive to the variation of the optical signals in the C-band (1530-1565nm) ,which can influence on the MMI coupler size and the performance. In order to overcome this problem, we choose GaN as the slot material. GaN has a low-index value compered to Si material and is also high-index value compared to alumina or silica. Thus, the MMI demultiplexer component based Si-GaN slot waveguide is not very sensitive to the variation of the effective refractive index that lead, the ability to separate closer wavelengths in the C-band inside the MMI coupler with good performances.

In this paper, we demonstrate a 1x8 wavelength MMI demultiplexer in slot Si-GaN waveguide structure that divides 8-ports in the C-band range with a spacing of 5nm between two ports. The operating wavelengths are: 1530nm (port 2), 1535nm (port 8), 1540nm (port 4), 1545nm (port 6), 1550nm (port 1), 1555nm (port 7), 1560nm (port 3) and 1565nm (port 5).

The device is based on 14 S-band, 7 units of 1x2 MMI couplers and 1 input taper. Numerical optimizations were carried out on the slot-waveguide structurer and the MMI coupler size in order to obtain a strong power confinements inside the slot region and to find the optimal values of the MMI coupler size.

Fig. 1 shows that the proposed device has low crosstalk ((-19.97)-(-13.77) dB) with a bandwidth range of 1.8-3.6nm. Therefore, this device can be used in optical networking systems that work on DWDM technology.

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## 10335-24, Session 6

# Short-wavelength infrared high resistive photoconductor based on Chalcogenide glasses for OASLM applications

Asi Solodar, Matvey Kalbanov, Ibrahim Abdulhalim, Ben-Gurion Univ. of the Negev (Israel)

In this work we have investigated highly resistive photoconductive samples based on Lead (II) sulfide (PbS) and GePbS as an active photosensitive layer for the SWIR spectrum range, obtained by thermal vacuum evaporation. As highly resistive layer we used chalcogenide As2S3 layer. In addition for OASLM applications the As2S3 layer can be utilized as a liquid crystal alignment layer instead of polymer spin coating method.

## 10335-25, Session 6

# Self-refraction in HMDs through adjustable focus lenses *(Invited Paper)*

Rob Stevens, Adlens, Ltd. (United Kingdom)

No Abstract Available

## 10335-26, Session 6

# A robust liquid crystal device with adjustable deflection and diffraction for multiple applications

Neal Weinstock, Soliddd Corp. (United States)

Based on the invention of Dr. Richard A. Muller, professor of physics at the University of California, Berkeley, the author's company proceeded to build a number of LC cells according to the initial design. The first design aimed at increasing pixel density equal to the inverse of the fill factor of a specific OLED display. The OLED display featured a fill factor of 25% and was run at a frame rate of 240Hz. The LC device featured a prism array with periodicity of 100 microns and height of 17 microns, which structure was chosen to minimize diffraction and moire from interaction with the underlying display. Light was deflected, as planned, in a sweep that was controllable by voltage ranging from 1V to 4V, by up to 2 degrees. The above prism array was bonded to one side of a single cell structure prepared with ITO coating, synchronized to the underlying display via the vertical sync signal. The desired four-times multiplied pixel density was

achieved with a constant deflection sweep of about 1 degree.

The system proved capable of highly accurate deflection at rates up to 1kHz and as low as 1Hz, with voltage which we found could be optimized to about 100 millivolts. At extremely low frequency, the deflection of light is easily apparent through the naked eye, and the device could be seen to displace any underlying image to either left or right. Very high light and color transmissivity were exhibited, and were clearly suitable for critical use in displays and other optical applications.

The experiment proved the system capable of deflecting light to much wider angles with the use of more acute prisms, thus removing the limit to pixel density increase imposed by the fill factor of the underlying display. When using a more complex wiring pattern to apply different voltage to different areas of the LC cell, the system also proved to be easily controllable for different degrees of deflection in different regions. This would allow for the relatively simple application of correcting for improper pixel alignment in the underlying display, or for inaccurate manufacturing or assembly of the prism array located within the LC cell.

Our success in these adaptations led to development of two additional adaptations of the same core technology. We have designed a cell that incorporates a Fresnel prism array, with voltage activated in concentric circles that are aligned with the Fresnel pattern. The goal of this system is to create a lens for vision adjustment in the range of four positive diopters. We expect to report on this ongoing development by the time we deliver the paper.

Finally, our experiments in limiting diffraction potentially caused by the system (which would be objectionable in our first application of increasing pixel density) have allowed us to understand how to adjust the amplitude and the frequency of the prism array. The potential, therefore, for a multiplier effect in the frequency of a diffraction grating, as well as a changed pattern, clearly exists. We expect to report on developments in this field by the time that we deliver the paper.

10335-27, Session 6

## A high-resolution optical rangefinder using tunable focus optics and spatial photonic signal processing

Tariq Shamim Khwaja, Mohsin Ali Mazhar, Haris Khan Niazi, Syed Azer Reza, Lahore Univ. of Management Sciences (Pakistan)

In this paper, we present the design of a proposed optical rangefinder to determine the distance of a semi-reflective target from the sensor module. The sensor module deploys a simple Tunable Focus Lens (TFL), a Laser Source (LS) with a Gaussian Beam profile and a digital beam profiler/imager to achieve its desired operation. We show that, owing to the nature of existing measurement methodologies, previous attempts to use a simple TFL in prior art to estimate target distance mostly deliver "one-shot" distance measurement estimates instead of obtaining and using a larger dataset which can significantly reduce the effect of some largely incorrect individual data points on the final distance estimate. Using a measurement dataset and calculating averages also helps smooth out measurement errors in individual data points through effectively low-pass filtering unexpectedly odd measurement offsets in individual data points. In this paper, we show that a simple setup deploying an LS, a TFL and a beam profiler or imager is capable of delivering an entire measurement dataset thus effectively mitigating the effects on measurement accuracy which are associated with "one-shot" measurement techniques. The technique we propose allows a Gaussian Beam from an LS to pass through the TFL. Tuning the focal length of the TFL results in altering the spot size of the beam at the beam imager plane. Recording these different spot radii at the plane of the beam profiler for each unique setting of the TFL provides us with a means to use this measurement dataset to obtain a significantly improved estimate of the target distance as opposed to relying on a single measurement. We show that an iterative least-squares curve-fit on the recorded data allows us to estimate distances of remote objects very precisely. We also show that using some basic ray-optics-based approximations, we also obtain an initial seed value for distance estimate and subsequently use this value to obtain a more precise estimate through an iterative residual reduction in the least-squares sense. In our experiments, we use a MEMS-based Digital Micro-mirror Device (DMD) as a beam imager/profiler as it delivers an accurate estimate of a Gaussian Beam profile. The proposed method, its working and the distance estimation methodology are discussed in detail. For a proof-of-concept, we back our claims with detailed experimental results showing a less than 3% measurement error for different target distances by using a reflective plane mirror as a target. We also demonstrate multiple orders of magnitude improvement in measurement accuracy when compared to existing techniques which deploy TFLs for target ranging applications.

10335-28, Session 6

## Arbitrary shaping of ultrafast Bessel beams with a phase-only spatial light modulator

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A Bessel beam is a diffraction-resistant beam. It is defined as a superposition of an infinite number of plane waves propagating at the same angle with respect to the optical axis. Its transverse spatial profile is featured by a hot central core with a width potentially below the wavelength surrounded by several peripheral rings with lower intensities. This diffraction-free nature and conical structure allow for propagation invariant regimes, even for high power lasers, which is very advantageous in many applications such as material processing and laser ablation. Due to the spatial limitation of experimentally generated Bessel beams, their on-axis intensity varies significantly along propagation.

In this context, arbitrary manipulation of their longitudinal propagation is necessary to control the peak intensity of the central core. We specifically aim to generate Bessel beams with flat-top and linear ramp on-axis intensity shapes. Theoretically, longitudinal beam shaping can be performed from Fourier space. This consists in the computation of the angular spectrum using a one-dimensional Fourier transform of the desired complex axial envelop. Since these two profiles involve abrupt intensity growth, they cannot be realized physically since this requires infinite spatial frequencies. We analytically express this limitation in terms of a convolution of the desired longitudinal intensity profile with a sinc-shaped function. We then show how to resolve this issue using smooth intensity profiles. In practice, arbitrary manipulation of the axial propagation of Bessel beams requires the modulation of both the spatial amplitude and phase of an incoming beam. In previous works, this has solely been performed using an iterative technique to encode the desired beam's spatial spectrum on a phase only spatial light modulator (SLM). Although this method allows for precise generation of target beam shapes, it yields a very low energy conversion (about 1.5 %), which makes it unsuitable for the application of Bessel beams in micro-nano machining. In our work, we use a non-iterative technique to exactly encode the optical field in a single SLM, from direct space, thus preserving high energy throughput. This technique is based on the modulation of the phase wrapping of a computer generated hologram, which allows to control the diffraction efficiency at each point of the phase mask. Our experimental setup is based on a 4f system and the desired optical field is retrieved at the first diffraction order. In contrast with previous works, our technique is generalized for arbitrary shapes of the incident laser beam on the SLM. This enables the conservation of a high-energy throughput by maintaining finite-size input illumination profiles of the SLM. In our experiments, we use a femtosecond laser source whose transverse spatial profile is in the form of imperfect Gaussian. We experimentally measure the intensity distributions along propagation of Bessel beams with different intensity profiles: a flat-top profile with parabolic leading and trailing edges; and linear ramp with a parabolic trailing edge. Our experimental results are in excellent agreement with numerical simulations. The measured energy conversion is typically ~10 %, which is one order of magnitude higher than the one obtained using Fourier-space beam shaping techniques. We anticipate this will open very novel perspectives for nonlinear optics and laser material processing. We acknowledge funding from the European Research Council (ERC) under Horizon 2020 program (GA N° 682032-PULSAR) in cooperation with Labex ACTION program, contract ANR-11-LABX-0001-01.

10335-29, Session 6

## Calibration and digital correction of aberrations in combined optical systems with interchangeable parts

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For many optical systems, mainly in photography, the correction of distortion and lateral colour aberration is a common step in the image processing pipeline. It is based on images of calibration targets and the determination of coefficients for a correction model. These coefficients are specific for the optical system which forms the aerial image for the sensor. If an exchange of the optical system is necessary, e.g. for offering optics for several applications like macro mode, wide-angle or tele-photo, the entire optical system is typically exchanged and not only parts of it. Using an technique for digital identification of the optical system, e.g. via an electronic interface, the corresponding correction coefficients can be obtained and applied. If the optical system to be exchanged is only a part of the entire optical system, the situation is more difficult. As an example, this is the case in the field of digital microscopy, where the objective lens has to be exchanged in order to offer a larger range of magnifications and resolutions. This objective lens is not an image forming optical system and needs at least a tube lens to produce an image for sampling with a sensor. Both optical systems produce contributions to the resulting overall aberrations, namely distortion and lateral colour aberration. For a particular pairing, coefficients for a correction model can be calibrated and applied. But in the case of an exchange of the objective, only a part of the optical system changes and a new calibration is needed. We will show how this problem can be solved using a mathematical operation and individual calibration of the distinct parts of the optical system. The advantage is, that the parts of the optical system can be arbitrarily combined and the correction-model coefficients of the combination can be computed from the corresponding coefficients of the individual parts. Hence, there's no need to calibrate every possible combination or to manage a calibration process at the customer's place. In addition, the manufacturing and calibration of objectives and tube lenses may take place at different locations. In addition, the optical design can benefit from the digital aberration correction although it is made up of interchangeable components.

10335-51, Session 6

## Adaptive digital stereo microscope to support 3D vision: optomechanical design and experimental validation

Carsten C. Reichert, Daniel Claus, Alois M. Herkommer, Institut für Technische Optik (Germany)

In this talk we present the opto-mechanical design and experimental results of an adaptive imaging system to simulate the human eye in a digital stereo microscope. The system allows for digital recording including the effects of accommodation and pupil shift, while offering a temporal resolution of better than 50ms (20Hz). Furthermore, a spatial resolution under 50 microns and a field of view of 30x30 mm is realized, which are common surgical microscope specifications. Special attention was given to the optical design of the recording system to match the imaging parameters and quality of a conventional stereo microscope. Important parameters, like NA, the position and size of the entrance pupil and the field of view match a conventional stereo microscope. The imaging performance of the recording system is good enough for during a surgery. The MTF and Seidel aberration coefficients demonstrate a good imaging performance of the adaptive digital stereo microscope.

In the digital stereo microscope accommodation is implemented via the addition of two tunable lenses from the company Optotune AG, one for each arm of the stereoscopic system. The optotune lens enables the application of a variable focal length of 80 mm to 200 mm. With this optotune lens in place the refocusing range of our system is 55 mm.

