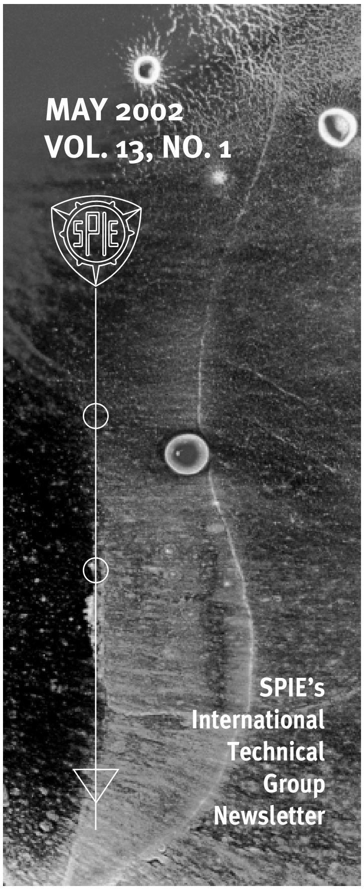

MAY 2002
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SPIE's
International
Technical
Group
Newsletter

HOLOGRAPHY

Portable, high-resolution, and user-friendly holographic camera

Holographic interferometry (HI) is a powerful whole-field optical method that allows contactless displacement measurements in the micron to sub-micron range. It is used in numerous applications including strain/stress analysis, flow/damage detection, and resonance-mode visualization and measurement. A crucial element of HI is the photosensitive medium used for holographic recording. Their principal figures of merit for such media are generally energetic sensitivity and diffraction efficiency, but other features—such as self-processing and the erasability/reusability of the medium—can appear more important in their practical applicability to HI.

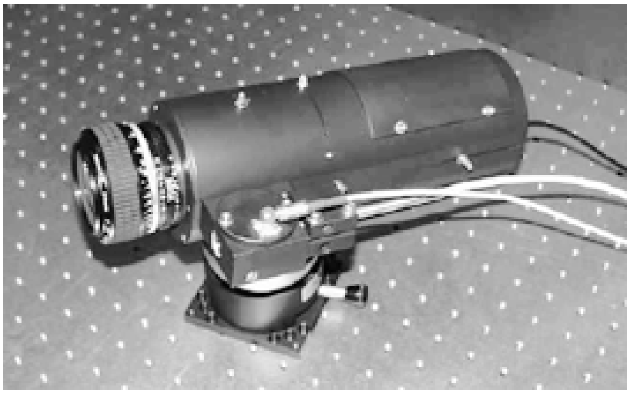

Figure 1. Compact, portable holographic camera.

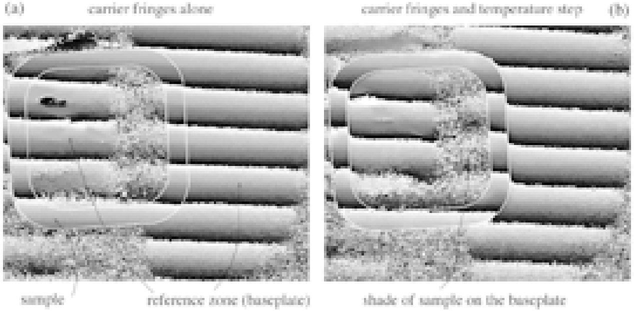

Figure 2. Interferograms used to deduce the coefficient thermal expansion of the sample (contour drawn in white). (a) Preliminary interferogram with a carrier fringe pattern alone. (b) Interferogram obtained after a temperature increase and the addition of carrier fringes.

Photorefractive crystals (PRCs)[1] of the sillenite family ($Bi_{12}SiO_{20}$, $Bi_{12}GeO_{20}$) are interesting recording media for HI. Although about 1000 times less sensitive than classical recording media (silver halides, thermoplastic plates), sillenite PRCs are self-developing and indefinitely reusable. They would allow holographic cameras that, like speckle interferometers, do not require any external operation or manipulation. However, here they would be of higher quality and have better measurement dynamics and lower noise levels that are typical of HI. We present here our new interferometer, which we designed to be compact, easy to handle, and capable of quantitative phase measurements to permit easy data interpretation.

We previously presented a first breadboard prototype[2,3] contained in a portable casing and including the laser, all necessary optical beam forming elements, the PRC, and the observation CCD camera. The laser was a compact, air-cooled, continuous-wave, diode-pumped, solid-state (DPSS), Nd:YAG emitting 490mW at 532nm. With such power, objects of 50×50cm^2 can typically be observed. This holographic camera has been used in a wide range of applications.

One problem experienced with this prototype, however, was that the laser was included in the breadboard. While portable, the instrument is too cumbersome and has to sit on a table. To overcome this problem, the laser must be remote from the breadboard, the light carried to the optical head by an fiber. To transfer Watts of laser power along meters of optical cable, a special mono-mode fi-

Continues on page 9.

***Technical Group Registration Form**—See page 11*

NEWSLETTER NOW AVAILABLE ON-LINE

Technical Group members are being offered the option of receiving the Holography Newsletter electronically. An e-mail is being sent to all group members with advice of the web location for this issue, and asking members to choose between the electronic and printed version for future issues. If you are a member and have not yet received this message, then SPIE does not have your correct e-mail address.

To receive future issues electronically please send your e-mail address to:

`spie-membership@spie.org`

with the word `holography` in the subject line of the message and the words `electronic version` in the body of the message.

If you prefer to receive the newsletter in the printed format, but want to send your correct e-mail address for our database, include the words `print version preferred` in the body of your message.

OBITUARY

Daniel K. Schweitzer: 1946-2001

Photo by Mary Harman

Daniel K. Schweitzer, a pioneer in art holography, lost his battle with lung cancer on the 5th of December, 2001, just over two weeks before his fifty-fifth birthday.

Schweitzer worked with holography for more than two decades as an artist and teacher, coming to the visual arts with a background in theater. He moved to New York city in the early 1970s, which remained his home base throughout his career. In 1974 he completed a course of study at the New York School of Holography, of which he later became a faculty member. He and Sam Moree founded New York Holographic Laboratories in 1977, where Dan taught courses in practical holography and created the major body of his holographic artwork using modest continuous-wave laser systems. He continued to teach and educate new generations of art holographers at Parson's School of Design, The New School, and The School of Visual Arts: all institutions of higher learning in New York city. In 1998 he co-founded the Center of Holographic Arts (CHA)[1] with Ana Maria Nicholson. CHA offers an Artist-In-Residence program using a pulsed-ruby laser, has stationary and traveling exhibitions, puts on a series of talks, and maintains a web site with a newsletter, ECHO.

