An Updatable Three-Dimensional Display via Direct Optical Fringe Writing of Computer-Generated Holographic Stereograms in Photorefractive Polymer

by Sundeep Jolly

A Proposal Submitted to the Program in Media Arts and Sciences
In Partial Fulfillment of the Requirements for the Degree of
Master of Science in Media Arts and Sciences
at the Massachusetts Institute of Technology

Object-Based Media Group
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Abstract

This thesis aims to assess the feasibility of an updatable three-dimensional display based on the direct fringe writing of computer-generated holographic gratings into a novel photorefractive polymer. The photorefractive polymer in question has many attractive properties for the 3-D display application, including long image persistence, rapid erasure, high diffraction efficiency, and large area; however, current display systems based around its use involve optical interference methods that complicate their optical and computational architectures. A direct fringe writing approach may potentially provide similar display performance with reduced system footprint, complexity, and cost. Candidate methods for direct imaging of holographic fringes into the photorefractive polymer are presented and a system pipeline encompassing fringe computation, optical imaging, and image reconstruction is proposed. A pipeline for optical modeling and simulation is presented as a critical component of system development and characterization.

Contents

1 Introduction & Motivation

Holography is widely used for wavefront storage and reconstruction via optical interference and diffraction in a variety of applications, including optical metrology, imaging, spectroscopy, high-density data storage, and three-dimensional display. Conventional optical recording of holograms is accomplished through the interference of a signal beam with a mutually coherent reference beam on the surface or within the volume of a recording medium; reconstruction of the wavefront of the original signal beam is then accomplished via illumination of the recorded hologram. Typical holographic recording materials include dichromated gelatin, silver halide films, photopolymer, photorefractive crystals, and photorefractive polymer [1–3].

In tandem with the development of optical-based methods for generating holograms, mathematical- and computer-based methods for holographic fringe pattern generation (i.e., as in computer-generated holography) have matured considerably and are now widely used for creating diffractive optical elements and display holograms [1]. Methods for computer-based display hologram generation include physically-based interference modeling algorithms and diffraction-specific approaches, several of which are now mature enough to support small-scale, video-rate hologram generation [4].

In contrast to optical interference-based methods for fabricating holographic gratings, holographic gratings that have been generated synthetically (e.g., on computer) can be directly written into photosensitive media. Electron-beam and micro-optical lithographic techniques are often used for fabrication of holographic optical elements and computer-generated display holograms in massive quantity; however, their use is prohibitive in several applications due to the high cost and specialized equipment involved [5]. Direct optical writing of holographic fringe patterns into photosensitive media has been previously reported in the literature. Sakamoto *et al.* demonstrated direct writing of CGHs onto recordable compact-disc media in a pixel-by-pixel approach [6]. Yoshikawa *et al.* demonstrated direct optical imaging of fringe patterns displayed on spatial light modulators onto holographic film in a spatial multiplexing approach [5, 7].

Recently, researchers at the University of Arizona's College of Optical Sciences and Nitto Denko Technical Corporation reported on the development of a photorefractive polymer for rewritable holographic recording having properties including high diffraction efficiency, long image persistence, fast writing, rapid erasure, and large area – a combination that makes the polymer especially well-suited for application in updatable 3-D holographic displays [8]. The subsequent development of a 3-D holographic display based on this material has allowed images to be written to the polymer and refreshed as desired, up to a rate of $1/2$ Hz in one of the system variants [9, 10]. However, the holographic recording process is based on the conventional holographic stereogram recording technique – optical interference of a signal beam modulated with intermediate ("hogel") representations of 3-D scenes and a reference beam – thereby complicating the computational and optical architectures and limiting the system compactness, flexibility, and extensibility.