Based on the latency of the human eyes with regards to changing pupil position, the temporal requirement imposed is 50 ms (20 Hz). Therefore, a conventional manual x-y stages were modified by the attachment of two linear actuators from the company Nanotec Electronic GmbH & Co. KG, which enable a maximum speed of 140 mm / s. To cover the same amount of shift at the entrance pupil in our adaptive digital stereo microscope in comparison to the conventional system, the diaphragm must be displaced by ±0.6 mm. However, the total amount of shift that can be applied without significant loss caused by vignetting is ± 7mm.

The camera employed (XIMEA MQ013MG-E2) has a pixel pitch of 5.3 µm. To ensure sufficient sampling of the high-resolution elements the pixel pitch was multiplied by factor of 2.5. The magnification of the system is 0.25. Hence our system can deliver a maximum lateral resolution of 53µm. To confirm this theoretically calculated resolution a USAF test target has been employed. The resolution has been determined in accordance to the contrast threshold defined by Rayleigh's criterion applied to the averaged cross section plot of the respective test target element. A maximum spatial frequency of 17,96 line pairs / mm (Group 4, Element 2) could be achieved, which corresponds to a lateral resolution of 55,68 µm. The recovery of depth information as accomplished by the eye in the process of accommodation could be demonstrated using a cuboid. Applying different voltage settings to the optotune lens enables the recovery of different axial planes for the digital stereo microscope. Different perspective images are obtained by means of moving the diaphragm. A three-dimensional device has been printed. This device consists of two bars located at a distance of 70 mm to the in-focus object plane, which project a shadow on the in-focus object plane. Changing the location of the aperture in the intermediate pupil plane enables the recovery of object details which have previously been hidden by the shadow.

10335-30, Session 7

## Large holographic 3D display for real-time computer-generated holography *(Invited Paper)*

Ralf Häussler, Norbert Leister, Hagen Stolle, SeeReal Technologies GmbH (Germany)

SeeReal's proprietary concept of real-time holography is based on Sub-Hologram (SH) encoding and tracked Viewing Windows (VWs). A small VW is located at the eye pupil and contains the holographic information that is required to see a 3D scene. A SH can be considered as a small encoded lens function that reconstructs an object point in the 3D scene. The SH is only as large as is required to illuminate a VW. The small VW size and SH encoding, combined with other proprietary optimizations of SeeReal, lead to significant reduction of pixel count and computation effort compared to conventional holography concepts, thus making large real-time holographic displays feasible.

SeeReal presented its patented concept and holographic displays already several years ago. These displays used mainly off-the-shelve components. Meanwhile, improved full-color holographic displays were built with dedicated components. The most recent display has 300 mm x 200 mm active area.

Progress has been made on several components:

1) Lasers are used as light sources. They are more energy efficient, well suited for diffractive elements in the display sandwich and provide larger color gamut than the previously used LEDs.

2) A holographic display requires large-area collimated light. Parabolic mirrors or large lenses are not an option for a commercial display. Therefore, a flat backlight unit (BLU) was built that uses volume gratings (VG) to expand the light in compact size. The VGs are exposed in thin photopolymer films.

3) The hologram is encoded on a spatial light modulator (SLM). The SLM comprises a phase-modulating and an amplitude-modulating liquid-crystal display. The two displays were aligned pixel-to-pixel and laminated as a sandwich. Thus, the SLM modulates amplitude and phase of light.

4) A field lens made up of two VGs focuses the light into the VW. This lens replaces a bulky glass lens.

5) The holograms are calculated in real time on a computer graphics card or FPGA system.

A camera was placed at the VW and photographs of holographic reconstructed full-color 3D scenes were taken. Only the depth region on which the focus of the camera lens is set is in focus while the other depth regions are out of focus. Selective focus is possible while the same hologram is displayed. These photographs demonstrate that the 3D scene is reconstructed in depth and that SeeReal's holographic display supports accommodation of the eye lenses. Hence, the display is a solution to overcome the accommodation-convergence conflict that is inherent for stereoscopic 3D displays. Other depth cues are also supported and contribute to natural depth perception.

The main components, the progress and results of the holographic display with 300 mm x 200 mm active area will be described in the presentation. Furthermore, photographs of holographic reconstructed 3D scenes will be shown.

10335-31, Session 7

## 3D color reconstructions in single DMD holographic display with LED source and complex coding scheme

Maksymilian Chlipala, Tomasz Kozacki, Warsaw Univ. of Technology (Poland)

Nowadays there is high demand on displays, which allows 3D imaging. Several systems were proposed but most of them gives only the impression of three-dimensionality by use of stereoscopy, polarization effects, volumetric imaging and others. Among them only holographic displays enable to obtain 3D object reconstruction with full perspective and parallax. With recent and further improvement of display technology (smaller pixel size and higher frequencies of work) building color holographic display is becoming more realistic.

Highest resolution of reconstructed holograms is achieved for monochromatic point source and it drops down when the source of decreased coherence is used. Incoherent LED source limits the depth of focus and resolution of holographic display. However, such a source is interesting one because it enables reconstruction of holograms with no speckle noise, cause no eye hazard, has small size and is already widely available in displays.

In the literature there are several color holographic displays based on SLM (Spatial Light Modulators) and LED sources[1-4]. In our previous work we presented single SLM holographic display with white light LED, which allows to reconstruct high quality 3D objects[5]. The phase-only SLM has improved quality of reconstructed holograms. However its disadvantage is long response time. Thus it has limited possibility of implementing time multiplexing. For that reason many researchers decide to utilize DMD modulators [6,7] in holographic displays and investigate possibilities of color reconstruction [8] as well as using incoherent LED source [9].

In this work we decided to use our experience with holographic display and incoherent sources. We propose holographic display setup with DMD and LED source. We choose DMD since it has high speed response, which allows to increase the resolution and obtain color reconstruction of 3D objects with time multiplexing. Additionally, illuminated with correct angle DMD can work as blaze grating, which increase efficiency and allows to obtain large separation between diffraction orders.

In experimental part of this work we investigate the possibility of color reconstructions of holograms with single DMD and incoherent LED illumination. Our holographic display design employs complex coding scheme achieved with frequency filtering in Fourier plane of 4F imaging system, which allows to center reconstruction volume around display surface. To reduce noise and improve the resolution of reconstructed 3D objects we utilize time multiplexing method. Since DMD is binary modulator it is important to ensure correct binarization for RGB channels in order to obtain proper color mixing. This work is accompanied with computer simulations where we investigate quality of reconstructed holograms obtained for coherent and incoherent source as a function of reconstruction distance. We analyze influence of temporal and spatial coherence of source. During optical reconstructions we analyze quality of reconstructed holograms for several distances from DMD plane and compare display efficiency for each RGB color component. We show that in presented holographic display it is possible to obtain color holographic reconstructions of different content: 2D and 3D computer generated hologram.

10335-33, Session 7

## Autonomous generation of extended images of dynamic phase objects in a depth volume sample using a simple focusing criterion and K-means clustering

María-Luisa Cruz-López, Univ. Panamericana (Mexico); Miguel Alcaraz-Rivera, Univ. Panamericana (Mexico); Pinhas Girshovitz, Natan T. Shaked, Tel Aviv University (Israel); Bahram Javidi, University of Connecticut (United States)

The study of the movements of microscopic phase objects, like biological cells, is of high interest in the scientific community. In microbiology, environment pollution and medicine it is important to analyze the movement pattern of cell or microparticles in real time with a non-invasive technique. Digital Holographic Microscopy (DHM) is a good candidate for this proposal. In the last years, it had been wide used for analysis of phase objects with different interferometric setups. DHM can record, in one shot, the whole sample complex field: amplitude and phase. Then the complex field is refocused in several planes for the 3D sample reconstruction. The focus depth of the hologram is limited by the focus depth of the system used in the recording process. In a thick sample, this condition arouses than only some of the retrieved object are in focus. The entire sample is recovered propagating the field to each object distance location or focus distance. When in the view field there are several cells at different distances from the hologram plane, the correct location of each cell is critical for the analysis of the sample. There are diverse approaches for finding the optimal focusing distance of a phase object. One of the most used is the criterion of look for a maximum in the integrate intensity of the propagated wave for phase object and a minimum for the amplitude object. This method requires the location in the view field and the definition of the analysis area for each object. Some proposals had incorporated the use of complementary segmentation methods to set these parameters automatically. However, the segmentation process is strongly linked to the object shape. In the case of a biological sample, some cells change its shape as they swim in the sample. We present the analysis of moving phase objects, using an alternative focusing criterion that introduces the use different sized windows it the analysis of the integrated intensity. The use of the various sized windows allows detecting the object focus distance without to define a specify analysis area for each object. The view field is divided into a grid of sampling points, and the method is applied in each point of the grid. With this criterion, we create a depth map with the focus distance calculated for each point. The method measures the variation of the integrated intensity not only in the longitudinal direction but also in the transversal direction. See Fig. 1, where a graph of the integrated intensity of one point inside of a cell is analyzed with the different sized windows for all the propagation distances. We set a threshold in the variation of the integrated intensity as a criterion for the discrimination of the phase objects from the background area in the depth map, see Fig. 2. The depth map is segmented with the clustering K-means method, and each cluster is analyzed to determine the optimal focusing distance for each object. The method is implemented in the C++ language, and the OpenCV libraries are used in the clustering analysis. For each cluster, we select a focus distance. We propose two criterions to choose the focus distance of each cluster. One is the median, and the other is the mean of the detected focus plane in the depth map. We present the results of both criteria in the selection of the cluster focus distance. The recovered complex field is propagated to the focus distances detected, and using the cluster zones as a reference, we segmented the complex field and composed an extended focus image of the sample in amplitude and phase. See Fig. 3. The phase is unwrapped before the segmentation. The process is optimized with a multithreading routine in the focus detection process and the composition of the extended image. The integrated intensity analysis of each propagated plane is processed in a different thread, and the results are recorded in one matrix. The reconstruction of each object is also assigned to different threads. These operations reduce the processing time for the extended focus image generation. The method can detect autonomously when a new cell enters the view field and calculate its focusing distance. The resulting images present all the cells in the sample well focused, and can be used for counting or tracking purposes. We present simulated and experimental results.

10335-34, Session 7

## An optical method for compensating phase discontinuity in a 360-degree viewable tabletop digital holographic display system

Yongjun Lim, Keehoon Hong, Hayan Kim, Hyon-Gon Choo, Minsik Park, Jin-Woong Kim, Electronics and Telecommunications Research Institute (Korea, Republic of)

Recently, various methods for implementing 360-degree viewable tabletop systems have been reported, and our proposed system implementing the 360-degree viewable holograms was published in Optic Express titled "360-degree tabletop electronic holographic display" in October in 2016 [1]. Generally, many researchers interested in holographic display systems have proposed or focused on methods for overcoming low space bandwidth product of currently-available (or commercially-available) spatial light modulators (SLMs). Representative techniques to overcome low space bandwidth product of SLMs are spatial multiplexing, time-division (temporal) multiplexing and combination of those two techniques. In our recently-published work, spatially-tiled digital micro-mirror devices (DMDs) are used to generate holograms to provide an increased-size hologram.

In addition, lots of applications based on quantitative phase imaging methods such as digital holography (DH) and transport of intensity equation (TIE) have shown unprecedented ways to perform phase imaging that can provide three dimensional images and views [2]. However, they are usually used to detect wavefront of optical waves coming out of micron-sized or submicron-sized objects. In our proposed work, we are going to present the feasibility of transport of intensity equation technique to estimate holograms generated by a holographic display system based on spatially-tiled digital micro-mirror devices (DMDs) which are used as spatial light modulators.

Specifically, in our 360-degree table-top electronic holographic display system, to extend the size of the generated hologram, more than two DMDs are used. To stitch those DMDs seamlessly in a resultant hologram plane, it is necessary to establish well-aligned optical systems. However, the imperfection in optical alignment causes the discontinuity in the boundary between two adjacent DMDs in an optically-tiled hologram plane. Consequently, it is necessary to adopt an appropriate technique to estimate reconstructed holograms in using multiple numbers of DMDs, and we are going to extract the phase profile of the generated holograms by the use of the TIE method proposed by M. R. Teague [3]. Moreover, by comparing the extracted phase profile given by the TIE method with the conventional interferometric results based on a phase-shifting DH technique, we are going to guarantee the accuracy of the phase information obtained by the TIE technique. And then, after identifying the phase discontinuity between two DMDs, we are going to suggest an optical method to compensate for the phase discontinuity between them.