Over his twenty-five plus years in the field, Dan created a remarkable body of holographic art. His work has a cinema graphic and theatrical flair, combining holograms with small, sculpted figures posing in tableau on 'holographic stages'. He explored white-light transmission holography extensively, concentrating on the Benton rainbow method and combining it with a variety of other techniques. Most of his work is made up of monotypes and limited-edition pieces. He created some of the first flat integral holograms, this work culminating in a highly recognized piece entitled *The Movie Theatre* (1977), which harkens back to his first love. The holographic scene combines a 'movie' of Dan reaching through the screen in a dark theatre and plucking a viewer out of the front row in the audience (the integral), with a conventional rainbow of the audience: the latter extends the apparent volume of the scene forward to the film plane and intensifies the perception of depth and movement. Although this piece was commercially produced and innovative for the time, it is a crossover work that can equally be appreciated for its artistic merit. It also set the stage for his artistic exploration and concern with, as he expressed it, "...the issues of time, space and our perception of them."

Ever the image innovator, Schweitzer achieved stunning optical animations by using items such as a dented curved mirror:*The Seed* (1980) depicts a whirling composition derived from mundane objects that have been transformed into all manner of the sublime, including a portrait of Einstein that folds into and out of a distorted image. *The Gallery* (1984) depicts an art exhibition of holograms. In a way, this triptych of 30×40cm holograms (derived from 18) serves as a model for Dan's ambition to create large format holograms. *The Gallery* often blurs the line between inside and outside by giving the viewer a role to play in the very setting portrayed and, in so doing, an opportunity to conceptually engage both sides of the hologram simultaneously. He coined the term 'hyper parallax' to describe his use of optical techniques plus 2D and 3D details with which he enlarged the viewing experience. In his later works, the mixed media 'holo-sculptures,' he joined physical objects with his holographic images resulting in small-scale tableaux: many resemble stage sets like *Doorway* (1989), *Paradox* (1993), or *Intersection* (1995). His hyper-parallax explorations led to a proposal for what he termed a, "unique publishing concept," an event. He planned to write a novel, a science fiction, loosely based on his creative exploration of holography and illustrated with many of the works he created. To the end it was a work in progress. He commented, "it seemed that all along I was illustrating a story yet to be told."

His work has been shown in numerous solo and group exhibitions including: *Light Dimensions* (1983) at the National Center for Photography, Bath, UK; *Licht - Blicke* (1984) at the Deutsches Filmmuseum, Frankfurt, Germany; *As We See It* (1989) at the Smithsonian Institution, Washington, DC; *The Edge of Light: Second Stages* (1992) at the Museum of Holography, NY, NY; and *Generations In Holography: Expanding a Collection* (1997) at the MIT Museum, Cambridge, MA. Art museums, galleries and major holography exhibitions throughout the world continue to show his work.

Dan also received numerous awards throughout his career. One he received from the National Endowment for the Arts to the Cabin Creek Center funded *The Movie Theatre*. *The Gallery* was funded in part by his Artist-In-Residence grant from the Museum of Holography. In 1987, he was among the first group of artists to receive the prestigious Shearwater Foundation Holography Award, which acknowledges the pre-eminent artists in the field and contributes to the financial support of their continued efforts.

He is survived by his wife Gloria Schweitzer; a brother David Schweitzer with his wife Margaret and their three children Erica, Blake and Charles; and a brother Alan Schweitzer with his wife Barbara and their son Matthew.

Rebecca Deem

Reference

1. *Holocenter announces AIR awards,* **Holography 12** (2), November 2001.

Rebecca Deem is an artist, holographer, teacher, and writer based in Southern California.

X-ray fluorescence holography

The knowledge of atomic and molecular structures is fundamental to physics, chemistry, and biology. From the beginning of this century, much effort has been put into the development of reliable methods for structure determination. Diffraction techniques are the most common and the most highly developed for structural studies. However, not all problems can be solved by diffraction: well-known difficulties are that single crystals cannot be grown for all substances, and that a full structure determination is difficult from powder data alone. Sometimes the phase problem causes diffraction to fail: even with single crystals. As for non-periodic systems—amorphous materials, quasi crystals, etc.—detailed structural information cannot easily be derived. Further difficulties arise with new artificial materials that have structures which cannot always be solved by traditional crystallographic methods. The study of the local environment of low-concentration impurities in a sample, for instance, is problematic: as is the atomic order in buried interfaces, and the atomic environment of surface adsorbates.

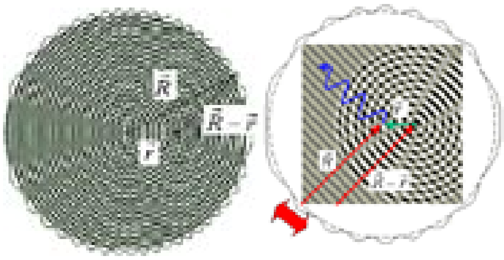

Figure 1. The x-ray fluorescence holography (XFH) principle for (a) inside "source" and (b) "detector" holography.

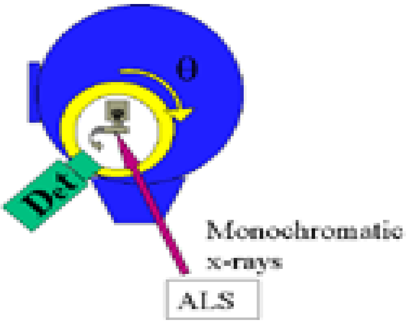

Figure 2. Sketch of the experimental setup installed at Advanced Light Source for the study of hard-x-ray holographic measurements.

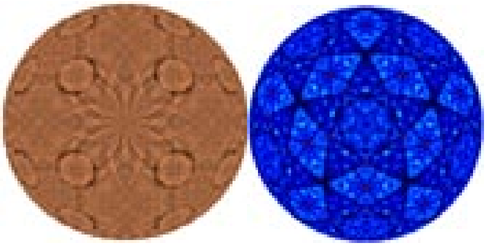

Figure 3. Holograms and standing-wave line patterns taken from samples having their surfaces parallel to the crystallographic plane with (a) 4- (MnO) and (b) 5-fold (AlPdMn) axis.

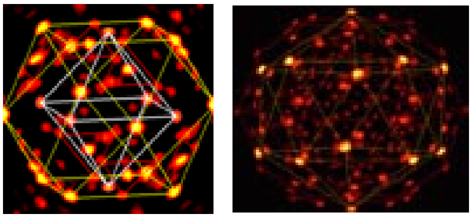

Figure 4. The 3D arrangement of atoms around the Mn site, reconstructed from the holograms of Figure 3.

It is not surprising, therefore, that scientists are trying to find new techniques for structural investigations. Recently, atomic-resolution X-ray holography has emerged. It is based on the same principles as traditional holography with light: i.e. a coherent reference wave illuminates the object and the detector surface. The intensity modulation caused by the interference between the reference and the wave scattered by the object is recorded. This interference pattern contains both the phase and the amplitude information of the object wave. Therefore, the original wavefront can be reconstructed, giving the 3D spatial arrangement of the objects.