2 Problem Statement

Consistent with the ongoing collaboration between MIT and the University of Arizona on holographic display systems, the current research aims to realize a proof-of-concept system for updatable three-dimensional display via the direct fringe writing of computer-generated display holograms into the volume of the aforementioned photorefractive polymer. In contrast to the current interference-based holographic display systems, such a system may potentially simplify computational and optical architectures, reduce total system footprint, correct inconsistent depth cues, and lower cost with minimal adverse impact on overall display performance. Additionally, a direct-write system can afford greater control over the type of holographic fringe pattern recorded in the material relative to the current holographic stereogram recording method, thereby allowing for control over reconstructed wavefront curvature.

However, such a direct-write system presents several challenges:

1. Display holograms with a nominal viewing (i.e., maximally diffracted) angle of $30°$ require an imaged feature size in the fringe pattern roughly on the order of the illumination wavelength (i.e., $\lambda = 450$ nm to $\lambda = 650$ nm). Given that the smallest pixel size in commercially available spatial light modulators (SLM) is close to 10x this feature size (i.e., 5 μm), one-to-one imaging of fringe patterns from such an SLM will not produce a hologram with suitable viewing angle; therefore, an optical system for imaging fringe patterns must be capable of the requisite de-magnification and image-space resolution.

2. Because inducing the space-charge field in photorefractive polymer requires sufficient overlap between the applied electric field and the grating vector, a non-symmetrical slanted writing geometry is needed [11–13]. Therefore, the imaging system must also be able to handle a slanted image plane while minimizing distortions and retaining acceptably sharp focus.

3. De-magnification of a fringe pattern from a typical commercially-available spatial light modulator (e.g., a digital micromirror device with XGA resolution and 15 μm pixel pitch) results in an image with reduced dimension of less than 1 mm. In order to achieve a large holographic image, a scheme for spatially multiplexing all parts of a composite large-resolution fringe pattern must be employed.

4. In order to faithfully reproduce a 3-D scene, the computed fringe pattern should provide smooth motion parallax and acceptably correct occlusion, accomodation, and vergence cues upon reconstruction.

5. Finally, a computational control scheme must be developed to handle all aspects of system operation, including fringe computation, exposure control, and spatial multiplexing (i.e., raster scanning).

This thesis aims at investigating candidate approaches for handling these issues as well as developing a proof-of-concept direct fringe writing display system for comparison to the existing display systems based around this photorefractive polymer.

3 Scope and Research Goals

While the ultimate goal of this endeavor is to realize a direct fringe writing system that meets or exceeds the performance metrics (e.g., fringe pattern feature size, diffraction efficiency, size of 3-D image, writing speed, perceptual quality of 3-D image) of the current interference-based systems while reducing system complexity and cost, managing the project to limit the scope of this thesis involves compromises. The primary, and lowest-level goal of this thesis will be to realize an updatable holographic three-dimensional display based around a direct fringe writing approach for this photorefractive polymer, in a horizontal-parallax only imaging and display scheme and with reasonable image size and viewing angle. While it is anticipated that this viewing angle can exceed $30°$ in both directions (corresponding to an imaged feature size of ≤ 0.5 μm) with a direct-write approach, the minimally expected viewing angle achievable by the completion of this thesis is $15°$ (corresponding to an imaged feature size of roughly 1 μm) in both directions.

As a higher-level objective, the development of a full-parallax imaging and display scheme is described here, although the degree of progress on this objective that can be reasonably achieved within the time frame alloted for this thesis is uncertain.

Modeling and simulation efforts and results will be commensurate with the progress on the development of the display system.

4 Proposed Research

4.1 System Concept

Two variants of the direct fringe writing system are envisioned: one for handing horizontal-parallax only (HPO) holographic imaging, and another for handling full-parallax holographic imaging. The systems will be comprised of a computer for control and fringe computation, the photorefractive polymer, laser light source, a liquid-crystal-on-silicon (LCoS) or digital micromirror device (DMD) spatial light modulator for display of the computed fringe patterns, imaging system optics for transferring the fringe pattern from SLM to photorefractive polymer with de-magnification, a multi-axis precision translation stage for raster scanning of the complete hologram, and voltage source for biasing the photorefractive polymer.