In our 360 degree table-top electronic holographic display system, the laser with the wavelength of 532 nm is used as a light source, and the DMD which has 1024 (horizontal) ? 768 (vertical) pixels is used as a spatial light modulator to display binary patterns of the computer generated holograms (CGHs). To remove unwanted signals in reconstructing holograms, where the DMD is used as an SLM, 4-f optics configuration composed of two lenses with the focal length of 180 mm and a spatial filter is implemented. By optically aligning multiple numbers of the DMD based on the 4-f configuration, it is possible to form a reimaged DMD plane composed of more than two DMDs. The reconstructed holograms are captured by a charge coupled device (CCD), and the position of the CCD is adjusted to adopt the TIE method. After extracting phase profile of the reconstructed holograms, the phase discontinuity between two adjacent DMDs are numerically estimated.

10335-36, Session 8

## The promises and pitfalls of real-time holographic display *(Invited Paper)*

Joel S. Kollin, Microsoft Corp. (United States)

No Abstract Available

10335-37, Session 8

## VR versus LF: towards the limitation-free 3D

Tibor Balogh, Holografika Kft. (Hungary); Peter A. Kara, WMN Research Group, Kingston University (United Kingdom)

The evolution of 3D technologies shows cyclical learning curve with series of hypes and dead-ends, with mistakes and consequences. 3D images contain significantly more information than corresponding 2D. 3D display systems should be built on more pixels, or higher speed components1. For true 3D this factor is in the order of 100x, a real technology challenge. If not fulfilled, 3D systems' capabilities will be compromised: headgears will be needed, or viewers should be positioned / tracked, single user devices, lack of parallax, missing cues, etc.

The temptation is always there: why to provide all the information, just what the person absorbs that moment (subjective or objective visualization). This leaded to the short-cut to 3D: 2x stereo, the 3DTV hype (rather 2 x ?). The 3D the industry promised and what people expected was not what they got. Was it a mistake? Yes, since 3DTV failed, but we learnt a lot about the artifacts, camera rigs, view synthesis (depth/disparity, inter /extrapolation), stereo content editing, audience reactions, etc.

VR glasses were around for more than two decades. With the latest technical improvements and the market start signal by the 2B$ acquisition of Oculus, VR became the next hype. 3D immersion was added, as a new phenomenon, however VR represents an isolated experience, requires headgears and a controlled environment (AR in this sense if different). Will VR/AR hype with the headgears be a mistake? Might be. On the other hand it will be B$ business and we will learn that 3D requires more information (and more than 2 cameras). Although the geometry of next-generation 3D systems may be different, as shown in Figure 1., we will learn a lot about camera arrays, high-performance 3D computation, immersive 3D content, complementing technologies, like 3D tracking, motion platforms, haptic feedback, etc., and range of novel VR/AR applications, areas, professions will be born.

"While VR headsets may sell better than smart glasses or 3D TV glasses, also consider that using the technology may require a set of behavioral changes that the majority of people do not want to make"2. Displays and technologies that restrict viewers, or cause any discomfort will not be accepted on the long term.

The newer wave of 3D is forecasted to 2018-2020, answering the need for unaided limitation-free 3D experience. Light Field (LF) systems represent the next-generation in 3D. The HoloVizio3,4 system, having ~100x capacity, offers natural, restrictions-free 3D on a full FOV, enabling collaborative use for unlimited number of viewers even in a wider immersive space. As a scalable technology, the display range goes from monitor style units, through automotive 3D HUDs, screen-less solutions, up to cinema systems and Holografika is working on interactive large-scale immersive systems and glasses-free 3D LED walls.

Acknowledgment

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10335-38, Session 8

## Volumetric graphics in liquid using holographic femtosecond laser pulse excitations

Kota Kumagai, Utsunomiya Univ. (Japan); Yoshio Hayasaki, Utsunomiya Univ (Japan)

Volumetric display has paid much attention for three-dimensional (3D) display in fields of optics and computer graphics. This display can render the 3D graphics that is observed from any surrounding viewpoints without to wear any special devices and physiologic discomfort for displaying visual information having binocular parallax. Volumetric displays are classified into two types, depending on the characteristics of the voxels: the light-reflecting type and the light-emitting type. Reflecting types using projection rotating screen, water drops, and floating small particles have been constructed. Light-emitting types using optical fibers, 3D cubic array of light-emitting diodes (LEDs), and laser irradiation have been demonstrated. The laser irradiation type has a wide viewing angle and does not require any physical connection between the light source and the display volume. Laser-irradiation-based volumetric displays have been demonstrated by using various media, such as air, liquids, and solids. With these previous approaches, however, the number of voxels in the volumetric display is not high enough for rendering practical volumetric images because they are limited by the repetition frequency of the laser and the speed of the 3D scanning system.

In our previous work, we demonstrated the volumetric display system based on holographic parallel optical access and two-photon excitation using a computer-generated hologram displayed on a liquid crystal spatial light modulator, and the multilayer fluorescence screen. The holographic method has not only increased the maximum number of voxels that can be rendered but also enabled the formation of brighter volumetric images. In addition, two-color display composed of red voxels and blue-green voxels has been achieved using a fluorescence place containing different fluorescence moolecules.

In this presentation, we demonstrated a volumetric display based on holographic femtosecond-laser induced micro bubbles. The volumetric display system is generally composed of a light source, a modulator of light, and a screen. In our system, the light source is an amplified femtosecond pulse laser in order to excite a liquid screen via multi-photon absorption. The modulators perform three-dimensional beam scanning of the focal points for a laser drawing of voxels. The screen is a liquid with high-viscosity. The holographic parallel access technique based on a computer-generated hologram displayed on a liquid crystal on silicone spatial light modulator. First, the holographic technique is an effective way to increase the number of voxels of the volumetric graphics per unit time. Second, it controls the size and shape of voxels. Various shapes of beam like a line-focused beam and a focal point corrected spherical aberration can be achieved. Third, it synthesizes different patterns in a single beam. When a femtosecond laser is focused inside a liquid, bubbles are formed via through nonlinear processes called breakdown. Our motivation is achieving the volumetric display with femtosecond laser-induced bubbles.

We demonstrate two-dimensional and three-dimensional bubble graphics rendered by femtosecond laser-induced micro bubbles. We also some features of bubble graphics such as the relation between the structure and speed of bubbles for the irradiation energy of femtosecond laser pulses, the voxel structure controlled with the holographic parallel excitations, and color changes using a light projection.

10335-39, Session 8

## Distortion-free 3D imaging using wavefront shaping

Martin Teich, Jeremy Sturm, Lars Büttner, Jürgen W. Czarske, TU Dresden (Germany)

3-dimensional imaging often requires substantial effort since information along the optical axis is not straight forward gatherable. In many applications it is aimed for depth information along the direction of view. For example fluidic mixing processes and the environmental interaction on a microscopic scale are of particular importance for pharmaceutical applications [1] and often demand for 3D information. Beside micro- and nano-fluidic applications also surveillance systems usually exhibit a lag of depth mapping ability [2]. This problem is often solved by stereoscopic approaches, where two cameras are used in order to gather depth information by triangulation technique. Another approach is to scan the object through the focal plane in order to get sharp images of each layer, which is not suitable for every application. Since all the before mentioned approaches require a lot of video data to be evaluated it would be more convenient to get depth mapping within a single camera recording and without scanning. Here we present a tunable 3D depth-mapping camera technique in combination with dynamic aberration control. It is a scan-free, shadow and fluorescence imaging technique for 3D trajectory and velocity measurement of flow fields [3]. By using an incoherent light source, only one camera and a spatial light modulator (LCoS-SLM) loaded with a spiral phase mask that generates double-images of the measurement object, it is a simply applicable and highly scalable technique [4]. A double-helix point spread function (DH-PSF) is generated for light emerging from the observed focal plane. Each object appears as a double-image on the camera. Within the orientation of the double-image, depth information along the optical axis is encoded. By using an additional adaptive element (deformable mirror) the technique is combined with wide-field aberration correction [5]. Here we combine a tunable 3D depth camera with dynamic aberration control in one imaging systems.

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10335-40, Session 8

## Autostereoscopic image creation by hyperview matrix controlled single pixel rendering

Armin Grasnick, FernUniv. in Hagen (Germany)

Just as the increasing awareness level of the stereoscopic cinema, so the perception of limitations while watching movies with 3d glasses has been emerged as well. It is not only that the additional glasses are uncomfortable and annoying; there are some tangible arguments for avoiding 3d glasses. These "stereoscopic deficits" are caused by the 3d glasses itself.

In contrast to natural viewing with naked eyes, the artificial 3d viewing with 3d glasses introduces specific "unnatural" side effects. The most of the moviegoers has experienced unspecific discomfort in 3d cinema, which they may have associated with insufficient image quality. Obviously, quality problems with 3d glasses can be solved by technical improvement. But this simple answer can -and already has- mislead some decision makers to relax on the existing 3d glasses solution. It needs to be underlined, that there are inherent difficulties with the glasses, which can never be solved with modest advancement – as the 3d glasses initiate them.

To overcome the limitations of stereoscopy in display applications, several technologies have been proposed to create a 3d impression without the need of 3d glasses, known as autostereoscopy. But even todays autostereoscopic displays cannot solve all viewing problems and still show limitations. A hyperview display could be a suitable candidate, if it would be possible to create an affordable device and also generate the necessary content in an acceptable timeframe.

All autostereoscopic displays, based on the idea of lightfield, integral photography or super-multiview could be unified within the concept of hyperview. It is essential for functionality that every of these display technologies uses numerousness of different perspective images to create the 3d impression. Such a calculation of a very high number of views will require much more computing time as for the formation of a simple stereoscopic image pair.

The hyperview concept allows to describe the screen image of any 3d technology just with a simple equation. This formula can be utilized to create a specific hyperview matrix for a certain 3d display – independent from the technology used. A hyperview matrix may contain the references to loads of images and act as an instruction for a subsequent rendering process of particular pixels. Naturally, a single pixel will deliver an image with no resolution and does not provide any idea of the rendered scene. However, by implementing the method of pixel recycling, a 3d image can be perceived, even if all source images are different. It will be proven that several millions of perspectives can be rendered with the support of GPU rendering and benefit from the hyperview matrix.

In result, a conventional autostereoscopic display which is designed to represented only a few perspectives can be used to show a hyperview image by using a suitable hyperview matrix.

It will be shown that a millions-of-views-hyperview-image can be presented on a conventional autostereoscopic display (designed for 5 or 8 images by default). For such an hyperview image it is required that all pixels of the displays are allocated by different source images. Controlled by the hyperview matrix, an adapted renderer can render a full hyperview image in realtime.

### 10335-41, Session 9

## Smart spin-orbit photonics using liquid crystals

Etienne Brasselet, Univ. Bordeaux 1 (France)

Liquid crystals are well-known for their exquisite sensitivity to external fields and their ability to tailor the amplitude, phase and polarization of light fields. The interplay between the topological features of liquid crystals and that of electromagnetic fields offers a playground for the development of self-engineered spin-orbit optical elements with unique functionalities. Recent progresses will be reviewed.

### 10335-42, Session 9

## Holographically generated structured illumination for cell stimulation in optogenetics

Felix Schmieder, Lars Büttner, Jürgen W. Czarske, TU Dresden (Germany); Maria Leilani Torres, Leibniz Univ. Hannover (Germany); Alexander Heisterkamp, Leibniz Univ. Hannover (Germany) and Laser Zentrum Hannover e.V. (Germany); Simon Klapper, Volker Busskamp, DFG-Ctr. for Regenerative Therapies Dresden (Germany)

Computer generated holograms (CGH) cover a wide range of applications, e.g. the calculation of customized diffractive optics [1]. In conjunction with a spatial light modulator (SLM), such a digital holographic system can be used for holographic displays [2] or even adaptive beam forming in material inspection systems [3]. A research field which has roused much interest lately and will greatly benefit from digital holographic systems is optogenetics [4]. Here cells, neurons or cardiac cells, are genetically altered to produce for example the light-sensitive protein Channelrhodopsin-2. Illuminating these cells induces action potentials or contractions and therefore allows to control electrical activity. Thus, light-induced cell stimulation can be used to gain insight to various biological processes. In our contribution, we present a digital holographic system for the patterned, spatially resolved stimulation of cell networks. We employ a fast ferroelectric liquid crystal on silicon SLM, which can display computer generated holograms at a rate of up to 1.7 kHz. We calculate the holograms of our sparse patterns by convolving a Fresnel zone plate with the pattern, followed by two steps of error diffusion for the conversion into a binary hologram. We employ a quasi-free-space holographic setup to be able to use the light-efficient zero-order diffraction and to somewhat alleviate the need for pseudo-random illumination patterns reported in literature [4]. With an effective working distance of 33 mm, we achieve a focus of 10 µm at a positioning accuracy of the individual foci of about 8 µm. We utilized our setup for the optogenetic stimulation of clusters of cardiac cells derived from induced pluripotent stem cells and were able to observe contractions correlated to both temporal frequency and spatial power distribution of the light incident on the cell clusters. Thus, future single-cell-based optogenetics research will benefit from the digital holographic system presented in our contribution, e.g. in the probing of signal pathways in cell networks.