Although holography is used in many areas of science and everyday life, atoms in solids could not be holographically imaged until recently. This is because the resolution is limited by the pixel size of the detector, or the size of the source, and the wavelength. While it is relatively easy to decrease the wavelength to the Ångström level, giving the possibility of atomic resolution, it is difficult to reduce the source size or to improve the detector's resolution. Abraham Szöke pointed out that individual atoms in a solid could be used as sources of radiation.[1] An atom in a single molecule does not provide enough signal to obtain the measurement in a reasonable time. For this reason one has to use multiple copies of the same molecule with the same orientation to obtain multiple measurements in one time. The obvious candidates of oriented molecules are single crystals. Based on his idea, experiments were performed: first using electrons,[2] and later using photons[3] as hologram-forming waves. Moreover, Gog and coworkers showed that the atoms present in a sample could be used as detectors instead of sources of radiation.[4]

In our experiments, we use the electronic systems of the atoms as 'sources' or 'detectors' of x-ray radiation. Figure 1(a) shows the formation of a hologram in the case where the atoms act as point sources. A central atom is excited by an external source. In the de-excitation process, a fluorescent photon is emitted in the form of a spherical wave. This wave can reach the detector directly or after scattering by the neighboring atoms. The two waves interfere producing an intensity modulation, which is measured on a spherical surface surrounding the sample. The intensity modulation contains the hologram. The main advantage of this method with respect to the one that follows is that the hologram can be made with a position-sensitive detector without moving any part of the experiment.

In the other case, that is when atoms are used as point detectors, the external wave is incident to the sample in the form of a plane wave (see Figure 1(b)). This can reach the central atom directly or by scattering from the neighboring atoms. The two waves interfere at the detector atom (central atom) and the resulting field excites the electronic system. The probability of excitation is proportional to the strength of the field. Changing the direction of the incident radiation changes the phase relation between the direct and scattered waves resulting in oscillations of the fluorescent intensity. These oscillations contain the holographic information.[5] The advantage of this method is that the holographic information depends on the wavelength of the incident beam, and this can be tuned to measure multi-wavelengths holograms.

Experimental developments

The main difference between the two types of measurement is that, in the inside-source case, the fluorescent radiation has to be measured as a function of the detector position in relation to the sample. While using the atoms as point detectors, the direction of the incident beam has to be varied and the external detector has to collect the fluorescent photons from the full solid angle about the sample.

The experimental setup, developed at Advanced Light Source (ALS) at the Lawrence Berkeley National Laboratory, is shown in Fig-

Continues on page 10.

Shearwater foundation holography grants for 2001

The Shearwater Foundation has awarded $104,500 in grants through its Holography Program this year. The Shearwater Foundation provides funding to groups, institutions and associations that contribute to the understanding and appreciation of art holography worldwide. It also gives an Holography Award to artists who are exemplary in the field.

The Center for the Holographic Arts, Long Island City, USA, received a maintaining grant of $50,000 towards the running and developmental costs of its Artist-in-Residence program. The residencies were established by the Center in 1998 to provide creative and technical facilities for artists wishing to develop their work with holography. The Center, under the guidance of founding Directors Ana Maria Nicholson and Dan Schweitzer, has become a focus of excellence, attracting new and established artists from around the world.

Stephanie Hunt, Boston, USA, received a grant of $9,500, to research and develop *Eye on Holography*, an interactive online resource for students, teachers, and the general public. Her aim is to provide material that will allow visitors to understand the basic ideas upon which holographic imaging is founded. This grant will allow her to expand her research and technical development and include greater detail about the creative aspects of the medium and the artists who are working with it. The project, begun during her studies in the Technology in Education program at the Harvard Graduate School of Education, will be developed with the MIT Museum.

The Nederlandse Stichting voor Waarneming + Holografie, Holland, received $1,000, the second payment of a two-year grant towards the production of *Optische Fenomenen*. This internationally distributed publication—founded, produced and edited by Jan Broeders—covers aspects of visual perception and three-dimensional imaging. The funding was provided to assist with the inclusion of more information about creative holography and to increase the publication's international distribution.

The Holography Purchase Project, established last year, was made into a permanent part of the Foundation's grant giving during 2001. The Butler Institute of American Art, Youngstown, USA, received a grant of $4,000 towards the purchase of *Lucy in a Tin Hat*, a dichromated gelatin version of the hologram by British artist Patrick Boyd. This will now be archived as part of the Institute's permanent collection.

The Shearwater Foundation Holography Award was given to four artists in recognition of their outstanding activities in the field of creative holography. They have demonstrated a clear understanding of the aesthetic and technical qualities of the medium and developed an individual body of work which extends beyond the optical and physical qualities of the holographic process. As in previous years, they were nominated by an international group of advisors (which is newly appointed each year the award is made) and receive a personal award of $10,000. The artists were: Marie-Christiane Mathieu, Canada; Matthew Schreiber, USA; Harriet Casdin-Silver, USA; Rudie Berkhout, USA/Netherlands.

Everyone involved with The Shearwater Foundation would like to express their deep sadness at the death, on December 5th, of Dan Schweitzer. He was a driving force in creative holography and was able, through his leadership of the Center and through his own work, to pass on his skills and sensitivity so that other artists could share his excitement for the medium he so enthusiastically developed. Days before his death he was planning, with the Center's board of directors, how the Center's activities might continue and improve. Ana Maria Nicholson will carry on as director and, with the help of all those who have supported the Center, will continue to teach and encourage artists.

Shearwater Foundation Holography Program
46 Crosby Road, West Bridgford
Nottingham, England, UK NG2 5GH
Tel: +44 115 914-3483
Fax: +44 115 914-3483
E-mail: info@ShearwaterFoundation.org
http://www.ShearwaterFoundation.org

High density holographic data storage

Continued from page 6.

tration, optical distortion, and material shrinkage that currently hamper page-oriented holographic storage systems.

Geoffrey W. Burr and Laure Menetrier
IBM Almaden Research Center
650 Harry Road
San Jose, California 95120
Tel: 408/927-1512
Fax: 408/927-2100
E-mail: burr@almaden.ibm.com

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Tell us about your news, ideas, and events!

If you're interested in sending in an article for the newsletter, have ideas for future issues, or would like to publicize an event that is coming up, we'd like to hear from you. Contact our technical editor, Sunny Bains (sunny@spie.org) to let her know what you have in mind and she'll work with you to get something ready for publication.

Deadline for the next edition, 13.2, is:

14 June 2002: Calendar items for the twelve months starting August 2002.

Deadlines for 14.1 are:

5 August 2002: Suggestions for special issues and guest editors.

19 August 2002: Ideas for articles you'd like to write (or read).

18 October 2002: Calendar items for the twelve months starting January 2003.

Polymers for real-time holography fabricated via injection molding and sensitized by two-photon absorption

Photorefractive polymers emerged in the nineties and now provide a low-cost alternative to their inorganic crystalline counterparts. With their dynamic response, they have been used in real-time holographic applications including storage, time-averaged interferometry, imaging through scattering media, optical correlation, optical limiting, homodyne detection of ultrasound, and novelty filtering. In the past decade, significant progress has been achieved in improving their dynamic range, response time, gain coefficient, and phase stability. Lately, we have focussed our research in this area towards two objectives: demonstrating that these photorefractive polymers have the potential to be mass produced at low cost using standard plastic manufacturing techniques, and achieving non-destructive read-out using a nonlinear recording scheme.

