A Holography Course in Toronto

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ABSTRACT

Holography is one of the most intuitive methods to teach optics, covering many concepts of introductory optics courses, in a visual manner. At the same time it provides a bridge between sciences and art.

For these reasons, the Institute for Optical Sciences at the University of Toronto in collaboration with the Ontario College of Art and Design (OCAD) has started an undergraduate course on holography. This course is unique from a number of perspectives. It is a collaboration between two Toronto post secondary education institutions. Also, it enrolls both science and art students, and teaches both the artistic and scientific aspects of holography. Besides the direct learning outcome of the course material, an equally important gain is for art and science students to work together on projects, learning from each others' strengths.

The course is completely hands-on, with students given individual access to the holography studio (under the supervision of a teaching assistant) to complete the required projects in the course. The projects are complemented with lectures that cover the necessary concepts in holography, such as wave propagation, interference and diffraction. The students also receive an introduction to other uses of interference and diffraction. Since the course is taken by art as well as science students, the lectures are delivered very conceptually.

Students produced some stunning holograms as part of their projects and rated the course very positively with enthusiastic reviews.

KEYWORDS

Holography, undergraduate teaching, art and science, 3D visualization, computer graphics.

1. INTRODUCTION

Holography, as proposed in 1947 by Dennis Gabor, is the method of recording three-dimensional (3D) images with full parallax in a two-dimensional (2D) film. Even though holograms can be used to record very striking images, they are not well-known or understood outside the optics community. In addition, holography can be used to perform very high-precision measurements of mechanical strain and vibrations.

Holograms rely on the wave-nature of light. Recording of holograms involves interference between two light beams, with the resulting standing wave interference pattern recorded in holographic film as a diffraction grating. Playback of the resulting hologram happens through diffraction. Light diffracts off the periodic pattern recorded in the film, and "bends" to form the holographic image. Since the diffraction grating can be represented with a grating vector equal in magnitude to the difference in wave vectors of the two initial interfering waves, the grating will recreate all original rays of the image. In particular, the recording is done with a reference beam striking the holographic film directly, in addition to the light scattered by the object, with the interference between these two beams forming the diffraction grating. For playback, a beam coming from the same direction as the original reference beam will diffract to recreate the original object. We can therefore assume that the hologram acts like a window with memory: during recording, the film records all rays traversing it. During playback, it recreates all these rays, in their original directions. Therefore, the object is reproduced at the original depth with full 3D information. Since the main phenomenon is the formation of standing waves, the interfering waves must be monochromatic sinusoids of a defined phase, and holograms are most easily recorded with coherent light produced by a laser.

As summarized above, holography involves most of the important concepts of optics and electromagnetism that are normally covered in undergraduate courses. This includes wave propagation, interference, diffraction, colour perception, optical coherence and laser operation. These concepts make holography a natural medium for the hands-on teaching of optics.

At the same time, holography is a very rich artistic medium, stimulating the creativity of art students. Owing to its recent introduction and stringent requirements, it is not as widely explored as some of the other new media. The combination of full parallax, along with the ability to record both virtual reality and real subjects gives considerable freedom.

Based on these unique properties, our goal is to use holography as a multi-faceted teaching tool of both science and art. Half the class is composed of science students, while the other half is composed of art students. The material covered and marking scheme employed is also divided between science and art. Two instructors are needed for these two components. As a result, our course teaches optics in a very hands-on and accessible manner to scientists and non-scientists alike, making this very important but not well-understood science available to a larger number of students. Of equal importance, however, the course teaches science and art students to work with each other and to learn from each other. Science students are required to take non-science breadth requirements, and art students must have a few science credits. These requirements, however, rarely lead to collaboration and dialog between these distinct student communities. Quite often, the courses offered as science credits for non-science students are not the same courses that students with science or engineering majors take, and the communities remain separate.

Our course, therefore, emphasizes and requires collaboration between art and science students. Projects are done in groups of two students. They require both an understanding of the physics of holography, and also an artistically creative concept for the subject to be recorded. Students are encouraged to form the teams with one art and one science student. They will then help each other, and learn from each other, establishing a very fruitful dialog between these two, normally separated, groups.

As mentioned above, holography involves concepts of interference, diffraction, optical coherence and lasers. Normally, these are taught in a very mathematical way, with the help of many equations. Given our diverse student background, however, we cannot use this standard approach in this course. Instead we teach these topics very conceptually, relying on the hands-on work in the lab and on geometrical constructions instead of the typical mathematical abstraction. This turns out to be one of the most challenging aspects of teaching the course.