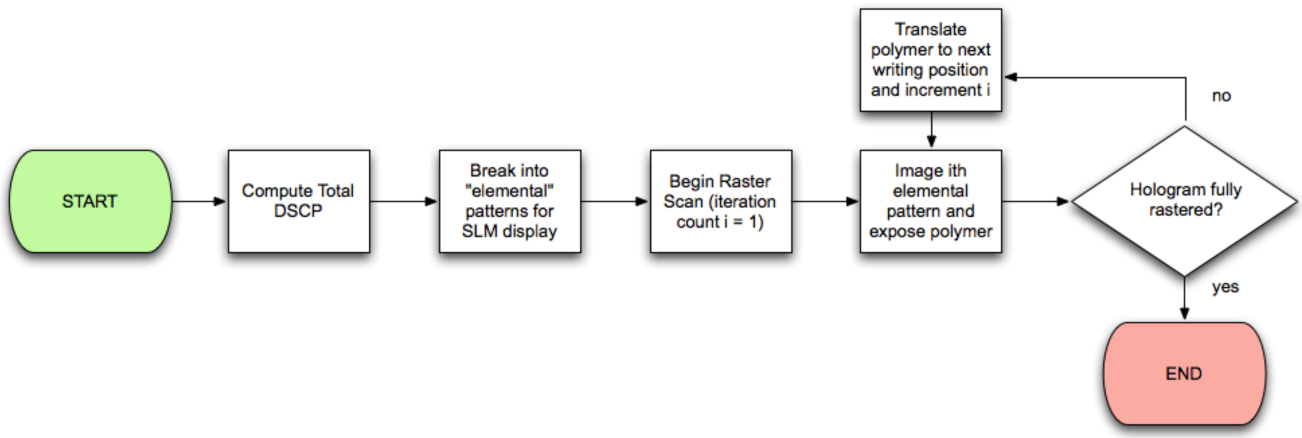

Figure 1: System pipeline for large image writing via spatial multiplexing.

A high-level system pipeline for the three-dimensional display described here is depicted in Fig. 1. In general, a large resolution holographic fringe pattern is fully computed and broken up into several "elemental" fringe patterns (each of which has resolution equal to the chosen SLM's native resolution). The system then enters into a spatial multiplexing loop, in which the photorefractive polymer is exposed with each elemental fringe pattern with appropriate re-positioning (i.e., in a raster scan) of the photorefractive polymer in between exposures until the total composite fringe pattern has been written.

4.1.1 Fringe Computation

Holographic fringe computation will be accomplished via a recent diffraction-specific algorithm for holographic stereogram computation developed at the MIT Media Lab, the diffraction-specific coherent panoramagram (DSCP) [14, 15]. The DSCP is a fast algorithm providing correct wavefront curvature upon reconstruction (and therefore correct visual accommodation cues, unlike most other holographic stereogram algorithms) which has originally been developed for use with the MIT Mark II and Mark III electroholographic video displays. In the DSCP algorithm, depth information from a 3-D scene is used to appropriately compute holographic basis functions (variable rate chirped gratings, in the current HPO implementation). The chirped gratings are then modulated with the scene's intensity information and appropriately tiled to create the complete holographic fringe pattern.

Because the DSCP algorithm is currently adapted for use with the MIT Mark II electroholographic display system in a horizontal-parallax only configuration, the software will be modified for output to a general-purpose SLM.

Furthermore, and for the full-parallax variant of the system, the DSCP algorithm will be modified and extended to handle the case of generating full-parallax holographic stereograms. In this case, the holographic basis functions become variable-rate 2-D Fresnel zone plate basis functions rather than variable-rate 1-D chirped gratings. As in the 1-D case, the chirp rate of the Fresnel zone plate basis functions will be computed from scene depth information, the zone plates will be modulated with the intensity information of the scene, and the zone plates will be appropriately tiled to construct the entire holographic grating.