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### 10335-43, Session 9

## Design and quality metrics of point patterns for coded structured light illumination with diffractive optical elements in optical 3D sensors

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Structured light has become a widespread technique for the development of camera-based 3D sensors. The structured illumination provides texture to homogeneous objects and thus allows for the reliable determination of the disparity of each object point in a stereo-camera setting. Even a monocular 3D sensor is possible if the light projector has a fixed relative position to the camera and if the structured light is coded, i.e. the position within the whole light pattern can be reconstructed uniquely from a small local window of the pattern, the uniqueness window. Coded patterns with such a uniqueness property are called Perfect SubMaps (PSM).

In principle, the PSMs can contain any number of brightness levels. The maximum signal-to-noise ratio, however, which is particularly important for monocular 3D cameras, is achieved if only two brightness levels are used and if the light spots are isolated. In this case the PSM is a binary grid pattern with code symbols that are either 0 or 1, and each 1 is surrounded by zeros. For most optical 3D sensors it is sufficient that only a repeating part of the structured light pattern is a PSM, i.e. the complete pattern consists of identical tiles that are toroidal PSMs (TPSM)., The toroidal property ensures that the uniqueness property is not lost at the border of the tiles. The most efficient way to build powerful structured light projectors with a small size is to combine a collimated diode laser with a diffractive optical element (DOE) that generates the PSM from the collimated laser beam. In applications, large projection angles, high contrast, and a good suppression of the undesired undiffracted (zeroth-order) laser beam are required. This can be achieved only with binary DOEs that are point-symmetric with respect to the 0th order of diffraction, i.e. the center of the pattern.

Therefore, in our paper we focus on the design and the evaluation of symmetric isolated binary toroidal PSMs (SIBTPSM) for structured light DOEs. We define several quality metrics that are relevant for the practical use of PSMs in a 3D sensor: the size of the PSM, the size of the uniqueness window, the Hamming distance, the density, and the homogeneity.

We have created SIBTPSMs using our own dedicated algorithms and have designed and fabricated DOEs that produce these patterns with large fan angles of 61° x 47° when used with near-infrared diode lasers (?=830nm).

We analyze the influence of the above mentioned quality characteristics on the 3D measurement process by theory, simulations, and experiments. The patterns of publicly available DOEs based on SIBTPSMs are used for comparison and reference.

Our results show that the width of the PSM, the size of the uniqueness window, the minimum and the average Hamming distance, and the homogeneity have strong impact on either the speed or the quality of the 3D reconstruction, whereas the point density and the height of the PSM are of minor importance.

### 10335-44, Session 9

## Structured illumination 3D microscopy using adaptive lenses and multimode fibers

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Microscopic techniques with high spatial and temporal resolution are required for in vivo studying biological cells and tissues. Adaptive lenses exhibit strong potential for fast motion-free axial scanning. However, they also lead to a degradation of the achievable resolution because of aberrations. This hurdle can be overcome by computational imaging. We present a novel High-and-Low-frequency (HiLo) 3D-microscope using structured illumination and an adaptive lens [1]. A uniform illumination image is used to obtain optical sectioning for the high-frequency (Hi) components of the image, and a nonuniform illumination image is used to obtain optical sectioning for the low-frequency (Lo) components of the image. To generate the nonuniform illumination we use an optical multimode fiber [2]. The nonuniform illumination ensures stability against optical aberrations of the adaptive lens. The depth-of-field of our microscope can be adjusted a-posteriori by computational optics. It enables to create flexible scans, which compensate for irregular axial measurement positions. The adaptive HiLo 3D-microscope provides an axial scanning range of 1 mm with an axial resolution of about 4 microns and sub-micron lateral resolution over the full scanning range. In result, volumetric measurements with high temporal and spatial resolution are provided. Demonstration measurements of zebrafish embryos with reporter gene-driven fluorescence in the thyroid gland are presented. Furthermore, we demonstrate how multimode fibers can be employed to transfer images with spatio-temporal resolution [2].

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### 10335-45, Session 9

## Imaging and pattern projection through multicore fibers using the memory effect

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Microendoscopy through optical fibers permits high-resolution optical imaging inside tissues at depths not accessible using conventional microscopy [1, 2], while also being minimally invasive. Clinically used microendoscopes are usually made with multicore fibers (MCFs), optical fibers consisting of a common cladding and several single mode (or few modes) cores arranged in a quasi-periodic array. Each core probes information for one pixel of the final image. Thus, the attained image will be pixelated by the core spacing, which limits the resolution of these endoscopes to a several micrometers. In fact, to avoid inter-core coupling, the spacing between cores has to be sufficiently large, so that the information carried by each core is independent from its neighbors. Here we show how with a single calibration step, wavefront shaping enables light control through a MCF at a resolution below the core-to-core spacing. We demonstrate both imaging and complex pattern projection through a MCF with a resolution dictated by the numerical aperture of the cores of the MCF.

A focus spot can be created through a MCF using wavefront shaping techniques [3–6], where the wavefront of the laser beam entering the MCF is properly modified using a spatial light modulator (SLM) in order to focus light in a specific location in front of the optical fiber. In this work we used digital phase conjugation (DPC) [7] as the wavefront shaping technique. A calibration spot was focused in front of the MCF, and then by measuring the field at the other end of the fiber and phase conjugating it, a focus spot is recreated at the calibration position. The size of the spot (or the point spread function – PSF – of the imaging system) depends on the highest spatial frequency that can contribute in the specific location in front of the fiber. In this case, it depends on the numerical aperture of the cores and not on the inter-core distance. For a large enough numerical aperture, the obtained PSF has, as a consequence, a resolution finer than the core-to-core spacing.

The focus spot can be shifted across the imaging plane by tilting the angle of the wavefront incident on the MCF [3], [5], [8]. This effect is similar to the memory effect observed in scattering media [9], [10]. The ability to focus and scan light in a regular grid (Figure 1(a)), enabled us to image with a resolution finer than the core-to-core spacing (Figure 1(b)). Also, thanks to the memory effect, the spots can be projected in several locations simultaneously. Combining several spots permitted the projection of patterns with the same high-resolution determined by the numerical aperture of the core. We demonstrate the projection of simple patterns, such as the combination of several foci, and complex patterns (Figure 1(c)), using the phase only SLM as amplitude and phase modulator.

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### 10335-18, Session PS2

## Aerial 3D display by use of a 3D-shaped screen with aerial imaging by retro-reflection (AIRR)

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[CONTEXT] One of the big dreams in imaging technology is to realize a three-dimensional display that is floating in mid-air. One of the prospective techniques to realize such a floating display is aerial imaging by retro-reflection(AIRR) [H. Yamamoto, Opt. Exp. 22, 26919 (2014)]. AIRR forms the real image of a source display plane-symmetrically regarding a beam splitter by use of a retro-reflector to converge lights. In order to avoid the loss of reflected and transmitted lights at the beam splitter, polarization modulation has been introduced to AIRR. This setup is called polarized AIRR (pAIRR) [M. Nakajima, Proc. CLEO-PR, 25B1-2 (2015)]. Previously reported systems formed a 2D screen in mid-air. [OBJECTIVE] The purpose of this paper is to realize an aerial 3D display. We design optical system that places a 3D-shaped screen and a projector below a retro-reflector. [METHOD] Our proposed new optical system is composed of a 3D-shaped screen, a projector, a quarter-wave retarder, a retro-reflector, and a reflective polarizer. Because AIRR forms aerial images that are plane-symmetric of the light sources regarding the reflective polarizer, the shape of the 3D screen is the inverted shape of the desired aerial 3D image. In order to expand view angle, the 3D-shaped screen is surrounded by a retro-reflector. In order to separate the aerial image from reflected lights on the retro-reflector surface, the retro-reflector is tilted by 30 degrees. A projector is located below the retro-reflector at the same height of the 3D-shaped screen. The optical axis of the projector is orthogonal to the 3D-shaped screen. Scattered light on the 3D-shaped screen forms the aerial 3D image. [RESULTS] A corner-cube-shaped screen is used for the 3D-shaped screen. Its color is white. Its area length is 100 mm. Thus, the aerial 3D image is a cube that is floating above a reflective polarizer. We used a DLP projector (PT-DX820 made by Panasonic). The brightness of the projector is 7,000 lumens. In order to confirm the optical design, an aerial green cube is formed by projecting a calculated image on the 3D-shaped screen. The green cube image is digitally inverted in depth by our developed software. Our software can adjust the projected image to the size, the direction, and the location of the 3D-shaped screen. The side retro-reflectors have 340 mm height and 600 mm width. The central retro-reflector has 170 mm height and 480 mm width. The formed aerial 3D image is floating at 150 mm height from the reflective polarizer. Viewing positions are designed at 500 mm distance from the aerial 3D image and at 160 mm height. Thus, we have succeeded to form aerial 3D image with our designed optical system. Our optical system has overcome the following two problems. The first problem is low luminance of the aerial image that is formed by scattered light on an object. The second problem is that aerial 3D image depth is inverted. [NOVELTY] This is the first report on forming the 3D aerial image by use of a 3D-shaped screen with AIRR.

## 10335-56, Session PS2

## Real-time aberration correction simulation of multimode beam by SPGD algorithm

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With the increase of the laser output power, heat effect and nonlinear effect on the beam quality become increasingly serious, directly limit the improvement of laser brightness output. Multimode laser has fewer restrictions on the structure, so it can be able to withstand higher power output. But the multimode beams with poor beam quality decline the beam quality of imaging system and far field. As a result, improving beam quality of the multimode beams by aberration control is of great significance. In this paper, a real-time dynamic closed loop control method of multimode beams is proposed that use the wave-front aberration measurement data and phase correction device as the core. It has a very good reference value for subsequent application in imaging system in beam quality measurement.

In this paper, the physical properties of multimode beam are analysed by using the theory of partially coherent light. Based on the spatial coherence measurement results of a multimode fiber laser, we provide a theoretical basis for aberration correction for multimode beams. To improve the beam quality of multimode lasers, phase correction of multimode laser based on a dual-phase-only liquid-crystal spatial light modulator (LC-SLMs) is presented which is used as aberration correction device. The phase distribution was optimized by the stochastic parallel gradient descent (SPGD) algorithm. In this paper the power in the bucket (PIB) of the far field was used as the evaluation function and the multimode beam included multiple higher order Laguerre-Gaussian beam modes. The PIB of single high-order mode beam, coherent and incoherent multimode beam are simulated respectively. According to the result of the PIB, the parameters of SPGD algorithm can be adjusted and the efficiency and practicability of the algorithm are determined.

In conclusion, the real-time dynamic closed loop aberration correction of multimode beam based on the SPGD algorithm can efficiently improve the imaging quality, and it may be a useful means to preserve beam quality both in fiber laser system and imaging system.

## 10335-58, Session PS2

## CPU architecture for a fast and energy-saving calculation of convolution neural networks

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The increasing computing power in recent years allows more and more complex algorithms for the implementation of adaptive artificial intelligence. Deep Learning is one approach for adaptive intelligence. For the task of pattern recognition the family of Convolution Neural Networks (CNN) is applied. The best example is the image search on the internet. Here CNN are used for classifying 1000 different objects in one picture [1]. In addition these networks are used for example for autonomous driving. These networks learn how to behave on the street and also the recognition of the road signs [2]. Another application is the detection of human faces [3] and there emotions. The CNN is used as an interface between humans and robots [4]. CNN can even be trained to calculate the calories in a meal. The user only has to make an image of his meal with a smartphone [5]. Another use of the CNN is to recognize emotions in audio data or images [6]. The first CNN worked for optical character recognition (OCR). Le Cun has developed networks with an accuracy of about 98% [7]-[8].

In this paper a CNN is used for plant detection in organic farming. In paper [9]-[10] the basics, the sensor-configuration and parts of the classification task of the project were already presented. The biggest problem is still the speed and power consumption of the algorithms. Although large search engine companies own specially developed hardware to provide the necessary computing power, for the conventional user only remains the state of the art method, which is the use of a graphic processing unit (GPU) as a computational basis. Although these processors are well suited for large matrix computations, they need massive energy. Therefore a new processor on the basis of a field programmable gate array (FPGA) has been developed and is optimized for the application of deep learning. This processor is presented in this paper as well. The processor can be adapted for a particular application (in this paper to an organic farming application). The power consumption is only a fraction of a GPU application and should therefore be well suited for energy-saving applications.