The course, called *Holography for 3D Visualization* is one of several educational activities of the Institute for Optical Sciences[1]. It was offered for the first time at the University of Toronto in the spring of 2008. In the spring of 2009 it was offered in collaboration with the Ontario College of Art and Design, which was responsible for the art component of the course, while the science component was delivered by the University of Toronto. The course is 13 weeks long, as is typical of our half-courses. It includes class-room lectures, lab demonstrations, computer labs for the production of 3D computer-generated images and projects for students to produce their own holograms. These are described below.

2. LECTURES

The lectures run for two hours per week, covering general concepts of optics, detailed concepts of holography, the history and art of holography, as well as the necessary concepts of laser safety and other areas of application of the concepts that students have learned.

The first lecture serves as a motivation for the course. Since few students have seen holograms before, we include a small in-class exhibition, with both professionally made holograms and student work from past years. Topics discussed include early studies on visualization, the history of holography, as well as opinions of artists in holography regarding the unique features of this artistic medium.

In the labs, described below, students will be using a Class IV laser, which poses significant dangers especially for eye safety. It is therefore mandatory that all students undergo laser safety training. This is the topic of the second lecture. The training is done by the University's Laser Safety Officer. This is the only course at the University of Toronto where students are required to work with lasers above Class II. Therefore, a special training package was developed for this course, based on elements of the standard training course for researchers who use lasers in their work. This is a compulsory lecture – for safety reasons, those who do not complete the training are not allowed to continue in the course.

The following two lectures are devoted to general topics in optics that are necessary for holography. These are: ray and wave optics; interference and diffraction; polarization of light; light emission and lasers; coherence. Given the diverse student background, we teach these in a conceptual manner, with equations reduced to a minimum. At the same time, we emphasize the understanding of the underlying physical concepts. For interference and diffraction, however, we found equations to be essential. Since these phenomena are at the core of the recording and reconstruction of holograms, we need to be able to calculate angles and wavelengths correctly.

With a solid understanding of interference and diffraction we are now ready to apply them to holography[2]. We first prove the following: If two plane waves (*a* and *b*) interfere and the resulting standing wave pattern is recorded in holographic film we form a diffraction grating. After development we place the film back in the original position, and continue to shine wave *a* on it. This wave will diffract into wave *b*. Alternatively, we can shine wave *b* onto the film, which will diffract into wave *a*. We can then repeat this procedure with wave *a* as before, but wave *b* as a superposition of many rays that form a complex image. After recording, as long as we can recreate wave *a* in the original direction, it will diffract into the many rays *b* that form the image. This leads to the conclusion that the hologram is a window that records all rays going through it, and plays them back in the original position and direction. With this concept, questions regarding the recording of holograms can be reduced to geometrical optics problems, with relatively simple solutions.

We can now explore the different kinds of holograms, explaining the difference between master and transfer holograms, reflection vs. transmission holograms, and the various techniques to obtain white-light-viewable holograms. These concepts are very easily understood at this point, since the students have already seen how such holograms are recorded in the lab, and can link the lab experience with the theoretical explanations in the lecture.

The next topic to be discussed is the chemistry of holographic film and the development process. Here we connect to the chemistry of photography, which is very similar, given that both processes use silver halide emulsions. We also introduce non-silver processes for holography, with their advantages and disadvantages.

The remaining topics in holography are the production of holograms from digitally created computer graphics and colour in holography. Both are required for the later lab demonstrations and student projects. We discuss how to record master holograms from computer graphics as an extension of the multiple channel hologram, with many channels. We also mention alternative techniques such as the direct-write technique printing individual pixels (hogels) in the hologram, avoiding the master-transfer process. For the recording of holograms in full colours we discuss briefly the technique of recording holograms with 3 laser colours simultaneously, and the pre-swelling of emulsions with triethanolamine. We focus, however, on the full colour white light transmission hologram, since this will be used by students in their projects.

The lecture on digital and colour holography is complemented by a lecture on human perception of depth and colour. We discuss the clues used in human vision to give depth-related information. For colour perception, we describe the physiology of colour vision, along with its defects, and the various methods to quantize colours.

To close up the discussion of holography we describe other scientific uses of this phenomenon. We include holographic measurements and non-destructive testing, as well as applications in data storage, medicine and security. We also introduce emerging trends in holography. Finally, we discuss other areas of optics that are now accessible to our students, after acquiring an in-depth practical understanding of interference and diffraction. We discuss interferometers and their use in precision metrology, the operation of fibre Bragg gratings and their importance in fibre optic networks. As another example of interference, we describe the production techniques for fibre Bragg gratings.

3. LAB DEMONSTRATIONS

A very important aspect of our course is the hands-on approach to holography in the lab. Students assist in the recording of several holograms before we consider their theory in class. This serves as excellent motivation for the lectures. The lab sessions are 3 hours long, and are run roughly every second week.