4.1.2 Imaging System Design & Optical Setup

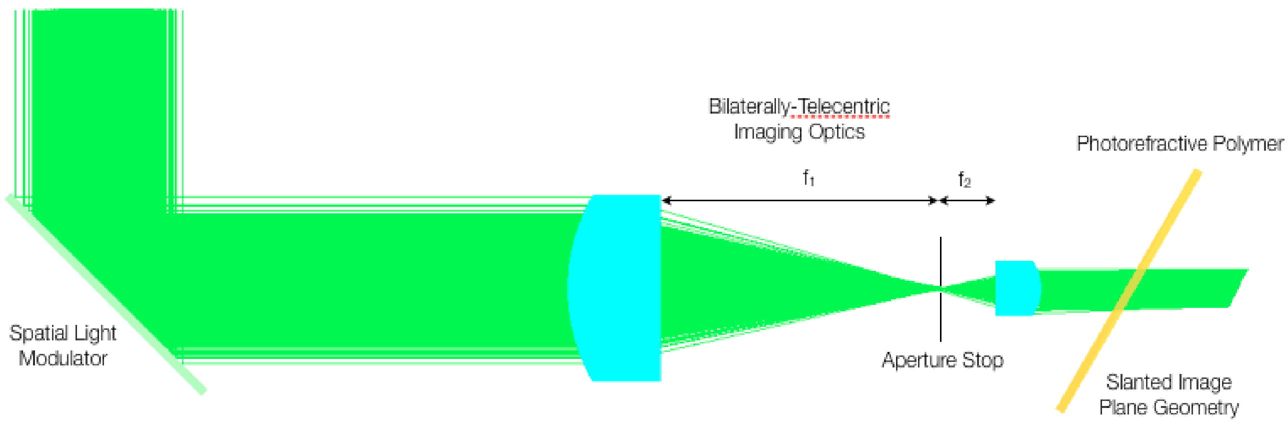

Figure 2: Candidate bilaterally-telecentric horizontal parallax only fringe imaging system, consisting of a spatial light modulator, telescopic pair of cylindrical lenses, and slanted photorefractive polymer.

Two variants of the fringe writing system are envisioned: one for horizontal-parallax only imaging, and a second for full-parallax imaging. In both cases, the imaging setups will be likely be based on bilaterally-telecentric imaging optics. A depiction of a candidate bilaterally-telecentric imaging system is depicted in Fig. 2. In such a setup, the amplitude-only SLM displaying the fringe pattern to be imaged is illuminated with collimated, monochromatic laser light (from a DPSS laser at $\lambda = 532$ nm, with output power to be determined). The SLM is then imaged through the telescoping optics, with de-magnification (equivalent to the ratio of focal length of the second lens to that of the first lens, i.e., $M = f_2/f_1$) occurring in the horizontal direction for the HPO variant and in both the horizontal and vertical directions for the full-parallax variant. The HPO variant uses cylindrical optics whereas the full-parallax variant uses spherical optics. Regardless of the variant, the telecentric imaging system provides an image with propagation-invariant field size after exit from the system.

In order to achieve a high viewing angle with the imaged hologram, a feature size of $\leq 1\ \mu$m is desirable; therefore, the imaging system must be capable of resolving such fine features with sufficient contrast. The characterization of the image-space resolution (i.e., contrast) as a function of spatial frequency is described by the modulation transfer function (MTF) [16]. An MTF curve obtained for a representative bilaterally-telecentric imaging system is depicted in Fig. 3.