The first aspect of our work relates to the fabrication of photorefractive polymers by injection molding.[1] Precision injection molding of synthetic organic polymers is an important technology for producing objects in varying shapes at low cost and in high volume. It is playing an important role in enabling the fabrication of numerous inexpensive optical elements, including optical disks for storage, light pipes for liquid crystal displays, and connectors for single mode fibers. Recently, the replication functions that injection molding provides have also been used to fabricate waveguide couplers and diffractive optical elements.

An injection-molding process involves four steps. First, the raw plastic material is fed into a heated barrel where it is melted: the temperature of the melt is specific to the material used to meet the particular flow requirements for fabrication of a given component. Next, the melted plastic is injected into a mold through a nozzle by applying pressure to the melt in the barrel. The mold is a custom-tooled cavity representing the negative volume of the component to be manufactured. Third, plastic cools down rapidly inside the mold and solidifies. In a final step, the mold is opened and the finished part is released and removed.

Figure 1. Photograph of thick photorefractive-polymer samples fabricated via injection molding.

Figure 2. The photorefractive polymer sample on the left has linear absorption at 633nm. In contrast, the sample on the right is fully transparent at the same operating wavelength under continuous wave excitation and becomes absorptive only under pulsed excitation.

In our experiments we used a 22ton vertical travel press (Morgan Industries G55-T). The mold cavities allowed the fabrication of bulk samples with dimensions of 60×13×3mm or 10×15×1mm. For our demonstration, we used photorefractive polymer compositions comprised of a low-birefringence co-polymer that provided samples with good optical quality. Photorefractive behavior was obtained by adding a sensitizer and a bi-functional dopant that provided simultaneously for charge transport and electro-optic activity. An example of a sample fabricated by injection molding is shown in Figure 1. In the best samples, diffraction efficiencies of 20% were obtained and net gain demonstrated. The response time in these materials is quite slow at this stage (330s) and requires optimization. Our work shows that multi-functional polymers are amenable to high volume production through well-established plastic manufacturing techniques, and can meet the low cost targets required for many emerging optical applications.

The second aspect of our work relates to the demonstration of non-destructive read-out in a photorefractive polymer by using nonlinear absorption to record information.[2] In holography, information is recorded optically in the medium using two interfering laser beams at a given wavelength. It is retrieved optically with a third laser beam at the same wavelength. In all photorefractive polymers known to date, the read-out of the information was also causing its partial erasure (destructive read-out). Such a recording might find some applications in the entertainment industry, where a customer could rent a video recorded on such a material and view it only once as the information is erased on reconstruction. For most storage applications, however, the reading process should be non-destructive.

We achieved this in a new polymer by recording with high-intensity pulses and reading with continuous laser beams. This way, on recording, the peak intensity is high and the sample is sensitive to light through two-photon absorption (a nonlinear optical process only observed with high intensity pulses). With low-intensity continuous beams, the sample is transparent. The reading beam is therefore diffracted by the hologram without erasing it. This is the first demonstration of non-destructive read-out in a photorefractive polymer, and was inspired by the early work of von der Linde in inorganic crystals.

This work was supported by an NSF CAREER grant.

Bernard Kippelen
Associate Professor at the
Optical Sciences Center
The University of Arizona
Tucson, AZ, USA
E-mail: kippelen@u.arizona.edu

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High density holographic data storage despite misaligned data pages

One of the attractive features of holographic data storage is its massively parallel input/output, made possible by storing and then retrieving data as large pixellated 2D data pages.[1] To relax the alignment constraints between each page of retrieved optical data and the waiting grid of detector pixels, a post-processing algorithm was recently proposed and demonstrated.[2] This *shift-compensation* algorithm accounted for both the linear and quadratic interpixel crosstalk contributions expected for intensity detection of coherent light, and reallocated them to the appropriate neighboring pixels. However, page misalignments close to ±0.5 pixel were difficult to correct to acceptable bit-error-rate (BER) due to error propagation in the iterative procedure.

It was postulated[2] that introducing an intentional magnification error might possibly reduce the problematic error-propagation, since the rapidly changing local offsets would pass quickly through $|d_{x,y}| \sim 0.5$ in isolated patches. Since all possible local shifts would be represented across the data page under any global misregistration, the poor performance of the algorithm under a half-pixel shift would be balanced by the presence of data that is locally registered. We have now experimentally implemented such an intentional magnification error,[3] using the difference in pixel pitch between the input SLM (12.8μm) and output CCD (12.0μm) to provide a magnification of 16:15. A portion of a 1×1 pixel checkerboard pattern, holographically reconstructed by phase-conjugate readout, is shown in Figure 1(a). It shows the expected variation from local alignment to half-pixel misalignment and back again over every 16 pixels. Figure 1(b) shows the results of post-processing the received data page in Figure 1(a) with a modified version of the shift-compensation algorithm: the original 1×1 checkerboard pattern is successfully recovered.

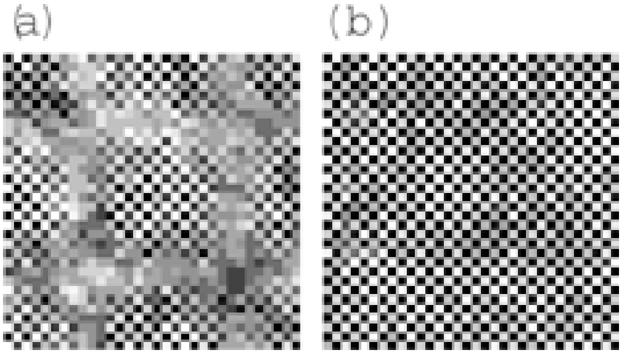

Figure 1. Experimental results: portion of 1×1 checkerboard pattern; (left) as relayed directly from SLM plane (12.8μm pitch) to CCD plane (12.0μm pitch) by phase-conjugate holographic reconstruction; and (right) after correction with the improved shift-compensation algorithm.

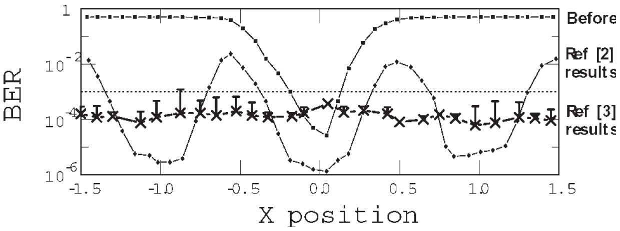

Figure 2. Experimental results: dependence of raw-BER (with an 8:12 modulation code[4]) before and after shift-compensation post-processing, as a function of x *shift. Data from Reference [2] taken under 1:1 imaging. Data for the improved shift-compensation algorithm taken under 16:15 magnification by phase-conjugate readout.[3]*