To further increase the performance of the FPGA solution, the ALU should be set up several times so that more calculations are possible at the same time. Since we have only consumed about 3% of the FPGA's required resources at present, a multiplication of the ALU is not a big problem. A further optimization is the implementation of a pipeline structure to eliminate unnecessary course times. We hope that we can present the next generation of our CPU in the future.

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10335-59, Session PS2

## Method of synthesis of abstract images with high self-similarity

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Abstract image with high self-similarity could be used for drug-free stress therapy. This based on the fact that a complex visual environment has a high affective appraisal. Comlex structure of the picture is constructed from the different complicated geometric shapes of different colors. The pattern is projected to the dome for additional effect of immersion to the visual environment.

To create such an image we can use the setup based on the three laser sources of small power and different colors (Red, Green, Blue), the image results resulting from reflecting and refracting by the object of the complicated form placed into the laser ray paths. Using three laser sources provides the possibility of different colors of the patterns, the shape of the object defines the structure of the pattern. The more complicated is the object surfaces the more complicated is the image projected on the dome surface.

Different object forms were used for pattern forming, as a result the images were obtained experimentally which showed the good therapy effect on the group of volunteers. However, to find and to choose the object which gives needed image structure requires many trials if it chosen experimentally because of the high non-linear structure of the necessary image.

Of cause the design task can be solved using the non-imaging optics methods. In fact this means obtaining the necessary irradiance distribution on the given surface. In the given case this task is very complicated because of the complicated structure of the illuminance distribution and its high non-linearity.

The goal of the work is to develop a method and a procedure of finding the object form which can provide the necessary structure of the image when placed into the ray paths.

So we propose during the modeling of the optical system using ray tracing technique to locate the object zones responsible for the area of interest in the future image. It means that we have a few objects with complex and highly non-linear surfaces, and the patterns that were generated in the setup in practice. We can create the 3D model of these objects that we can use in ray-tracing. During the ray tracing we can find the areas of the object surfaces what produce certain elements in the image patterns. We can assume what we would like to have in the image pattern, so the next step is the synthesis of the object (the 3d-model) using the different fragments of the found surfaces. This can speed up the synthesis procedure for the given image of the high self-similarity for the setups of drug-free therapy.

10335-60, Session PS2

## A study of wavefront coding technique applied to next generation digital optical system

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Kaohsiung First Univ. of Science and Technology (Taiwan); Cheng-Mu Tsai, National Chung Hsing Univ. (Taiwan)In this research, we mainly focuses on the development of wave-front coding digital algorithm and the design of an optical system which conforms to wavefront coding system. Therefore, we carried out two design, 1. Special design A phase plate is added to the optical system, 2. Design a lens that only has a significant effect on the defocus (the primary aberrations can not be too large), so the system can meet the wavefront coding technology.

In addition, this study will use some methods to simulate the intermediate image that is generated by defocus effect, and describe how to restore the intermediate image to the near-diffraction limit imaging results.

10335-61, Session PS2

## Analytic functions of optical choppers for Gaussian laser beams

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The present paper is focused on achieving and analyzing the analytic functions of optical choppers with disks with n symmetrical wings. A Gaussian laser beam distribution of the light beam to be chopped and a light bundle of small diameter in the plane of the chopper have been chosen. The functions of the transmitted flux and the transmission coefficient of a device are obtained. This allows for the designing calculus of choppers for different applications, taking into account the specific requirements to be met. A comparison between analytical results obtained in this work and the results from our previous modeling and simulations is shown – for different configurations of chopper wheels. Selected References: [1] Duma, V. F., "Theoretical approach on optical choppers for top-hat light beam distributions," Journal of Optics A: Pure and Applied Optics, 10(6), 064008 (2008). [2] Duma, V. F., "Optical choppers with circular-shaped windows: Modulation functions," Communications in Nonlinear Science and Numerical Simulation (CNSNS) 16, 2218-2224 (2011). [3] Duma V.-F., Prototypes and modulation functions of classical and novel configurations of optical chopper wheels, Latin American Journal of Solids and Structures 10(1), 5-18 (2013).

10335-62, Session PS2

## Adding polarimetric imaging to depth map using improved light field camera 2.0 structure

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Polarization information plays an important role in skylight navigation under complicated weather, target identification under complex background, and material identification from shot scene, while the correctness of depth information is the key to three-dimensional imaging, obtaining them both can not only help to rebuild the 3D scene comprehensively but also to improve the accuracy for each other. This paper describe a polarimetric imaging system based on light field 2.0 camera structure, which can calculate the polarization angle and the depth distance from reference plane for every objet point within a single shot. In this optical structure, a 3-quadrants Polaroid which has rotational symmetric polarizing angle in each quadrant is placed on pupil, and a honeycomb-liked micro lens array with three different micro lens focal lengths is placed near the system focal plane, at last a high resolution CCD is place on image plane of micro lens array, at the same time, rotate direction of the 3 quadrants is adjusted to match micro lens arrangement, and the F-number of main aperture is designed to equal the F-number of micro lens. By this means, main lens generates intermediate image, and micro lens array acts as camera array that focuses different patches of intermediate image onto CCD, that is to say, every patch is "looked" by a certain number of micro "eyes", whose number depending on how close the patch is to the camera, and every "eye" is equivalent to a window on main aperture, having a definite polarization state. Therefore, depth can be calculated by matching the relative offset of corresponding image patch, while polarization can be calculated by its relative intensity difference, and their resolution will be equal to each other. Whole algorithm and one of the applications on navigation under different weather conditions is proposed in next part, whose results show that this method has a high accuracy and strong robustness. Latest developments in other applications are discussed at the end of the article.

## 10335-63, Session PS2

# Modified 3D time-of-flight camera for object separation in organic farming

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The increase of plant earnings (food or energy plants) with simultaneous consideration of the protection of the environment will be a global task in the future. The manual weed control, used in organic farming, without chemical or synthetical agriculturalpesticides is one way to protect our environment. Manual weed elimination is very expensive. Our cooperation partner Westhof Bio in Germany for example, spends over 170.000 EUR per year for the manual weed elimination by human labor. Furthermore it is more and more difficult to find human workers for this task. Hence the need for research for automated non-chemical weed control systems is very large. But up to now no commercial system is available.

A major problem in organic farming is to separate the plants. It has to be detected which leaf belongs to which plant. This is not an easy task as many leafs overlap each other.

Therefore 3D information of the plants is needed. A simple option to create a 3D picture is to use Time of Flight cameras or laser scanners. Hence the used measurement setup and the 3D sensors tested are presented in section II. Subsequently the problems with the presented commercial 3D cameras from section II are described in in section III and the carried out modification of the Kinect II 3D camera are described in section IV. Finally in section V experimental results of the original and the modified Kinect II are presented. A summary of the results is given in section VI.

For the measurement recordings the mobile field robot BoniRob was used. The complete measurement setup including the results is explained in the paper.

The robot drove autonomously over the field at a rate of 20 mm/s. At 1 frame per second this speed allows an uninterrupted view of the field, with an overlap of the respective sensor data of around 20%. The interesting area, where the plants are growing on the wall has an average width of about 15cm. This area has been recorded among others with the Kinect II sensor, the CamCube 3 and the LMI Gocator 2350. All these sensors are recording 3D images.

Using this data from the same plants on different days it shall be figured out

- Which sensors
- Which configuration
- Which growth stage

is the best for the seperation and classification of carrot plants and weed. These sensors have the advantage over the stereo vision procedure, that the 3D image is created automatically without much computation time

Subsequently it is shown in practical measurements that 3D measurement methods are suitable for the problem. But only the Kinect II showed potential.

The camera is intended for recording the entire living room and serves as an interface for the players of a video game.

About two-thirds of the resolution is wasted in our application. Only a small strip of approximately 20 cm width is sufficient for the root recognition. The Kinect II had to be reconstructed in order to use the full resolution efficiently. Therefore, the camera was disassembled and provided with a new lens. Due to the small aperture, the entire resolution of 512 x 424 pixels can now be used on the small strip, where the roots grow.

In this article, we explained why 3D measurement procedures for plant identifications are necessary. Subsequently, it is shown in practical measurements that 3D measuring methods are suitable for the problem. The original and the modified Kinect II are compar by different measuring methods.

## 10335-64, Session PS2

# Calibration between a 3D camera and an aerial information screen

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[CONTEXT] An interactive 3D interface system is gathering attention. Direct handling of an aerial screen information can be realized by use of a 3D gesture recognition camera and an aerial screen. We have formed an aerial screen with aerial imaging by retro reflection (AIRR) [H. Yamamoto, Opt. Exp. 22, 26919 (2014)] and detected gestures of a user with a Kinect [Y. Tokuda, Proc. SIGGRAPH Asia'15, Emerging Technologies (2015)]. We faced a calibration problem. The calibration problem means that the coordinate systems of the aerial screen and the Kinect should be matched. In the previous demonstration, the calibration was conducted manually when the position or/and the direction of the Kinect were changed.

[OBJECTIVE] We propose a calibration method of a 3D gesture recognition camera and an aerial information screen. The proposed method is confirmed experimentally by use of our prototype aerial display with AIRR.

[METHOD] Our aerial display is composed of a source display, a reflective polarizer, a quarter-wave retarder, and a retro-reflector. The reflective polarizer is placed in crossed nicols regarding the polarizer on the source display. In this case, the light from the source display reflects at the reflective polarizer. The reflected light retro-reflects at the retro-reflector. The polarization angle of the retro-reflected light is rotated by 90 degrees after penetrating the quarter-wave retarder twice. Therefore, the retro-reflected light transmits through the reflective polarizer and converges into the plane symmetric position of the light source regarding the reflective polarizer. We used a Kinect v2 as a 3D gesture recognition camera. The Kinect detects positions of users' hands. Our system detects up to two users. We developed a calibration software and interactive applications by using Unity, which is a commonly-used platform for interactive software. In Unity, we prepared a camera for rendering, objects, and two squares that show hands' positions. Displayed image is rendered by use of the camera in Unity. The objects are displayed in the mid-air. In order to handle these aerial objects, our developed program detects collision between one of the hands and one of the objects. The collision is determined after calibration. The calibration is automatically conducted by adjusting the view angle and the position of the camera in Unity to match the Kinect. In the calibration process, a user is instructed to place one of the hands on four corners of an aerial calibration pattern, one after another. The x-coordinate and y-coordinate of the hand position in the Kinect coordinate system are used to calibrate the central position in Unity. The z-coordinate is used to judge collision because it shows the distance from the hand to the aerial image.

[RESULTS] We have formed a 43-inch aerial screen. The aerial screen, tilting by 30 degrees, is floating at 35 cm above a reflective polarizer. We have realized interaction: when a user touches an object, color of the object changes. Furthermore, we have created a balloon-popping game.

[NOVELTY] This is the first report on the calibration system by 3D gesture recognition camera and AIRR.

### 10335-65, Session PS2

## Power estimation of martial arts movement using 3D motion capture camera

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Motion capture camera (MOCAP) has been widely used in many areas such as biomechanics, physiology, animation, arts, etc. This project is done by approaching physics mechanics and the extended of MOCAP application through sports. Most researchers will use a force plate, but this will only can measure the force of impact, but for us, we are keen to observe the kinematics of the movement. Martial arts is one of the sports that uses more than one part of the human body. For this project, martial art 'Silat' was chosen because of its wide practice in Malaysia. 2 performers have been selected, one of them has an experienced in 'Silat' practice and another one have no experience at all so that we can compare the energy and force generated by the performers. Every performer will generate a punching with same posture which in this project, two types of punching move were selected. Before the measuring start, a calibration has been done so the software knows the area covered by the camera and reduce the error when analyze by using the T stick that have been pasted with a marker. A punching bag with mass 60 kg was hung on an iron bar as a target. The use of this punching bag is to determine the impact force of a performer when they punch. This punching bag also will be stuck with the optical marker so we can observe the movement after impact. 8 cameras have been used and placed with 2 cameras at every side of the wall with different angle in a rectangular room 270 ft2 and the camera covered approximately 50 ft2. We covered only a small area so less noise will be detected and make the measurement more accurate. A Marker has been pasted on the limb of the entire hand that we want to observe and measure. A passive marker used in this project has a characteristic to reflect the infrared that being generated by the camera. The infrared will reflected to the camera sensor so the marker position can be detected and show in software. The used of many cameras is to increase the precision and improve the accuracy of the marker. Performer movement was recorded and analyzed using software Cortex motion analysis where velocity and acceleration of a performer movement can be measured. With classical mechanics approach we have estimated the power and force of impact and shows that an experienced performer produces more power and force of impact is higher than the inexperienced performer.

### 10335-66, Session PS2

## Development of an optical radar for distance learning crevices Mars

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More recently, Mars became the object of research is associated primarily with the development of techniques and technologies that allow a detailed way to explore the planet's surface. These studies are quite relevant, because humanity sees Mars as their new home. For potential terraforming key factor is the presence of water on the red planet. At the moment there are two ways to study the surface: contact and contactless.