For imaged feature sizes of $1\ \mu$m and less, the MTF values at the corresponding spatial frequencies of 500 line pairs per mm (lp/mm) and greater are of interest. Although an ideal imaging system will properly transfer all spatial frequencies with 100% contrast in a broadband frequency response, real imaging systems act as low-pass filters and cannot resolve all spatial frequencies with perfect contrast. For the current application, it is desirable to have an

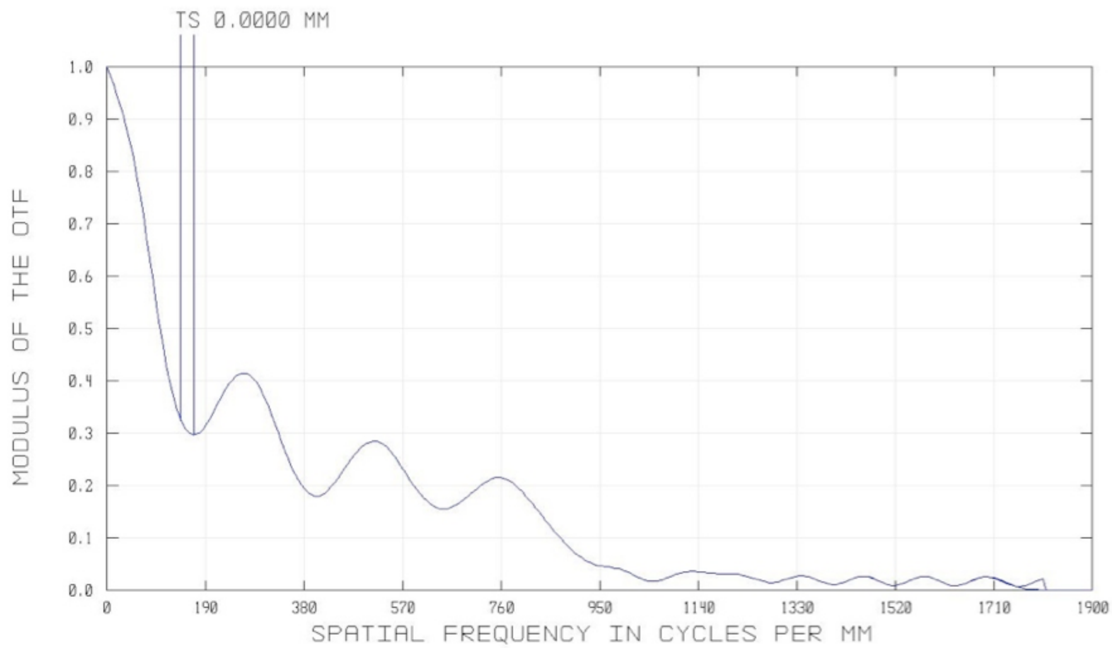

Figure 3: Typical modulation transfer function response for a bilaterally telecentric imaging system providing 6x de-magnification from an SLM.

MTF response of at least 20% at the spatial frequencies corresponding to the desired feature sizes in the imaged fringe pattern in order to preserve a suitable diffraction efficiency for viewing (note that this value is based upon preliminary results and is subject to change with further modeling and experimentation). In order to improve image space resolution and reduce system aberrations, aspheric/acylinder and multi-element spherical and cylindrical lenses may be employed.

In addition to the requirements imposed on imaged feature size and contrast, the photorefractive polymer requires a non-symmetrical writing geometry and therefore the image plane in the imaging system is slanted. The Scheimpflug imaging condition, commonly employed in view cameras and tilt-shift photography, states that planes at oblique angles to the lens plane can be imaged in focus at a slanted image plane, with the obliquity determined by the point at which the three planes intersect [17]. For the purposes of the fringe writing system, the object (i.e., SLM) plane will be tilted appropriately to meet the Scheimpflug condition for the slanted image (i.e., photorefractive polymer) plane.

4.1.3 Image Reconstruction

Reconstructing images from the recorded fringe patterns involves illumination with monochromatic (and not necessarily coherent) light at wavelength and angle necessary for satisfying the Bragg condition for the recorded grating within the material. Initially, reconstruction will be attempted with both incoherent LED sources and coherent laser sources at the recording wavelength before any particular source is deemed ideal.