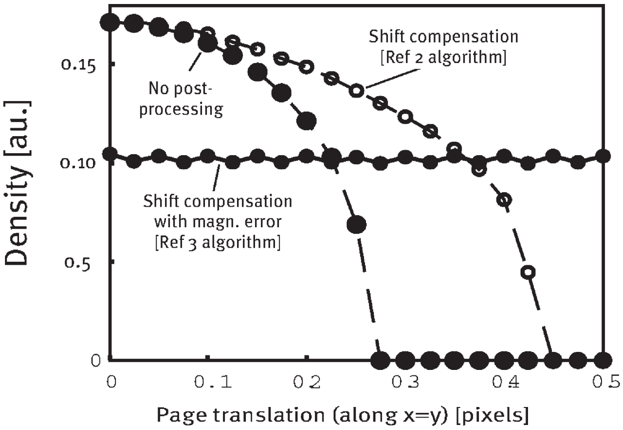

Figure 3. Simulation results: dependence of normalized density at a raw-BER of 10^{-3} under simple threshold decoding without shift-compensation, with the initial shift-compensation algorithm (with 1:1 imaging), and with the improved shift-compensation algorithm (with an intentional magnification error). Horizontal axis shows page misregistration along the diagonal x=y *axis.*

Figure 2 shows experimental results after post-processing near-megapel data pages (~900,000 pixels), as a function of shift along the *x* axis. The dependence of BER on transverse detector alignment is entirely removed, and an acceptably low raw-BER (average of 1.75×10^{-4}, worst-case < 10^{-3}) is maintained *independent* of the global misalignment of the data page.

To investigate the effect of data page misregistration and this subsequent signal processing on the areal storage density of holographic data storage systems, we have developed a set of numerical simulations.[5] A small data page (typically 50×50 pixels) populated with random binary data is subsampled at 40×40 samples per data pixel. A pair of 2D fast Fourier transforms simulate a 4F optical system with a square aperture at the central shared focal plane. The detected intensity is computed by integrating over each output pixel, and the BER measured either by applying the best-case intensity threshold or with a modulation code.[4] Simulation parameters can be varied to compute BER as a function of hologram aperture, page misregistration, intentional magnification error, pixel fill factors, and Gaussian additive intensity noise. By using Monte Carlo methods to add the random noise, the BER can also be computed after the simulated data page is post-processed with the shift-compensation algorithm. Even the impact of inaccurate measurements of page misregistration can be explored.

The $1/M^2$ dependence of signal on the number of holograms, (M), implies that a system that can tolerate twice as much relative noise can store $\sqrt{2}$ times as many holograms.[1] Thus, by determining the amount of relative noise required to push the BER over some target value (say, 10^{-3}), the achievable areal density can be determined for a variety of page misregistrations, band-limiting apertures, and pixel fill factors. For instance, Figure 3 quantifies the tradeoff in achievable density between three systems: a conventional system with little tolerance for misalignment, one that uses the earlier shift-compensation algorithm to obtain some tolerance to misalignment, and a system using the improved shift-compensation algorithm to obtain complete immunity to misalignment. Thus the shift-compensation algorithm can either partially relax or completely bypass the constraints on page regis-

Continues on page 4.

Non-local material response of photopolymer holographic recording materials

Dry photosensitive photopolymer layers are, at their simplest, solid-state suspensions of monomer and dye in an inert matrix. Illumination leads to polymerization, which involves the conversion of monomers into polymer. Polymer chains, once initiated, grow inside the medium until termination. As monomer is removed from a particular volume, monomer from areas that have been less strongly illuminated will tend to diffuse to equalize the concentration. If monomer is removed very rapidly during recording, or if the monomer cannot easily diffuse through the solid matrix, the recorded pattern will become distorted. The result of these effects can be most clearly identified for large grating periods (low recording spatial frequencies), as equalization of the monomer concentration distribution requires that monomer molecules travel considerable distances within the medium. The experimental result arising due to this phenomenon is known as *reciprocity failure* by the medium. Reciprocity failure can be reduced by staggering the exposure over time and allowing the material ‘rest periods’ during which the exposing beam is switched off and the monomer is allowed to return to a lower but more uniform monomer concentration distribution.

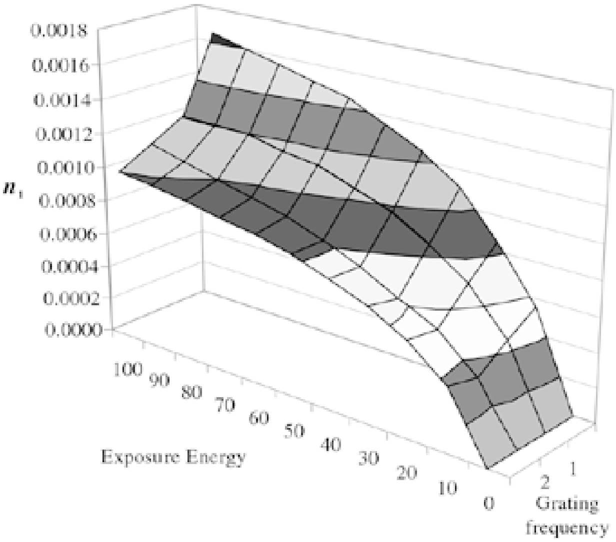

Figure 1. Refractive index modulation, n_1*, extracted from experimental diffraction efficiency measurements (corrected for Fresnel TE polarized reflections during exposure and replay). Measurements taken from unslanted, sinusoidal, phase, transmission gratings, recorded in a self-processing acrylamide layer. The results are presented as a function of grating spatial frequency (lines/μm) and exposure energy (*I_0t *mJ/m*^{2}*).*

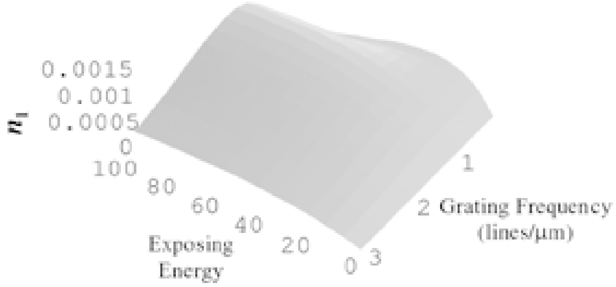

Figure 2. Refractive index modulation, n_1*, predicted using the derived analytic expression. The physical parameters used (rate of polymerization, diffusion, and chain-length variance), were estimated by fitting the analytic equation to the experimental data, (using a numerical, multi-parameter, least-squares-fitting program). Note: (a) reciprocity failure at low spatial frequencies and, (b) the roll-off response at high spatial frequencies.*

This description of the recording process does not, however, explain high spatial-frequency cut-off. In fact, as described, one might expect that a material whose behaviour is solely governed by diffusion processes would have improved response at high spatial frequencies. Given a low illumination beam power, and so a low rate of polymerization, a higher-spatial-frequency interference pattern will allow rapid equalization of concentration by diffusion of the monomer from dark regions to replace monomer removed in bright regions. Therefore, one might expect that the higher the spatial frequency, the higher the quality of the reproduction of the illuminating pattern. Unfortunately, photopolymers do not have infinitely high frequency response. Furthermore, although the response of the materials at low frequencies is of considerable interest, their major applications as media for data storage, holographic metrology, and HOE fabrication, are critically dependent on their ability to accurately record high information densities.