For contactless electronic methods include the latest telescopes based on Earth but telescopes do not provide accurate and detailed information, which in turn does not accelerate and simplify the study the planet's surface.

To contact methods include rovers, delivered to the surface of Mars. Unfortunately rovers have fairly low speed, which greatly increases the time spent on research alone, even a small portion of the surface. Also cross-country rover is not high enough, it also affects the speed of research.

At this time, none of the existing methods of probing the surface of Mars is not able to look into the deep Martian crevices, which according to preliminary estimates and may be of Martian water reserves. Therefore, to solve this problem will require the machine, orbiting Mars, which will be used as a special rangefinder.

On the surface of the red planet water was found in two of its aggregate states, namely water vapor and ice. However, September 29, 2015, when the average Martian temperature rose to -23 degrees Celsius, supersensitive equipment was able to detect a watery suspension.

Detailed spectral analysis showed that the aqueous slurry contains impurities, the most striking is its components $H_2S$ and HCL. Therefore, as the indicator substances, it was decided to select $H_2O$, $H_2S$ and HCL.

Given the structure of Mars atmosphere, namely the fact that it consists of $CO_2$ (95%), Ar (1.6%), $N_2$ (2.7%), $O_2$ (0.13%) and CO (0.07%), and taking into account the range of atmospheric transmittance should that the best area for sensing a UV range.

As a method for remote sensing of the most effective is the Raman scattering method that allows to detect several substances indicators without complicating the structure of the device, in contrast to the method of differential absorption and scattering, as for the detection of substances it requires two power sources, thus to detect three substances required indicators I have enormous energy.

Taking the existing at this time «NOMAD», the best option would be to use the circuits of the monostatic lidar, which will minimize the size of the device, since the receiver is in the immediate vicinity of the source, and it reduces the costs associated with the development and maintenance of such a device. So take a monostatic lidar scheme for constructing the basis for the most suitable option.

The aim is to create a model of such a device, which in the future will lead to the development of a prototype that can find water on the red planet.

### 10335-67, Session PS2

## Measuring the volume of brain tumour and determining its location in T2-weighted MRI images using hidden Markov random field: expectation maximization algorithm

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A brain tumour is an abnormal growth of tissue in the brain. Most tumour volume measurement processes are carried out manually by the radiographer and radiologist without relying on any auto program. This manual method is a time-consuming task and gives results may be inaccurate. Treatment, diagnosis, signs and symptoms of the brain tumours mainly depend on the tumour volume and its location. In this paper, an approach is proposed to improve volume measurement of brain tumors as well as using a new method to determine the brain tumour location. The current study presents a hybrid method that includes two methods. One method is hidden Markov random field ?- expectation maximization (HMRF-EM), which employs a positive initial ?classification of the image. The other method employs the threshold, which enables the final segmentation. In this method, ?the tumour volume is calculated using voxel dimension measurements. The accuracy of the proposed volume estimation method was validated by comparing it with the gold standard, which is obtained by using the water displacement method. The brain tumour location was determined accurately in T2- weighted MRI image using a new algorithm. According to the results, this process was proven to be more useful compared to the manual method. Thus, it

provides the possibility of calculating the volume and location of a brain tumour.

10335-68, Session PS2

## An efficient method to improve speed-of-focus of electronically tunable lenses for optical systems using Gaussian beams

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Various applications in optical imaging, vision correction, microscopy, sensing and target ranging deploy Tunable Focus Lenses (TFL) as part of a working system design. Several of these systems require tuning these TFLs to obtain a minimum spot size or the tightest focus of a Gaussian Beam in various locations. Such spot size minimization is often used in microscopes for a motion-free depth scan. Sometimes the knowledge of a TFL focal length which results in a minimum beam spot is also the means to determine the location of the plane where the minimum beam spot forms. Such a sensing mechanism has been used to determine shapes of objects, liquid level, pressure in a closed chamber and terrain mapping. Therefore, the use of TFLs to obtain a minimum spot size of a propagating Gaussian Beam at different planes is critical for several optical imaging and sensing applications. In general, the focal length of a TFL is controlled by varying the amplitude of an input voltage or the current signal. Hence, the response time of a TFL-based sensor or imaging system depends on the required duration to scan the input signal amplitude until an optimal amplitude value produces the required minimum beam spot size at a given plane. Thus, it can be inferred that the system response time or sampling rate depends on the number of voltage/current samples to correctly identify the TFL focal length value which yields a minimum beam spot. For sensing and imaging applications, tuning the TFL to the desired focal length by beginning the scan of the input signal amplitude at any corner or random voltage/current value and incrementally increasing or reducing it is highly inefficient as tuning to a minimum spot requires several scan steps resulting in a slow sensor response. In this paper, we propose an efficient method of scanning the focal length of a TFL which results in a significant reduction in the number of voltage/current steps to obtain a minimum beam spot size at any plane of observation. We demonstrate the effectiveness of our proposed method with experimental results and validate our claims by significantly reducing the required number of steps to tune a Gaussian Beam spot to a minimum possible at various chosen observation plane locations.

10335-69, Session PS2

## A MEMS and agile optics-based dual-mode variable optical power splitter with no moving parts

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In this paper, we present a novel design of an optical power splitter. Owing to the inherent variable power split ratios that the proposed design delivers, it is ideal for use in communications, sensing and signal processing applications where variable power splitting is often quintessential. The proposed power splitter module is dual mode as it combines the use of a Micro-Electro-Mechanical Systems (MEMS) based Digital Micro-mirror Device (DMD) and an Electronically Controlled Tunable Lens (ECTL) to split the power of an input optical signal between two output ports – the designated port and the surplus port. The use of a reflective Digital Spatial Light Modulator (DSLM) such as the DMD provides a motion-free digital control of the split ratio between the two output ports. Although the digital step between two possible successive split ratios can be fairly minimal with the use of a high resolution DMD but it is a challenge to correctly ascertain the exact image pattern on the DMD to obtain any desired specific split ratio. To counter this challenge, we propose the synchronized use of a circular pattern on the DMD, which serves as a circular clear aperture with a tunable radius, and an ECTL. The radius of the circular pattern on the DMD provides a digital control of the split ratio between the two ports whereas the ECTL, depending on its controller, can provide either an analog or a digital control by altering the beam radius which is incident at the DMD circular pattern. The radius of the circular pattern on the DMD can be minimally changed by one micro-pixel thickness. Setting the radius of the circular pattern on the DMD to an appropriate value provides the closest "ball-park" split ratio whereas further tuning the ECTL aids in slightly altering from this digitally set value to obtain the exact desired split ratio in-between any two digitally-set successive split ratios that correspond to any clear aperture radius of the DMD pattern and its incremental minimal allowable change of one micro-pixel. We provide a detailed scheme to calculate the desired DMD aperture radius as well as the focal length setting of the ECTL to obtain any given split ratio. By setting tolerance limits on the split ratio, we also show that our method affords diversity by providing multiple possible solutions to achieve a desired optical power split ratio within the specified tolerances. We also demonstrate the validation of the proposed concept with initial experimental results and discussions. These experimental results show a repeatable splitter operation and the resulting power split ratios according to the theoretical predictions. With the experimental data, we also demonstrate the effectiveness of the method in obtaining any particular split ratio through different DMD and TFL configurations with specific split ratio tolerance values.

10335-70, Session PS2

## A multispectral telescopic systems with a variable magnification

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Telescopic system is one of the most widespread types of the optical systems. They can be used as a standalone system and as a component of a more difficult system.

This type of the optical systems is applied in geodetic, astronomical, observation, goniometric, ranging devices, expansion of laser radiation systems, in high precision required systems, for example, in medicine when carrying out operations, etc. Telescopic systems can conditionally be divided like systems with constant, discretely or smoothly changing magnification. The well-known telescopic systems are constructed according to Galilei or Kepler's schemes belong to the first type of systems. In the telescopic system are created constructed according to Galilei's scheme the positive optical system is used as a lens, and as an eyepiece – negative is used. Advantages of the scheme of Galilei are the direct image and smaller length in a comparison with the Kepler's scheme. In Kepler's scheme a lens and an eyepiece is a positive optical system. The lens creates the inverted real image in the lens back focal plane of the lens. Shortcomings of the scheme of Kepler are: big length of optical system, the inverted image. For creation of the system with a discretely changing magnification we can used the earlier described two-component telescopic systems with a constant magnification by the turn of the system in general is used to receive two values of magnification. Or in the three component systems, each component is a group of lenses, one of the components have to be moved, under strictly certain law which will provide the magnification with the discrete step. The advantage of such systems undoubtedly is relative simplicity of a calculation and a realization. And the impossibility of use of these systems in conditions where a smooth magnification is required will be a shortcoming.

This work is devoted to receipt of the last type of telescopic systems with the smooth variable magnification, with a possibility of their application in a wide range of wavelengths covering visible and near infrared area of a range, that today will be an urgent task, especially if it turns out to reach the system of this sort, with highly resolving power. The main complexity in case of synthesis of this type of the systems is stabilization not only the planes of a subject and an image, but also preserving a position of an entrance and an exit pupils, especially if the system is a part of a more difficult system. Initially the shift of a component shall lead to change of the size of the image, but also with preserving the plane of its registration. Thus, calculating this type of the systems the following tasks arise:

1. The various realization of the primary scheme are possible because it consists at least of three components. Originally it requires choosing the optimum primary scheme which will be able to provide the higher

characteristics of the optical system. For providing required magnification the moving component has to be chosen.

2. the optical materials, which will be able to provide a transmission of the wide spectral range, ought to be determined.

3. The design data of the optical system ought to be calculated.

4. The law of a movement of the moving component, for providing required magnification has to be determined.

5. The analysis of quality of the received image, in case of all provisions of the moving component.

6. Admissions for elements of the received optical system have to be calculated.

7. Comparison of the received law of the movement of the chosen second component, with an opportunity its implementation in a real frame of the device.

In the course to work various circuit decisions for further work and implementation were considered. The three-component system with a moving negative central component containing the lens which is also moving according to the separate law concerning the all component was chosen. Optical materials for further work and implementation which have high transmission capacity in visible and infrared spectral ranges and available from catalogs Schott and also which would be able to be made at the Lytkarinsky factory of optical glasses were also chosen. Primary calculation of the design data of components of the telescopic optical system, taking into account the chosen optical materials is at the moment carried out.

### 10335-71, Session PS2

## Ghosting images processing methods for dynamic aberration detection in imaging systems

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For decades now, adaptive optics technique has played a tremendous role in many areas, such as laser propagation in the atmosphere, astronomical object imaging, eye medical treatment, etc. As a key component in the adaptive optics, the detecting errors of wavefront sensors is a major error source.

Wavefront reconstruction is based on light-spots centroid location in the application of conventional Hartmann-Shack (H-S) waveront sensor. Nowadays, the design of optical system becomes more and more complex with increasingly demanding on imaging performance and multispectral imaging sometimes. That way, multiple reflections from optical elements, or paraxial stray light from operating environment may cause double images (ghosting) in part of sub-aperture of H-S wavefront sensor, resulting in centroid detection errors, and so loss of the precision of wavefront reconstruction might occur. Of course, optimum design of optical coating and opto-mechanical structure can generator less ghosting to some extent, which can't eliminate completely the hidden trouble nevertheless. On the other hand, a suitable image digital processing technique can also diminish the effect of background noise or ghosting. At present, the threshold method is commonly used. Ghosting can been brought under effective control by this way, which leads to the loss of available information of light-spots in the meanwhile, especially high frequency information and leads to centroid detection errors.

This paper begins with the theoretical model analysis of various image processing techniques, conventional threshold method, convolution method, correlation algorithm and spectral-filter method included. And then, a numerical simulation platform is established which aiming at the research in the influence of ghosting images processing on wavefront reconstruction for H-S wavefront sensor. Based on this platform, the relative slope measurement errors of wavefront are tested in the comparative trials with different image processing algorithms. A improved methods is proposed by combining several algorithms, and the simulation results and practical application show that more available information of light-spots are kept through this way, which improves the accuracy of centroid detection and extends the applicability of H-S wavefront sensor.

### 10335-72, Session PS2

## Optical power transmission in a polygon mirror-based swept source optical coherence tomography system

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Optical Coherence Tomography (OCT) has a broad range of applications in 2D and volumetric, non-invasive imaging of micron scale structures, typically used to investigate the detail of tissue layers at different depths (retina, eye anterior, skin, larynx etc.). This application requires fast imaging speeds and high resolutions if it is to be used as a medical diagnostics tool.

In Swept Source OCT (SS-OCT), generally favoured for its faster operating speeds compared to Spectrometer Based OCT, the imaging speed is governed by the sweeping frequency of the source and the axial resolution is given by the total bandwidth generated.