4.1.4 Top-Level System Control

Top-level system control will be implemented using LabVIEW with interfaces for control of the system laser, SLM display, translation stage, and photorefractive polymer bias voltage generator. Appropriate interfaces for routing the output of the DSCP generator to the LabVIEW environment will be developed.

4.2 Optical Modeling & Characterization

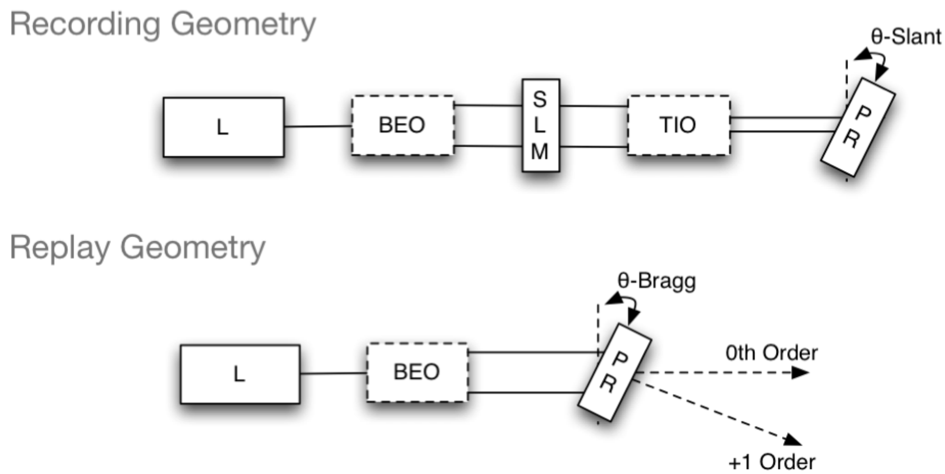

Figure 4: Generalized system block diagram for optical modeling and characterization. "L" is a monochromatic laser light source, "BEO" is a system for beam-expanding optics, "SLM" is the spatial light modulator (shown here as a transmissive mode SLM), "TIO" is a system for telecentric imaging optics, and "PR" is the photorefractive polymer.

End-to-end optical modeling and simulation is necessary to identify factors comprimising system performance as well as to aid in characterizing overall system performance. For purposes of modeling and simulation, the recording process will be considered separately from the readout process. In Fig. 4, the optical modeling is broken up into sections. Optical modeling will be carried out using MATLAB and ZEMAX optical design software.

4.2.1 Imaging System Characterization

Characterization of the imaging system involves analysis of the quality of image transfer from SLM to photorefractive polymer. ZEMAX optical design software will be used for optical design and simulation, specifically in characterization of the system's point spread function (PSF), describing the image of an ideal point source formed by the imaging system, and MTF, described earlier.

4.2.2 Image Formation

To model the exposure of the photorefractive polymer, the electric field distribution at all points within the volume of the photorefractive polymer needs to be known. The illumination of the SLM with collimated, monochromated light will be modeled as amplitude modulation of a coherent electric field representing a monochromatic plane wave as $U_M(x,y) = A_{SLM}(x,y)U_0e^{j2\pi\phi_0/\lambda}$, where $U_M(x,y)$ is the modulated field, $A_{SLM}(x,y)$ is the (binary) SLM modulation pattern, U_0 is the plane wave amplitude, ϕ_0 is random initial phase of the plane wave, and λ is the illumination wavelength. The modulated field $U_M(x,y)$ is then described after propagation to the front lens plane a distance z away from the SLM via the Fourier transform form of the Fresnel diffraction integral,

$$U_{FL}\left(x,y\right) = \frac{e^{jkz}}{j\lambda z} e^{\frac{jk}{2z}\left(x^2+y^2\right)} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} U_M\left(\xi,\eta\right) e^{\frac{jk}{2z}\left(\xi^2+\eta^2\right)} e^{-\frac{j2\pi}{\lambda z}\left(x\xi+y\eta\right)} d\xi d\eta \qquad (1)$$

where $U_{FL}(x, y)$ is the field at the front lens plane, (x, y) are the spatial coordinates at the front lens plane, $k = 2\pi/\lambda$ is the wavenumber, and (ξ, η) are the spatial coordinates at the plane of the SLM [16, 18]. Fresnel transformation is implemented in computer via 2-D fast Fourier transformation.