Commercial photopolymer materials with good high-spatial-frequency responses do exist (compared, for example, with standard commercial silver-halide materials). However, detailed information regarding their composition, and/or the process employed in arriving at their compositions, is not available in the literature.

The situation is further complicated by the fact that the rate of polymerisation is almost certainly not proportional to the illumination intensity but to the intensity raised to some power, e.g. ~1/2.

So although diffusion-based models well describe the low spatial frequency behaviour, they do not predict the expected roll-off in the high spatial-frequency material response. In a paper we published in 2000,[1] we proposed that the drop off in material response might arise due to the non-local nature of the response of the material. As the polymer chains are formed, they propagate away from the point of initiation, removing monomer at both a time and position separated from those of the original initiation. Due to this mechanism, the grating profile produced is a smeared-out version of the illuminating fringe pattern. As the grating period decreases, this smearing becomes more significant, resulting in a decrease in the visibility of the recorded polymer distribution.

Furthermore, if the chains grow quickly compared to the other processes taking place inside the material, the material response would appear to be well approximated by a purely spatial non-locality. The predictions of the model have been compared with experiment[2] (see Figure 1), and several forms of non-local response function have been examined.[3] Most recently, we have derived a relatively simple analytic expression that includes diffusion, a generalized relationship between the exposing intensity and the rate of polymerization, and the non-local material response. The resulting equations predict the material growth curve and spatial frequency response for a wide range of physical parameters[4] (see Figure 2). Applying our equation to analyze experimental results appearing in the literature over a thirty-year period, estimates of the rate of diffusion, rate of polymerization, and non-local variance have been extracted for a variety of materials.[5]

We conclude that control of the polymer-chain-length variance is critical if storage data densities in these media are to be improved. In a first attempt to do just this, experiments involving the use of photopolymer—which contain various concentrations of chemical inhibi-

Continues on page 9.

Volume holographic telescopes

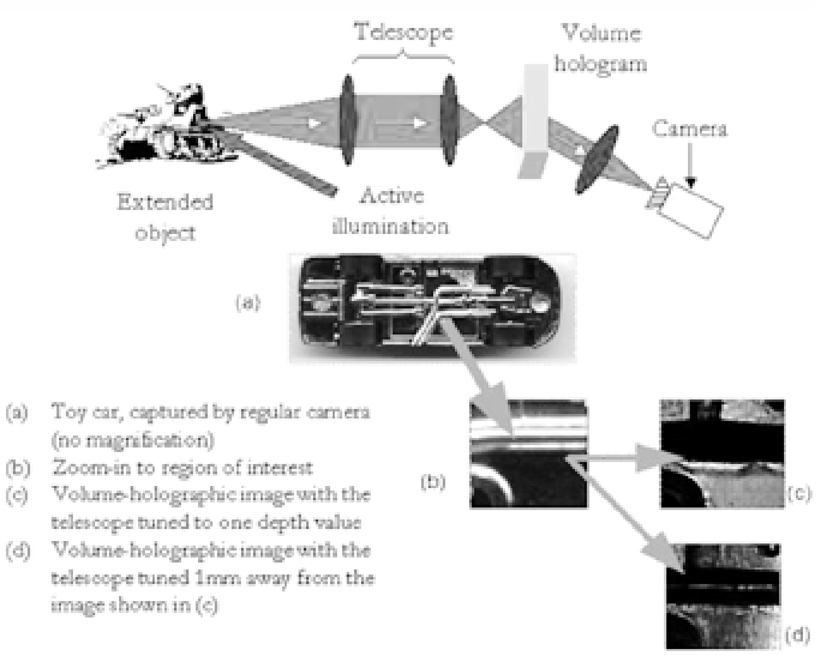

Figure 1. Volume holographic telescope schematic (top) and experimental results (bottom).

Precision imaging, ranging, and identification become increasingly difficult as the distance from the object increases. This is a serious challenge for autonomous robotic systems operating in demanding biological, industrial, and military environments. For example, industrial inspection of complex shapes is more useful if the information is returned as a three-dimensional (3D) shape rather than a planar projection. In biological specimens (cells, matrices, etc.) 3D spatial information as well as spectral information (e.g. the absorption or fluorescence spectrum) are both necessary to characterize the function of, and interactions among, biosystems. In the military context, modern autonomous scouts and smart munitions are required to inspect and identify valid targets while at the same time avoiding civilian or religious facilities and decoys. They must do this from distances ranging from a half to several miles: for instance, a typical flight altitude for a reconnaissance Unmanned Air Vehicle, UAV, is 1km.

In general, as we increase the distance between the object and the aperture plane of the imaging system, the angle that the object subtends towards the imaging system (i.e., the numerical aperture, NA) decreases. As a result, lateral resolution becomes worse, as 1/NA. Longitudinal resolution depends on aperture even more strongly, as $1/(NA)^2$. We have developed a novel class of imaging elements, based on volume holography, to meet this challenge. Holographic imaging[1,2] is based on using a smart holographic lens to replace elements of an imaging system (e.g. the objective lens). The holographic lens is pre-recorded as the interference pattern of two appropriately defined simple waves (e.g. two plane waves or a plane wave and a spherical wave) in a volume holographic material (e.g. lithium niobate or photopolymer). The hologram is then fixed and aligned with the rest of the imaging system.

When light scattered from a target enters the imaging system, the hologram selectively diffracts the Bragg-matched modes of the incoming illumination, while the remaining modes propagate undiffracted. Therefore, the hologram can be thought of as a matched filter, which 'sees' some selected aspects of the object and 'rejects' other aspects. This property allows the real-time extraction of complex information from objects, e.g. in the three spatial dimensions and the spectral dimension combined that would require scanning in most other types of imaging systems. Real-time spatial-spectral microscopic imaging has already been demonstrated with fluorescent microspheres by our group in collaboration with the Caltech Optics group.[3]

A volume holographic telescope is built by using a standard telescope (e.g. a 4F system) in conjunction with a volume holographic imaging element (VHIE), as shown in the schematic. The role of the telescope is to create a demagnified intermediate image of the target, which then serves as input to the VHIE. In general, the VHIE is composed of several multiplexed volume holograms, each tuned to a specific distance in the vicinity of the object. If a portion of the object surface matches one of these holograms, a strong signal is received at the detector. In general, this happens at the same time for several of the holograms contained in the VHIE (i.e., all the holograms whose tuned distances happen to lie on the object surface). The remaining holograms remain "silent." Therefore, the volume holographic telescope forms a distance-specific image. We computed and experimentally verified the longitudinal resolution of this element to $1.7l/(NA)^2$.

An additional benefit of our experimental arrangement is that the telescope determines the effective NA of the overall system. Therefore, by tuning the magnification appropriately, we can ensure that the desired performance is accomplished with a relatively small-area hologram. This keeps the cost and alignment sensitivity requirements of the system within reason. In our experimental system, we used a single hologram and instead scanned the object, a small toy car located approximately 0.5m away from the telescope. The results shown in Figure 1 correspond to longitudinal resolution better than 1mm with 3.5× magnification and 5mm hologram aperture.