We performed this study on a Polygon Mirror based SS-OCT system. Our sweeping configuration employs a mechanical method that enables a broad (100 nm) spectrum of light to be reduced to tunable narrow-band windows of width ??, which are individually selected through the use of a dispersive element (diffraction grating), a rotating polygon mirror and two achromatic lenses arranged telescopically in a Littman configuration (Fig. 1). After the polygon the beam is returned from a fixed end retroreflector (mirror). The rotation of the polygon mirror ensures that only light in a small range of wavelengths is coupled back in the originating single mode fibre at any one time and that this condition is sequentially fulfilled over the angular sweep range of the polygon.

Through theoretical development, ray-tracing modelling and measurement, this paper specifically addresses the geometric and radiometric vignetting associated with the spectrum reflected from an individual polygon mirrored facet (Fig. 2) and how this may impose limitations to the incident beam size and hence lead to variations and losses in the peak power available in the tunable spectral line, as well as the linewidth variation throughout the scanned spectral range.

Simulations were carried out using ZemaxTM ray-tracing software. The incident spectrum was split into 11 equally spaced wavelength windows over a bandwidth range of 125 nm centred at ?_c=1350 nm. Although this range is greater than that of the Semiconductor Optical Amplifier used in our system, its analysis offers an insight into the total wavelength acceptance range of our optical design. For each wavelength window, a suitably chosen polygon mirror angle maximised throughput at that wavelength to the end reflector, ensuring normal incidence. This allows the beam to return into the fibre along substantially the same path.

Calculations were also carried out on the beam propagation after the diffraction grating, assisted by the tracing of beams centred at wavelengths from ?_max to ?_min and covering the entire spectrum, through the Littman configuration in both directions. We found that, at the midfocal plane of the telescope, the function h(?) describing the deviation of the chief ray of each constituent wavelength from the telescope's optical axis exhibits non-linearities.

Collimated light propagating through the telescope is subject to changes in beam diameter dictated by the relative focal lengths of the lenses used. This has an impact on the shape and size of the spot on the polygon mirrors facets, which has an effect on the overall amount of vignetting the system experiences in each wavelength window. Our theoretical development of the function W_2 (?) gives the ideal beam width on the polygon mirror facet based on the grating constant and the incident beam diameter, W_0, exiting from the collimator prior to lens 1. Our simulation agrees with the theoretically predicted beam cross-section at lens 1 but differs non-linearly from those on lens 2 due to the inherent aberrations experience by the light passing through lens 1. W_2 decreases

and then increases again past a local minimum with a wavelength ?>?_c.

The beam strikes the polygon facet at an angle between 42° and 48° producing an elliptical spot for a circular incident beam. When the beam is not homogeneous the shape of the ellipse changes and contributes in a variable fashion to the amount of vignetting and hence to the proportion of light successfully reinserted back into the originating fibre.

Our results suggest that wavelengths near the centre of the spectrum experience higher losses than those further out with the exception of the light at the very edge of the spectrum, but this effect can be mitigated by small axial adjustments in the location of the telescope lenses which can be used to reshape the swept spectrum. However, we show that our simple telescope design cannot, on its own, result in a spectral envelope with a flat ceiling throughout the full range.

These non-linearities, in combination with facet vignetting and lens aberrations, contribute to a complex light coupling efficiency function that leads to light losses and non-uniformities in the swept spectrum, and also a reduction in the effective swept range to around half of the initial bandwidth of the Semiconductor Optical Amplifier.

10335-73, Session PS2

## A digital filtering algorithm fast implementation based on Catapult C

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With the increasing complexity of the algorithm in optical remote sensing camera video real-time data processing, direct design by hardware description languages becoming more and more difficult. By using EDA tools, directly convert complex algorithms described by high-level language into RTL code as described in HDL language. The design choices of Catapult C tool to complete the digital filtering algorithm from the C language to RTL design. Finally verify designed by Catapult for RTL code with c, Matlab function consistent. After hardware implementation performance, the design speed faster than the direct use of hardware description language several times to several times.

10335-74, Session PS2

## Medical photoacoustic beamforming using minimum variance-based delay multiply and sum

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Photoacoustic (PA) imaging is a promising biomedical imaging modality with the capability of providing Ultrasound (US) resolution and optical contrast. When a short duration laser pulse illuminates the tissue as a target of imaging, tissue induces US waves based on thermoelastic expansion and reflected waves at the detectors can be used to reconstruct the optical absorption distribution. Since the receiving part of PA consists of US waves, most of the US beamforming algorithms can be applied on PA imaging. Due to the simple implementation and the robust performance, Delay-And-Sum (DAS) is treated as the most common beamforming algorithm in US imaging. However, it suffers from limited resolution and high levels of sidelobe. To address these problems, a new algorithm namely Delay-Multiply-And-Sum (DMAS) was introduced. In DMAS, similar to DAS, corresponding samples for each element of array are calculated based on delays, but before the summation, samples are combinatorially multiplied, which can be interpreted as the cross correlation of the received signal at the elements of the array. In this paper, a modified version of DMAS beamforming algorithm is introduced based on Minimum Variance (MV) adaptive beamforming method namely Minimum Variance-Based DMAS (MVB-DMAS). It is shown that expanding the DMAS algorithm results in some terms where every term contains a DAS algebra. Since DAS is a simple algorithm with low levels of off-axis signals rejection, it is proposed to use MV adaptive beamformer instead of existing DAS algebra inside DMAS expansion. Numerical simulations for one-point and two-point targets are presented using proposed algorithm, DAS, DMAS and MV beamformers. Lateral variation for three depths of imaging in two cases of simulation is presented. Resolution and levels of sidelobe are evaluated and it is shown that using MVB-DMAS leads to valley of lateral variation reduction in all depths of imaging, which is regarded as the resolution enhancement. In other word, two points in two-point target are more distinguished and pronounced using MVB-DMAS in compare to other mentioned beamformers. In particular, for reconstructed image at depth of 70 mm, MVB-DMAS results in 26.96 dB, 20.55 dB and 17.88 dB reduction in case of valley of lateral variation in compare to DAS, DMAS and MV, respectively. Also, MVB-DMAS ends in levels of sidelobe reduction which is regarded as contrast enhancement and for another instance, for depth of 70 mm, it can be perceived that levels of sidelobe are reduced using MVB-DMAS for about 20 dB, 13 dB and 12 dB in compare to DAS, MV and DMAS, respectively. To make a quantitative comparison of mentioned beamformers, Full-Width-Half-Maximum (FWHM) in -3dB, is presented. It is shown that MVB-DMAS results in FWHM improvement in all depths of imaging. Considering depth of 60 mm, MVB-DMAS leads to 347 $\mu$m, while DAS, DMAS and MV result in 3836 $\mu$m, 2217 $\mu$m and 349 $\mu$m, respectively. It should be noted that all these enhancements are achieved at the expense of higher computational burden.

10335-75, Session PS2

## An adaptive weighted Lp metric for optimal margin classification: a theoretical framework for optical remote sensing data

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The rapid advancement in high-resolution remote sensing applications escalated the complexity of data diversity and higher oder dimensionality features. As such, the efficacy of any optical data sensing problems depends on the adequacy of the distance metric used for inter-sample distance computation of the remote sensing feature vectors, while taking into account of the wide variety of probability distributions of remote sensing data along with the inherent problems of optical source separation, background noise and outliers. The challenges of optimal mapping, varying feature index homogeneity and feature classification by combining distance metrics stems from the work of Chen, Lei, and Raymond Ng's time series analysis by fusion of metrics to handle local time shifting while improving the accuracy and log-likelihood significance of data correlations and noise disassociation by means of a linear transformation is the sole motivation of this work.

In this contribution, a novel incremental learning methodology combining the Mahalanobis and the Minkowski distance metrics along with cosine similarity was proposed to exploit the prior statistical entropy and diversity of optical remote sensing data for maximal inter-sample and minimal intra-sample separation. The robustness to outliers and scale variation sensitivity, while accounting for the statistical heterogeneity and non-isotropic reciprocity in the remote sensing feature components of hyperspectral imaging and remote sensing data have been explained. The fact that the scale invariance Mahalanobis distance accounts for the covariance of the feature vectors and rectify the data heterogeneity is used for disassociating the correlated feature components and weighing the different dimensions according to their statistical feature variations is used for generating the modified remote sensing feature space. While the combination of the cosine similarity signifying the degree of feature cohesion within the data clusters and the Minkowski metric gives a convex objective function subjected to convex constraints has been used for learning an adaptive metric of the feature space for maximal margin classification.

The conceptual architecture for the optimality criterion for learning optimal feature weights and the optimal Minkowski exponent, 'p', with its adaptiveness through semi-definite convex optimization for calculating the upper and lower bounds of the objective function have been shown. Theoretical proof of the optimal metric along with the optimal parameters bounds validates the suitability of the proposed metric in optical remote sensing applications.

10335-76, Session PS2

## Statistical classifiers on multifractal parameters for optical diagnosis of cervical cancer

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The augmented multifractal parameters provide better noise immunity, stability and discrimination for segregation of normal and precancerous elastic scattering spectroscopic data. The introduction of multiple distortion features to characterize the multifractal spectrum supplement the efficacy of MFDFA for heterogeneous dynamic of tissue abnormalities. In this contribution, the adequacy of geometrical attributes of the Multifractal spectrum with a proposed set of novel features for a potential biomarker for optical diagnosis of cancer is performed. Different classifiers are trained with the obtained features to compare the sensitivity and specificity for cervical cancer detection. The statistical classifiers with accuracy of 84.17% validate the adequacy of multi-feature MFDFA characterization of elastic scattering spectroscopy for cancer diagnosis.

10335-35, Session 10

## High-resolution LCOS microdisplay with sub-kHz frame rate for high performance, high precision 3D sensor

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We report the implementation of the LCOS microdisplay with 1920 by 1080 resolution and 720 Hz frame rate. The driving solution is FPGA-based. The input signal is converted from the ultrahigh-resolution HDMI 2.0 signal into HD frames, which follow with the specified 720 Hz frame rate. Alternatively the signal is generated directly on the FPGA with pattern generator. The display is showing switching times below 1.5 ms (rise plus fall) for the selected working temperature. The bit depth of the addressed image achieves 8 bit within each frame. The microdisplay is used in the 3D sensing system, implemented by Fraunhofer IOF.

10335-46, Session 10

## Sinusoids-assisted empirical mode decomposition profilometry

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Fringe projection profilometry has been a popular means for 3D surface measurement. As some group published, phase-shifting profilometry (PSP) has already been mature to a certain extent. However, this measures is always constrained by the high-speed hardware equipment if the measured object is moving. Single fringe projected profilometry (SFPP) has been researched for a long time, but the well-known Fourier transform profilometry (FTP) can only measure the simply constructed surface. To measure complex objects, the windowed FT (WFT), Wavelet transform (WT) and etc. are researched to achieve better accuracy, nevertheless these methods are either limited by the low efficiency or constrained by poor ability of time-frequency analysis due to the uncertainty theory. Hilbert-Huang transform (HHT) is an effective time-frequency-spectra analysis tool, where the Empirical Mode Decomposition (EMD) is the core of this method providing as a spatial filtering. Recently the EMD methods are frequently used in SFPP, especially for fringe pattern analysis. Among the published methods the Trusiak's automated selective reconstruction based on enhanced fast EMD (ASR-EFEMD) is outstandingly excellent because of the great efficiency and effectiveness. However, this method needs many artificial interventions, and in addition, it avoids solving the tricky mode mixing problem and hence can hardly be used in practice for SFPP if the measurement environment is complicated that may cause low-frequency mode mixing.

To resolve the above issues, recently we have developed a method named Regenerated Phase-Shifted Sinusoids assisted EMD (RPSEMD) which is very powerful for nonstationary signal processing. To meet with the requirement of both accuracy and efficiency, we also extend this algorithm to 2D space, i.e., the sinusoids-assisted bidimensional EMD (SBEMD). These sinusoids-assisted EMD (SEMD) methods have been proved efficient and accurate for fringe analysis to retrieve phase. Because the mode mixing problem is solved, a fringe pattern can be decomposed into a series of intrinsic modes that carry clear physical meaning, and then different modes can be processed combined with different frequency-spectra analysis. In this sense, we sufficiently used these SEMD methods to construct the for practical SFPP system, which is called SEMD profilometry (SEMDP): we propose a fast and convenient calibration method based on the SBEMD fringe analysis; we also propose a fast and robust phase unwrapping method based on the quality-guided maps using SBEMD combined spiral HT; furthermore, we try to correct the system error through the pre-code method also using the time-frequency-spectra of the SBEMD combined with the HT. Compared with the PSP and FTP, the developed SEMDP shows much superiority for practical use, such as high automation, high speed, satisfactory accuracy and strong robustness.