The field U_{FL} arriving at the front lens plane (i.e., entrance pupil) is transformed by the telecentric imaging system by means of phase transformation, in which the lenses are treated as phase-only transformation elements [16]. The phase transformation transmissive function for a single-element lens is described by $t(x, y) = L(x, y)e^{j2\pi n\Delta(x,y)/\lambda}$, where $L(x, y)$ is the two-dimensional (binary) aperture function for the lens, n is the refractive index, $\Delta(x, y)$ is the two-dimensional thickness function of the lens describing how its thickness varies over spatial coordinates, and λ is the wavelength. Note that this corresponds to a phase delay $\phi(x, y) = 2\pi n\Delta(x, y)/\lambda$ acting upon the incident wavefront. Modeling multi-element lenses (e.g., doublets, triplets) involves taking into account air-gaps in calculation of the overall phase delay (but neglecting diffractive effects in these regions).

To model the effect of the overall imaging system, the field U_{FL} is first multiplied by the phase transformation transmissive function $t_1(x, y)$ representing the first lens, then the new field $U_{FL'}(x, y) = U_{FL}(x, y)t_1(x, y)$ is then described after propagation to the next successive lens element by Fresnel diffraction as above. The next phase transformation transmissive function $t_2(x, y)$ is applied to that field to yield the field U_{BL} at the back lens plane exiting the imaging system.

4.2.3 Photorefractive Polymer Exposure

The field $U_{PR}(x, y, z)$ arriving at all points within the volume of the photopolymer is calculated in discrete "steps" along the propagation direction $\hat{z}$ using Fresnel diffraction for a range of propagation distances $z \in [z_0, z_0 + T]$, where z_0 is the distance from the back plane (exit pupil) of the imaging system to the plane at which the extent of the slanted photorefractive polymer terminates ($\sim z_c - \frac{L}{2}\sin\theta$, where z_c is the z-coordinate of the center of rotation for the photorefractive polymer, L is the width of the polymer, and θ is the rotation angle) and $T \approx L\sin\theta$ (neglecting the thickness of the polymer). Because of the obliquity of the photorefractive polymer relative to the optical axis, appropriate geometrical considerations will be made to determine exactly the portions of the calculated field distribution that are within the volume of the photorefractive polymer.

The incident intensity ($I(x, y, z) = |U_{PR}(x, y, z)|^2$) in the volume of the photorefractive polymer is converted to a phase volume hologram by means of dielectric permittivity (i.e., refractive index) modulation, modeled as $\varepsilon(x, y, z) = (n_0 + \alpha t|U_{PR}(x, y, z)|^2)^2$, where n_0 is the average unmodulated refractive index for the material, α is a constant for the material describing the strength of the photorefractive modulation, and t is exposure time [19–21]. In actuality, the photorefractive modulation is also dependent on the orientation of the polymer (*orientational photorefractivity*) and the applied bias voltage [3]; these factors will be included in the complete model.