Further improvements in imaging performance are obtained by combining two volume holographic telescopes to obtain an image of the same target simultaneously. The binocular telescope essentially over-constrains the location of the object surface. Then, the dependence of longitudinal resolution on numerical aperture becomes better than $1/(NA)^2$ (it becomes 1/NA if the two telescope axes are orthogonal to each other). We have extrapolated omni-directional resolution of ~1cm for a target located 1km away, using moderate optics (~0.5m primary mirror diameter). Experiments to verify this prediction are currently underway.

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George Barbastathis and Arnab Sinha
MIT Mechanical Engineering
Room 3-461c, 77 Massachusetts Ave
Cambridge, MA 02139
E-mail: {gbarb, arnab}@mit.edu

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Artists work in digital holography

Continued from page 12.

phistication of digital workstations continually increases while costs come down. Hence, holographic technology is no longer solely responsible for its own evolution.

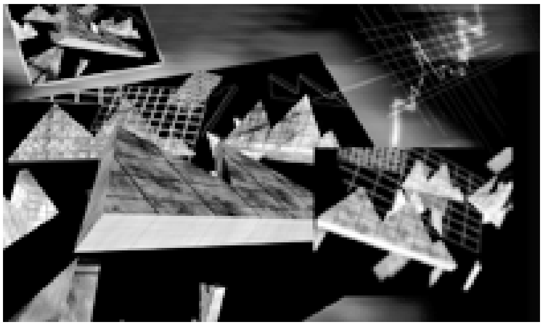

Figure 2. Detail of a still image of the author's work in digital holography entitled "Charts and Graphs".

Work continues to further bridge the gap between conventional image-creation systems and digital holography with the development of plug-ins, filters, and templates for popular animation software as well as medical and scientific dimensional imaging systems including: 3D Studio Max, Softimage, eFILM, Protein Data Bank, Zeiss Confocal Microscopy, and SCM data.

The use of ready-made content has also served to broaden the user base. The human head hologram (Figure 2) shows the soft tissue, skull and brain/cerebral cortex as different 3D views. This model was created in 3D Studio Max as part of a medical-educational video animation. With very little modification it became camera-ready artwork for the light-valve printer.

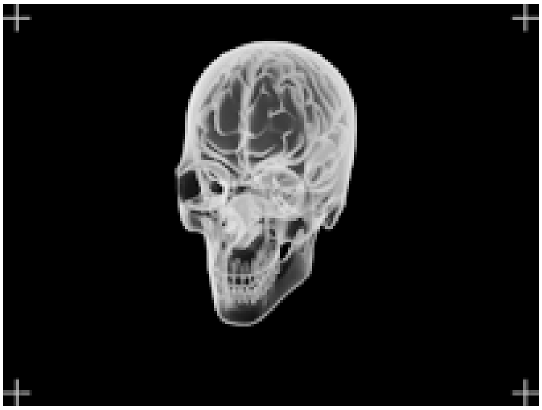

Figure 3. Large-format, light-valve hologram from biomedical animation courtesy of InViVo Communications.

The proliferation of digital photography and the internet have created a new means origination for holographic stereograms. Three images taken from different perspectives and transmitted via the web can than be interpolated into a three-dimensional animation, then printed holographically.

There are currently two projects in the works that involve professional artists in digital holography. The first is the publication of a book of hand-made holograms from the light valve printer. These limited edition hand-sewn books will be exhibited in Toronto in the fall. A second project will put six artists who have never worked in holography together with six skilled holographers to produce a body of large-format work using the light valve printer.

William Molteni presented a paper at Lake Forest in 1985 entitled *Computer-Aided Drawing of Holographic Stereograms.* The fanciful vision of illustrating in 3D may have pointed to a future where artists working in holography are fully empowered and enjoy the freedom of Molteni's expanded palette (see, for example, Figure 3).

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Michael Page
Photonix Imaging
401 Richmond St. W.
Suite B-003
Toronto, Ontario
Canada M5V 3A8
Tel: 416/599-9332
E-mail: michael@photoniximaging.com
http://www.photoniximaging.com

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Non-local material response of photopolymer holographic recording materials

Continued from page 7.

tors and can be used to control polymer chain lengths—have been reported by us.[6] Although much work remains to be done, we believe our results provide the community with an invaluable tool: one which can be used in conjunction with Kogelnik's coupled-wave theory to understand and improve the performance of photopolymer, holographic materials, and the resulting holographic optical components and systems.

John T. Sheridan,* Feidhlim T. O'Neill,* and Justin R. Lawrence†
*Department of Electronic and Electrical Engineering
University College Dublin
National University of Ireland, Dublin
Belfield, D 4, Republic of Ireland (Eire)
E-mail: john.sheridan@ucd.ie
†School of Physics and Astronomy
University of St. Andrews
North Haugh, St. Andrews
Scotland, UK KY16 9SS

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X-ray fluorescence holography

Continued from page 3.

ure 2. The radiation is monochromatized by a double silicon-crystal reflection, and a slit at the entrance of the experimental chamber is used to define the beam. Inside the chamber the sample is mounted on a two-axis diffractometer. The measurement is performed in a spiral motion: the two axes rotate at high speed, the azimuth at 3600˚ per second, while the polar angle rotates at 2˚ per second from 0˚ (perpendicular to the surface) to 80˚. The azimuth stepper-motor pulses are used to synchronize the data acquisition to collect a full pattern of 3.2×10^5 pixels in about 40s. The measurement is repeated until the statistical noise and incident beam fluctuations are reduced to the desired level. The fluorescence radiation emitted by the sample is collected by a four-channel, high-speed, solid-state detector with single-photon-pulse analysis able to achieve up to 4GHz count-rate discrimination of photons of different energies.

Holographic images

Since we use the atoms as point sources or detectors in the hologram formation process, the hologram created shows the local symmetry of their environments. This is illustrated in Figure 3. The pictures show the recorded fluorescence intensities as a function of the direction of the detector or incident beam. The sharp lines are due the periodic arrangement of the atoms: when the radiation emitted by a source atom satisfies the Bragg condition it can be diffracted and produce sharp intensity modulations. Underneath these lines there is the actual hologram: produced by the local environment of the source or detector atoms, and with lower spatial frequency.

Figures 3(a) and 3(b) were taken from samples with four- and five-fold symmetry axes perpendicular to their surface, respectively, from an MnO (100) single crystal measured at the Advanced Light Source in Berkeley, and an AlPdMn quasi-crystal obtained at the European Synchrotron Radiation Facility in Grenoble, France.[9] One can find other off-perpendicular symmetry points on these holograms from which the full local symmetry of the site can be deduced.[7] Of course, what we are finally interested in is the 3D arrangement of atoms in real space. The reconstructed image of the Mn atoms in a MnO crystal can be seen in Figure 4(a) and Figure 4(b) shows the reconstructed average atomic arrangements around the Mn sites obtained from Figure 3(a).