The lab is equipped with a vibration-isolated table of 120 by 240 cm and a 1-Watt 532-nm continous wave laser. We use a number of 1-inch mirrors to steer the beam. As beam expanders we use microscope objectives with spatial filters. To steer and collimate the expanded beam we use large-area (25 cm) flat and concave mirrors. In addition, for the recording of digital holograms, we have a laser screen and a moving slit assembly, both controlled by a computer. The laser screen uses the Liquid Crystal component of an LCD monitor, without its enclosure and with the back light removed. It serves to place an image on the laser beam. The moving slit assembly serves to only expose a small area on the master plate, resulting in a multiple channel hologram with up to 150 channels. With such a high number of channels, the parallax of individual channels becomes unimportant and we can use the 2D image on the LCD screen as the subject. Half-wave plates are used to compensate the polarization of the laser beam after passing through the LCD screen. The holograms recorded in the labs measure 20 by 30 cm in size. This is a size that is compact enough to handle on the optical table described above, yet is large enough to accommodate the subjects that most students choose.

The first 3 meetings in the labs are devoted to the recording of holograms from real objects. We start with 3 small demonstrations of a transmission master hologram, followed by reflection and rainbow transfers, to show the simplicity of the process. In the following weeks we record again reflection and rainbow holograms (along with the requisite master holograms) this time focusing on the visual aspects and quality of the hologram. These holograms will be the subject of the students' first project. As is typical in holography, the largest amount of time is spent setting up the table for each shot. We do this as a group activity, with the students taking turns aligning the various components.

The remaining two meetings in the labs are used for digital holograms. We start with a monochrome reflection hologram, to introduce students to the operation of the moving slit assembly, looking at how this process can be understood as an extreme version of a multiple-channel hologram. Because of time limitations in a 3 hours session, part of the table is already set up before the students arrive. Students are invited to provide their own digital files for this demonstration. In the last lab meeting, we record a white light transmission full colour hologram, as described in the lectures. Here again, we cannot perform all the steps during the lab session, and must prepare the master plate ahead of time.

4. COMPUTER LABS

For the second half of the course, the lab demonstrations and project focus on the recording of digital holograms from computer sources. This is a relatively new use of holography, which gives considerable freedom compared to the standard use of holography from real objects. Some of the advantages are: We no longer need to bring the subject to be recorded into the studio – all we need are the digital files. Also, we are no longer limited to life-size copies of real objects. Instead, we can represent subjects of any size. Finally, we are no longer limited to static objects. We can introduce motion in our subjects. In fact, digital holography opens the door to completely abstract subjects.

There are many ways to produce the necessary graphic files for digital holography. We use Autodesk 3DStudio Max to compose the subjects for our digital holograms. This software, used mainly for 3D animation, is able to provide the correct view of a scene from any given angle, while also allowing for motion of the subjects. With this program we can define the scene with three-dimensional detail for the placement of all elements. We can compose the scene elements ourselves, from geometrical shapes, or we can use pre-made models for many types of subjects: people, animals, furniture, plants, etc. The resulting scene is exported as a stack of 2D images, representing the view from the different angles of the hologram.

Since most students do not have experience with 3D graphics and animation when taking this course, we provide computer lab sessions for them to learn this software. These sessions take place during the lab times, in weeks when no lab demonstrations are scheduled. Students start with very basic 3D graphics task, and then focus on the subject necessary for the production of the necessary files for their project.

3D computer graphics are used much more widely than in holography. The techniques learned here can also be used for video animation in other fields.

5. STUDENT PROJECTS

During the course, students are required to complete two projects. The main part of each project is the production of a hologram with a meaningful artistic content. As mentioned above, students work in teams of two, and are encouraged to form the teams with one art and one science student. These are the major hands-on activities of the course, where students do most of the work themselves.

Since students do not yet have the necessary experience to decide what subjects will not work for holography, they must first submit a proposal describing briefly the contents of the holograms and the motivation for choosing this subject. Examples of the pitfalls we try to avoid are: Subjects that emit light, such as candles or computer screens; subjects that will vibrate during the exposure; subjects that will deform during the exposure, for example due to evaporation; subjects that are too big for our holographic plates, since real object holography does not allow a change in size; subjects that give specular reflections of light onto the holographic plate. At the same time, we use the proposals to evaluate and give feedback on the artistic content, since this will be a large part of the evaluation. This is especially important since many of the students have not been evaluated on artistic creativity before.

Due to laser safety concerns and the complexity of recording holograms, the students are not allowed in the holography lab without supervision. They must reserve a time slot in the lab ahead of time, and at the same time book an appointment with the teaching assistant. The teaching assistant will make sure that most common problems resulting in defective holograms are avoided. As with other artist materials, students must buy the holographic plates that they use. Since there are few local suppliers of holographic materials, however, we provide the plates to the students.

Once all holograms are produced, we organize a critiquing session in the following lecture time. Students present their holograms to the entire class and receive constructive comments from their colleagues. The critique sessions become a highlight of the course, allowing students to celebrate their work and their results.