4.2.4 Diffracted Image Readout

The diffracted field from the volume hologram readout can be described as a process of scattering of the incident light from a 3-D scattering potential and therefore the analysis can employ scalar scattering theory [20, 22–24]. Assuming monochromatic plane wave incidence upon readout, the scattered field from illumination of the transmission-mode volume hologram is given by the first-order Born approximation as:

$$U_d(\mathbf{r}) = \iiint_V \frac{e^{jk_p|\mathbf{r}-\mathbf{r}'|}}{4\pi|\mathbf{r}-\mathbf{r}'|} U_p(\mathbf{r}') \left[n_0^2 - \varepsilon(\mathbf{r}')\right] d^3\mathbf{r}' \tag{2}$$

where $\mathbf{r}$ is the position vector, $\mathbf{r}'$ is a position vector variable within the region of the photorefractive polymer for integration, $U_p(\mathbf{r})$ is an incident plane wave field, $\mathbf{k_p}$ is the wavevector for the input plane wave, $k_p = 2\pi/\lambda$ is the wavenumber for the input plane wave, $\varepsilon(\mathbf{r}')$ is the complex modulated permittivity within the volume of the photorefractive polymer, and the integral is evaluated over the volume of the photorefractive polymer.

4.2.5 Optimization Studies & Other Inquiries

Additional modeling and simulation will be conducted to further the understanding of the physical processes involved in the direct fringe writing system. These analyses will include characterization of the diffraction efficiency upon readout as a function of fringe visibility (i.e., contrast) and inquiries into the optimality of a volume holographic grating recorded by direct fringe imaging (e.g., as in [25]).

5 Project Schedule

November 2011: complete HPO imaging system optical design, complete adaptation of HPO DSCP software for SLM, begin modeling/simulation for diffracted output
December 2011: complete HPO LabVIEW interface, begin prototyping full HPO fringe imaging system, continue general modeling/simulation
January 2012: continue protyping HPO fringe imaging system, continue general modeling/simulation
February 2012: continue prototyping HPO fringe imaging system, revisit full-parallax optical design, begin adaptation of DSCP algorithm for full-parallax imaging, begin prototyping full-parallax fringe imaging system, continue general modeling/simulation
March 2012: complete full-parallax LabVIEW interface, complete adaptation of DSCP algorithm for full-parallax, continue prototyping full-parallax fringe imaging system, continue general modeling/simulation
April 2012: assess status, document results
May 2012: complete thesis

6 Resources Required

In addition to the resources already available for use (including a DPSS laser at $\lambda = 532$ nm with tunable power, DMD amplitude-only spatial light modulator, and some suitable imaging optics), the construction of an experimental setup for direct writing of holographic gratings may require the purchase of suitable imaging optics, a motorized translation stage for raster scanning, and LabVIEW software for system control.

7 Reader Biographies

George Barbastathis is Professor of Mechanical Engineering at MIT. He received the Diploma in Electrical and Computer Engineering from the National Technical University of Athens in 1993, and the M.Sc. and Ph.D. in Electrical Engineering from Caltech in 1994 and '97, respectively. Between 1997-99 he was a Post-doctoral Research Associate with the Beckman Institute at the University of Illinois, Urbana-Champaign. He has been Visiting Scholar with the School of Engineering and Applied Science at Harvard University (2006-7) and Research Scientist with the Singapore-MIT Alliance for Research and Technology (SMART) Centre in Singapore (2008- 9). His research is centered on the physics and engineering of 3D optical imaging systems based on phase recovery, volume holography and nanostructured gradient effective index optics with applications to optical imaging and metrology for biological, environmental, and energy related applications.

Pierre-Alexandre Blanche received the M.S. and Ph.D. degrees from the University of Liège, Liège, Belgium, in 1995 and 1999, respectively. In 2000, he held a Post-Doctoral position with the University of Arizona, Tucson, on the topic of photorefractive polymers and multiphoton spectroscopy. He then joined the Centre Spatial de Liège to work as a specialist on large-volume phase gratings, holographic optical elements, and spacecraft optical payload testing (2001–2006). He is the cofounder of Athol, a company that manufactures diffractive optical components. Currently, he is an Associate Research Professor with the College of Optical Sciences, University of Arizona. His principal research activities are diffractive optics, holography, photorefractive material and application, nonlinear optics and photovoltaic materials.

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