S. Marchesini, L. Zhao, and C. S. Fadley
Materials Sciences Division
Lawrence Berkeley National Laboratory
Berkeley, California, 94720
and Department of Physics
University of California at Davis

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Portable, high-resolution, and user-friendly holographic camera

Continued from cover.

ber has been developed with 80% transmission for an input power of 5W (patent pending): this is suitable for today's commercial solid state lasers, such as Coherent's VERDI.

Another improvement we made was to the reference beam-forming elements. Their size was greatly reduced using a special optical design that includes some exotic optical elements.

The final holographic head is a cylinder of 25cm length by 8cm diameter (weight 1kg) with exactly the same functionality, performance and quality as the previous prototype (see Figure 1). The laser head is included in a mobile rack, which also contains the light injection coupler for the fiber, an acousto-optic modulator for vibration measurement, and all necessary electronics for the instrument control (e.g. piezoelectric translator, shutter, and CCD camera power supplies). For applications involving small objects, small OEM Nd:YAG lasers (a few tens of milliwatts) could be directly attached to the camera itself (no fiber).

This novel system has been applied to various metrology problems.[4] Among these we can cite the measurement of the coefficient of thermal expansion (CTE) of aeronautical elements and structures made of carbon fiber. The object (a hollow rod in Figure 2) for which the CTE is to be measured is placed on on a metallic baseplate. The holographic camera observes the top of the object together with the base. HI measures the difference in displacement between the top and base of the object after a temperature step is applied. In Figure 2(a) an artificial carrier fringe pattern has been applied, but no temperature increase: consequently, no fringe displacement is observed between object and base. In figure 2(b), the same scene is shown, this time with a temperature increase.

This instrument, as well as photorefractive crystals, are now commercially available by the recently formed Optrion company.[5]

Marc P. Georges, Véronique S. Scauflaire, and Philippe C. Lemaire
Centre Spatial de Liège
Avenue du Pré Aily
B-4031 Angleur, Liège
Belgium
Tel: +32 4 367-6668
Fax : +32 4 367-5613
E-mail: mgeorges@ulg.ac.be

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Artists work in digital holography

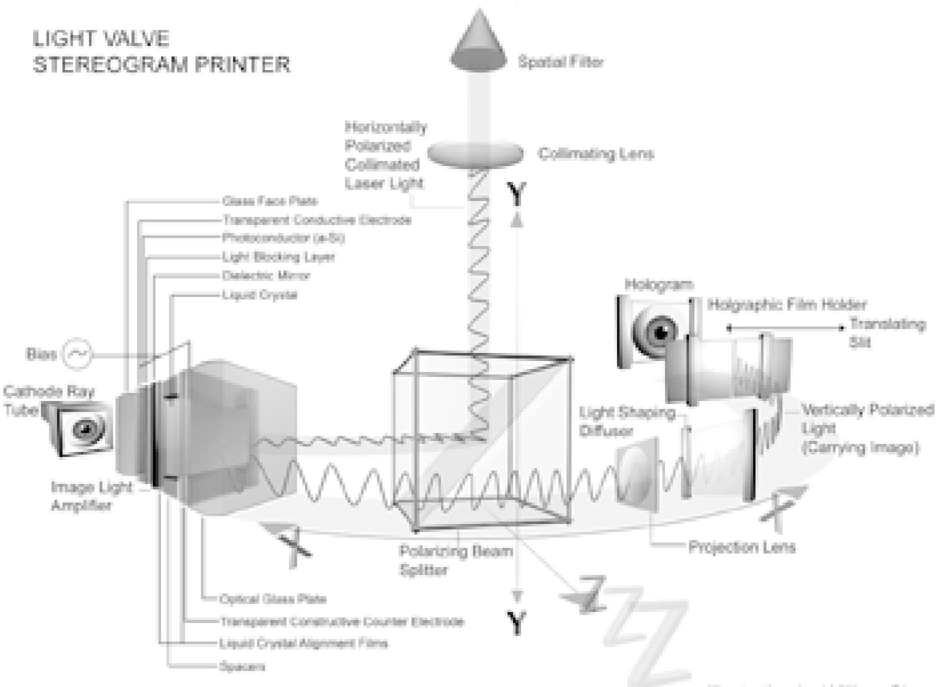

Illustration by William Chang

Figure 1. Light-valve Holographic Printer.

Large format full-colour holography has, for decades, remained the domain of major advertisers and a handful of artists with fully-endowed project funding. In addition, the holographic process has been unforgiving and stifling for many of those who might have wanted to explore creative aspects of the medium. LCD technology has led the way to the production of small computer generated work, however, these systems have lacked resolution and produced the familiar “fish scale” patina noticeable in all LCD displays.

Photonix Imaging is a group comprised of faculty, graduates, scientists and researchers from the Ontario College of Art & Design, the University of Toronto, and Photonics Research Ontario. Over the past two years, we have developed a holographic printer using an SLM (spatial light modulator).

The system uses a light valve or image light amplifier (ILA) originally invented by Dr.William Bleha with the notion of developing it into a holographic movie system. These high-resolution ILAs were first used by the Navy on warships as data projectors to show images of enemy positions. Later they became the foundation of digital cinema.

Students at OCAD now produce large, high-quality images from digital animation, video, photo series, and film using the light valve printer. This direct-from-digital process for printing holographic stereograms provides a fast and inexpensive means for student artists and designers to produce, modify, and re-print images of anything that can be represented in a computer graphic database. The result has been the rebirth of holographic imaging and an expanding user-base of artists, designers and others involved in dimensional imaging.

How the system works

A digital image from a graphics work-station is sent to a high resolution CRT (see Figure 1). The CRT is projected onto the rear of the ILA, a multi-layer device with a central liquid-crystal layer. The image on the rear face of the ILA is picked up by an amorphous-silicon layer after passing through a layer of conductive glass. A bias is applied between the rear conductive glass and a similar layer on the front face of the ILA. The light striking the silicon surface induces photo-conductivity in that layer in proportion to the brightness of the light at that point. The result is that the image displayed then results in the same pattern of voltage across the liquid crystal, and the liquid crystal is aligned to varying degrees corresponding to the image intensity.

The projection of digital graphics, in the form of coherent light, is possible due to the liquid-crystal’s birefringence (its index of refraction is different for light polarized in different directions). Polarized light passing through a birefringent material undergoes a change in polarization. The ILA is then read out by bringing in polarized light from a laser. The light passes through the liquid-crystal layer, reflects off the dielectric mirror, and then has its polarization altered based on the alignment of the liquid crystal (which is determined by the original image on the CRT). Passing the returning beam through a polarizer then produces a beam that is spatially imprinted with the image. A polarizing beam-splitter performs the function of bringing in the initial polarized beam and passing the shifted polarized beam for projection. The light-blocking layer prevents the transmission from the CRT through the ILA.

Applications

Digital convergence has brought a great deal to the holographic process. The same software tools employed in other digital media are exploited by holographers in the creation of digital holograms. My students, at an introductory level, often bring with them a knowledge of digital holography in the form of image-creation tools such as 3D animation software. The power and so-

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