10335-47, Session 10

## Phase unwrapping in fast fringe projection profilometry

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Fringe projection profilometry (FFP) has become one of the most popular 3D information acquisition techniques being developed over the past three decades. In FFP, phase unwrapping is a critical step in acquiring the correspondence information for 3D reconstruction. Unlike traditional FFP which uses methods such as temporal phase unwrapping, high-speed real time measurement FFP systems require phase unwrapping of single phase image probably with discontinuous objects. Phase unwrapping in Fast FPP such brings three difficulties, the separation of discontinuous wrapped phases, the unwrapping of each wrapped phase and the connection of the discontinuous phases. During FFP measurement of multiple objects. They may be positioned in different depths but with their phase maps located side by side. Object separation based on the modulation values could not well identify the discontinuous boundaries. In this paper, the object separation based on phase modulation is adapted first to remove the background and separate isolated wrapped phases. For each isolated wrapped phase, discontinuous phase separation based local orientation coherence is further used to identify the existence of discontinuous boundaries. After the separation, spatial unwrapping method is applied to each wrapped phase segments. We proposed an oriented unwrapping method that unwrap the phase along the direction perpendicular to the fringe orientation to minimize the error caused by noise. In the last, each continuous phase segments need to correct identify their corresponding positions before used for 3D reconstruction. A grid line is projected to establish the relative positions. Experimental results show that our algorithm works well for multiple and overlapping object measurement

10335-48, Session 10

## Feature selection from hyperspectral imaging for guava fruit defects detection

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Development of technology makes hyperspectral imaging commonly used for defect detection. In this research, a hyperspectral imaging

system was setup in lab to target for guava fruits defect detection. Guava fruit was selected as the object as to our knowledge, there is fewer attempts were made for guava defect detection based on hyperspectral imaging. The common fluorescent light source was used to represent the uncontrolled lighting condition in lab and analysis was carried out in a specific wavelength range due to inefficiency of this particular light source. Based on the data, the reflectance intensity of this specific setup could be categorized in two groups. Sequential feature selection with linear discriminant (LD) and quadratic discriminant (QD) function were used to select features that could potentially be used in defects detection. Besides the ordinary training method, training dataset in discriminant was separated in two to cater for the uncontrolled lighting condition. These two parts were separated based on the brighter and dimmer area. Four evaluation matrixes were evaluated which are LD with common training method, QD with common training method, LD with two part training method and QD with two part training method. These evaluation matrixes were evaluated using F1-score with total 48 defected areas. Experiment shown that F1-score of linear discriminant with the compensated method hitting 0.8 score, which is the highest score among all.

10335-50, Session 11

## Axial-resolution in depth from focus digital holography

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Sub-mm single shot depth resolved digital holography. Digital holography enables absolute distance measurements and full-field quantitative depth resolving of objects from a single image capture. This has been demonstrated in the past by calculating over a set of reconstruction distances a focus metric, such as variance of the intensity, for each pixel of the image. The distance where the focus metric peaks is an estimate for the distance from the object surface to the recording medium. This enables full-field optical depth resolving from a single holographic image, over distances from a few centimetres up to the coherence length of a laser source, a range traditionally not accessible for techniques such as (white light) interferometry or optical coherence tomography. However, currently the limit on the depth resolution lies in the order of a centimeter and is an obstacle to application of this technique to microstructure analysis. Furthermore, the limits of the resolution using this method have not been investigated.

We demonstrate from theory and experiment that the resolution can reach to the sub-mm level. We analyse the dependence of the variance as a function of the spatial frequency content of the object. The variance curve as a function of reconstruction distance can be represented as the sum of variance curves over all spatial frequencies contained in the intensity image. Due to the Talbot-effect, each individual curve associated with a single spatial frequency is periodic, hence, summation over all these curves gives a single maximum which is well defined in the sub-mm range. Based on our Talbot-representation, we also show that the focus curve has an inherent broadness regardless of the spatial frequencies present in the image, which defines the resolution limit of this depth resolving method. We experimentally validate our findings by resolving an object with multiple reflecting layers located at different depths. A Michelson interferometer setup is used in the acquisition of the holograms and 100 micron axial resolution is achieved. This is approximately 50 times better than previously reported and opens opportunities for characterising high resolution single shot surface topography of objects. We envisage applications of this technique in the study of art objects and in machine vision quality control.

10335-52, Session 11

## Optical sound wave recording by digital holography with heterodyne technique

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Visualization technique gives us the important information to see the behavior and to understand the mechanism of the physical phenomena. Sound wave is one of the invisible phenomena for human, but it is useful for many applications such as communication, damage detection, ultrasound imaging, sonar, SAW devices. Real-time measurement and visualization of the propagating sound wave is a challenging theme for optical sensing.

We proposed an optical voice recorder and a sound wave recorder based on digital holography [1]. Sound wave propagation modulates temporally and spatially the refractive index of the air. In proposed technique, the spatial and temporal phase distributions of an optical wave are recoded by an off-axis digital holography by a high-speed image sensor when the optical wave is modulated by the sound wave propagation. In the previous demonstration, a tuning fork operated at 440 Hz was recorded by an image sensor with a frame rate of 2000 frames per second (fps) [1]. To record the sound wave, it is required to use a high-speed image sensor that can record the holograms with more than two times faster than the frequency of the sound wave. This limits the observation frequency range of the sound wave. For engineering applications, the frequency up to Megahertz is required to observe the propagation of ultrasound waves.

In this presentation, we propose a method that uses a heterodyne technique for increasing the observation frequency range. For the heterodyne interferometer, the reference wave is modulated by a piezoelectric mirror. By tuning the frequency of the piezoelectric mirror, the central frequency of the observed sound wave can be changed. In the experiment, a tuning fork operated at 440 Hz is observed by an image sensor operated at 10 fps. The experimental results indicate that the different frequency can be obtained. We will present different frequency of tuning forks and human voices.

Reference

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10335-53, Session 11

## Spectrally resolved digital holography using a white light LED

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Several imaging techniques, such as OCT or digital light-in-flight holography, take advantage of low temporal coherence to examine three-dimensional objects. The use of a short coherence source in digital holography allows optical sectioning and hence enables the separation of light coming from different planes of the sample under investigation [1]. Due to the short coherence, the interference is just observed when the optical path lengths of reference and object beams are matched. In addition, shape measurement can be performed when selecting two or more quantitative wavelength reconstructions in order to generate a synthetic wavelength, which is of the magnitude of the object under investigation [2].

The spectral information can be used to study microscopic objects, such as described in [3], where a supercontinuum fibre laser (wavelength range 0.45 to 2 $\mu$m) has been employed.

We will demonstrate that digital holography using a broadband source (white light LED) can provide spectral information and also be used for optical sectioning and metrology. Furthermore its application to biological tissues can provide the capability of cells or tissue discrimination.

A Mach-Zehnder setup has been used for recording spectrally resolved digital holograms in combination with a white light LED source, see Fig. 1. The spatial coherence has been increased by placing a pinhole of 25 $\mu$m diameter directly in front the emitting surface of the LED. The light leaving the pinhole is divided into two arms (reference and object beam). After interaction with the sample, the object beam is superimposed with the light coming from the reference beam. Due to the large spectral width of the white light LED (ranging from 400-700nm) interference is only observed within a short axial range of theoretically less than a micron, at which both path lengths are perfectly matched. After carefully matching the optical path lengths of both interfering arms, a mirror mounted on piezoelectric actuator is moved to introduce a path length difference between the two beams. The length of the reference beam is consecutively changed (typically step of 100 nm) by moving the PZT and after each step a hologram is recorded. Typically more than 1000 holograms are recorded and stored in a stack. If we consider a single pixel in each hologram and plot its value along the z-direction, a signal describing the temporal changing interference is obtained, as shown in Fig. 2. Since the LED used has low temporal coherence only within a small range an interference appears. The information about the spectrum of the light after passage through the sample can simply be obtained via a Fourier transformation along the z-axis. The complex spectral information is equally spaced with regards to the wavenumber, which corresponds to the reciprocal value of the wavelength. In that manner, a wavelength or a wavelength range can be selected and by inverse Fourier transform the amplitude and phase along the z-axis is obtained. This process is repeated for each pixel of the stack, enabling the recovery of spectrally resolved modulus and phase information for shape and spectral measurement.

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10335-54, Session 11

## Ptychographic phase retrieval by applying hybrid input-output (HIO) iterations sequentially

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Coherent diffractive imaging (CDI) is a technique that can be used to image an sample without having to use lenses. Especially for X-ray imaging this may be useful, since the reconstructed image will not suffer due to low-quality focusing optics. One particular method for CDI is ptychography, in which the probe that illuminates the sample is shifted to different positions, and for each position a far-field diffraction pattern is recorded.

To reconstruct the sample, the Ptychographical Iterative Engine (PIE) applies iterations of the Error Reduction (ER) algorithm for each probe position sequentially. However, it is well known that the Hybrid Input-Output (HIO) algorithm outperforms ER. The difference between HIO and ER is that HIO uses a feedback function that improves convergence to the correct solution and avoids stagnation. Also, PIE is known to perform better when the updates of the reconstruction are applied for each probe position sequentially, rather than updating the entire reconstruction at once each iteration.

In this research, we have designed a ptychographical algorithm (HIO-PIE) in which HIO iterations are applied for each probe position sequentially. The important insight is that for each probe position a separate HIO-feedback function needs to be introduced, which is to be stored separately from the reconstructed image. With simulations we compared our proposed algorithm (sequential HIO-PIE) to three other algorithms that were already known from the literature: sequential PIE, simultaneous PIE, and simultaneous HIO-PIE. We compared the algorithm for the noise-free case as well as for the case of shot noise. Also, we compared their ePIE (extended PIE) variants which reconstruct the object and the probe simultaneously (thus making the image reconstruction robust against unknown aberrations in the probe).

Simulations indicate that sequential HIO-(e)PIE tends to outperform (e) PIE even in the presence of shot noise, especially when the number of probe positions is small. Thus, this adaptation may reduce the number of scan positions required for a successful image reconstruction, thereby relaxing the constraints on an experimental setup.

10335-55, Session 11

## Imaging particles in full 3D parallax mode with two-wavelength off-axis Fresnel holography

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Digital holography and digital holographic microscopy are techniques for recording and reconstructing three-dimensional images of objects. The principle is to directly recording a hologram with an image sensor CCD sensor and then reconstructing it digitally with a computer. Actually, holographic digital imaging provides a 2.5D image because it lacks parallax by the fact that digital holography is not able to "see behind the object". In particular, this property is a limiting factor for the imaging of particles when the number of particles is high. It is then not fully possible to discriminate 2 particles aligned along the axis of the sight view. An alternative approach is to increase the number of sight views but without multiplying the number of sensors. In this context, Boucherit et al described a two-view technique based on angular multiplexing using a single reference beam which makes it possible to discriminate along the propagation axis. The technique has the disadvantage that the spatial multiplexing performed by the coherent mixing of the 3 waves (2 views and a reference) does not always lead to a clear separation of the diffraction orders. In addition, in the Fresnel configuration, the distance between sensor and particles has to be increased to permit a correct separation of the orders. This leads to a decrease in the spatial resolution of the reconstructed images of the particles. In order to overcome such limitations; this paper proposes an approach based on 2 sight of views and 2 wavelengths. The advantages of using two wavelength is that there will be no cross mixing between diffraction orders and that the reference waves can be adjusted separately. So, independent adjustment of the spatial frequencies of the two reference waves leads to a very good separation of diffraction orders.

In this set-up, two wavelengths illuminate the region of interest (tank filled with water and particles) along two orthogonal directions. Spatio-chromatic multiplexing makes it possible to encode the information on a single two-color digital hologram. Recording of color holograms is performed using a 3CCD sensor from Hamamatsu with 1024x1344 pixels having pixel pitches at 6.45?m and 8-bit digitization. In the set-up the distances from the useful area to the sensor depends on the wavelength and they are not the same. So, digital holographic reconstructions must be performed for different wavelength. It follows that in order to provide the full 3D location of any particle in the tank, the field of views must have the same set of reference axis along the two views. In this set-up, the Y axis must be the same along the two views, whereas the X axis is the 2nd axis of the blue line and the Z axis that of the green line. Since the same sensor is used to detect both wavelengths, sampling along X and Z axis is rigorously identical. A calibration has to be carried out to ensure that the set of reference axis along the two view have the same (0,0,0) center point. To do this we propose a calibration method based on the Fourier modulation theorem to identify the position of any particle in a single XYZ frame.

The set-up is applied to the study of 3D trajectory of particles moving in the tank. Experimental results are provided and confirm the suitability of the proposed approach.