After the critiques, students are allowed to take the hologram home. In these sessions students present surprisingly successful holograms.

The first project involves real object holography. Students are required to produce either a reflection or a rainbow hologram. They will prepare the materials to be recorded ahead of time, and will bring them to the lab for shooting. Most students have spent considerable effort in selecting and building the correct composition for their project, a direct manifestation of the enthusiasm for the course. The biggest challenge here is to ensure that the subjects will not vibrate during exposure.

The second project for the students requires a full-colour digital hologram. Students prepare the files ahead of time, and submit them by the appropriate deadline. Since the process of recording the master holograms is quite time consuming and very mechanical, all master plates are recorded by the teaching assistant. Students are only involved in setting up the table for this purpose. When recording the transfer, however, students must determine the correct colour balance. Therefore, they will record this hologram themselves, under the supervision of the teaching assistant, as for project 1.

6. STUDENT EVALUATION

Evaluation of students in this course is trying to achieve a balance between the science and art components and also to encourage students to keep up with the lecture material. For the scientific aspects we have 3 assignments, based on lecture material, along with midterm and final examinations. Artistic aspects are tested with some questions on the midterm and final examinations, but mainly through the two projects. Here we consider three components: the proposal, the concept and premise for the hologram, and the execution of this concept.

7. CHALLENGES

In the introduction of this new and unique course we had to overcome a number challenges. The most important are mentioned here. Most of them are due to the combination of art and science into one course, and to the very hands-on nature of our approach.

When delivering the lectures, the biggest challenge was to present the material in a manner that is engaging and stimulating for both groups of students, even though these groups have very different backgrounds from previous courses and from personal interests. The science components need to be taught in a way that is challenging enough for science students, yet still accessible to art students. The same also holds for the art components. A related problem is that of student evaluations, especially when it comes to science questions. Science students have taken many more quantitative tests in the past, and are used to difficult questions that must be solved mathematically under time pressure. This is, however, not usual for art students. As a result, we avoid questions involving mathematics on the tests. Instead we focus on the conceptual understanding of the material.

A second set of challenges came from the complex equipment needed for holography. Due to cost, size and the requirement to work in a dark room, we can only have one holographic setup available, and students must take turns. Also, students can only work when the teaching assistant is available, which requires considerable time flexibility on the part of the assistant. Even though all students have the same deadline, some must record the hologram much earlier than others, since work cannot be done in parallel. Limited time slots in the lab also mean that students do not usually have the opportunity to retry a hologram, something quite unusual for the production of art: the hologram is recorded on the first try, and is presented as is. There is usually no time to correct minor problems. This also means that students only get one hologram, even though they work in groups of two. Most of the time both group partners would like to get a hologram. Additional copies of these holograms are recorded during the summer, when more time is available.

Finally, the cost of such a course must also be considered. The equipment used here is not usually seen in an undergraduate laboratory. The need for individual supervision of student work means that the class size must be limited to a number much smaller than is typical for a second year course. This, however, means that students will have much more direct contact with the instructors, something of great value with today's very large lower year classes.

8. OTHER STUDENTS INVOLVED IN HOLOGRAPHY

The entire holographic setup described here was assembled, tested and fine-tuned by a number of undergraduate students working at the Institute for Optical Sciences during the summers, since 2006. Since our holographic equipment is custom-made in house, the students had the very challenging task of making sure that everything works correctly. These students acquired not only a very deep understanding of optics and holography, but also problem-solving, debugging and time-management skills. Working closely with other students and staff, they were introduced to the University's research activities, something that most undergraduate students do not experience. Most of these students are continuing to graduate studies in engineering or science.

9. CONCLUSIONS

In the course *Holography for 3D Visualization*, we have used the topic of holography to deliver a student experience that is unique from many points of view. We teach optics to undergraduate students with hands-on activities. By allowing students to record their own holograms, we provide an excellent motivation for students to learn optics and the properties of light, especially the phenomena of interference, diffraction, coherence etc. More importantly, however, we use holography to bridge the very distinct science and art student communities. The class has both science and art students and teaches both science and art. The very diverse student background provides a very rich learning experience with students learning both from the instructor and from each other. Art and science students working in teams to solve problems that involve both artistic and scientific challenges allows students to form a dialog with each other, and to learn each others' strengths.

The course has now been offered for two years in a row. The holograms produced by students as part of their projects are stunning, both visually and conceptually. In both years, the course received unanimously positive reviews form students. The undergraduate students appreciated especially the opportunity to work in an optics lab, and the freedom to record their own holograms. Science and art students had surprisingly similar feedback at the end of the course. The student response to this course shows that there is a real need among undergraduate students for courses that emphasize hands-on work, and direct contact with the instructors and teaching assistants.

REFERENCES

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