Direct Optical Fringe Writing of Diffraction Specific Coherent Panoramagrams in Photorefractive Polymer for Updatable Three-Dimensional Holographic Display

Sundeep Jolly and V. Michael Bove, Jr.
MIT Media Lab, Massachusetts Institute of Technology, Cambridge, Massachusetts, United States
E-mail: sjolly@media.mit.edu

Abstract. Progress in the development of an updatable holographic display system based around the direct transfer of computer-generated holographic fringe patterns from LCoS SLMs into photorefractive polymeric materials is presented. This architecture is poised as a simplifying alternative to previous demonstrations of updatable holographic displays in photorefractive polymeric materials based around conventional interference-based holographic stereogram techniques. Our system concept – comprised of fringe pattern generation on computer, fringe pattern transfer from SLM to photorefractive polymer, and spatial multiplexing for large-image generation – reintroduces accommodation cues to the resulting holographic images and represents a reduction of system footprint, complexity, and cost relative to the current interference-based systems. We present the adaptation of our Diffraction Specific Coherent Panoramagram fringe computation method – originally developed to drive AOM-based holographic displays at video rates while preserving all depth cues, including accommodation – to the current display architecture and depict methods for direct fringe transfer from SLM to photorefractive polymer. Preliminary results of horizontal parallax-only images on this display are presented and directions for performance improvements and system extensions are explored.

1. Introduction
1.1. Background
Dynamic three-dimensional holographic displays have a potential wide range of imaging applications in military, medical, and consumer entertainment contexts. Early implementations of dynamic holographic displays have employed various techniques for spatial light modulation driven with computer-generated holograms but are limited in size and resolution.

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 dynamic 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 [1]. 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 [2, 3].

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However, the current 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 – and thereby requires an optical architecture capable of producing such interference and limits flexibility in the type of hologram that can be recorded.

In contrast to optical interference-based methods for fabricating holographic gratings in photosensitive media, holographic gratings that have been generated algorithmically on computer can be directly written into a wide variety of materials. Electron-beam and 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 [4]. Direct optical writing of holographic fringe patterns into photosensitive media has been previously reported in the literature. Direct writing of computer-generated holograms onto recordable compact-disc media in a pixel-by-pixel approach has been demonstrated by Sakamoto et al. [5]. Furthermore, direct optical imaging of computer-generated fringe patterns displayed on spatial light modulators onto holographic film has been demonstrated in a spatial multiplexing approach by Yoshikawa et al. [4, 6].

Computer-based methods for holographic fringe pattern generation have matured considerably and are now widely used for creating display holograms [7]. 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 [8].

1.2. Motivation
Because of the combination of developments in novel photorefractive media for dynamic holography, demonstrated achievements in direct fringe printing for static holography, and fast methods of fringe calculation in computer-generated display holography, investigation into direct optical writing of holographic fringes into the novel photorefractive media is merited.

Direct writing of holographic fringes can potentially provide several benefits to a dynamic photorefractive holographic imager. In contrast to the current interference-based systems, a direct-write system can potentially simplify computational and optical architectures, reduce total system footprint, and lower cost with minimal adverse impact on overall display performance. Additionally, a direct-write system affords 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 and correction for inconsistent depth cues by removing the stereogram limitation.

To this end, the current study is an ongoing assessment of the feasibility and performance of direct fringe writing in the Nitto Denko photorefractive polymer for the dynamic display application.

2. Methods
Our approach to investigating viability of direct writing is depicted in Fig. 1 and involves the computation of fringe patterns, transfer of fringe patterns from spatial light modulator (SLM) to photorefractive polymer via de-magnifying optics, and spatial multiplexing for large-image generation.
2.1. Fringe Computation

The authors’ research group has previously introduced the Diffraction Specific Coherent Panorama-magram (DSCP) – a diffraction-specific approach toward multi-view stereogram generation that provides smooth motion parallax and correct accommodation cues with far fewer views than required with for a normal holographic stereogram. [9, 10]. Fig. 2 depicts the affordances in wavefront curvature allowed in a conventional holographic stereogram (via hogels) and those allowed in a DSCP (via wavefront elements, “wafels”). The wafel’s ability to directly generate arbitrary, positionally-variant wavefront curvature (rather than approximate such curvature through the ensemble of many constant-frequency wavelets) allows for better approximation of ideal wavefronts (and can therefore better provide accommodation cues).

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.

While the DSCP algorithm was originally developed for real-time generation of horizontal-parallax only (HPO) holographic fringes for output to the MIT Mark II and Mark III electro-holographic video displays at high frame rates, its current implementation for this feasibility assessment involves offline (i.e., non real-time) computation of holo-lines from synthetic 3-D models.
Figure 3. Schematic of optical system. \( L \) = continuous-wave laser at \( \lambda = 532 \) nm, \( BEO \) = beam-expanding optics, \( SLM \) = LCoS spatial light modulator, \( L1 \) = first cylindrical lens of telecentric optical system with \( f = 250 \) mm, \( L2 \) = second cylindrical lens of telecentric optical system with \( f = 50 \) mm, \( PR \) = photorefractive polymer (on translation stage for spatial multiplexing).

Figure 4. Schematic of illumination system. \( L \) = continuous-wave laser at \( \lambda = 632.8 \) nm, \( BEO \) = beam-expanding optics, \( PR \) = photorefractive polymer.

Figure 5. Photograph of the direct fringe writing setup.

2.2. High-Level Optical Setup

Direct fringe writing offers a simplified optical architecture in contrast to those necessitated by interference-based holographic recording schemes. The optical architectures used in the current writing scheme are depicted in Fig. 3 - Fig. 5. The writing system is comprised of a solid-state, diode-pumped continuous-wave laser at \( \lambda = 532 \) nm, beam expanding optics, liquid-crystal-
on-silicon (LCoS) spatial light modulator in crossed-polarizer configuration, telecentric optical system for fringe pattern transfer and demagnification, translation stage for spatial multiplexing, and photorefractive polymer. The readout system employs an expanded beam from a continuous-wave laser at $\lambda = 632.8$ nm for illumination.

2.2.1. Spatial Light Modulation

For the current study, we employ liquid crystal-on-silicon (LCoS) SLM panels furnished by Silicon Micro Display. These LCoS panels have 88% fill factor and 8.5 $\mu$m pixel pitch at a resolution of 1920x1080 (see Fig. 6). For amplitude modulation, we employ the LCoS device in a cross-polarizer configuration (depicted in Fig. 7) in which a polarizer is placed before the SLM to generate the proper polarization state (with alignment parallel to the native liquid crystal axis) and an analyzer is placed after the SLM to retrieve the modulated state.

2.2.2. Optical Imaging

Because the 8.5 $\mu$m pixel pitch of the SLM is not sufficiently small for direct viewing of display holograms, an optical system for imaging fringe patterns into photorefractive material is required and must be capable of the requisite demagnification for large viewing angle. Fringe transfer from the SLM is accomplished via a telecentric optical system comprised of cylindrical lens L1 with focal length $f = 250$ mm and cylindrical lens L2 with focal length $f = 50$ mm. Because the lenses are cylindrical, demagnification is only in the horizontal axis and is given by the ratio of focal lengths (5x demagnification for the current configuration). Given the pixel size on the SLM and the nominal demagnification, the nominal pixel size resulting from the telecentric imaging is 1.7 $\mu$m.

2.2.3. Photorefractive Polymer

In photorefractive materials, incident light intensities are converted into refractive index modulation via a process of spatial charge redistribution and trapping. Because of the mechanism required for the phase hologram generation, high operating voltages of several kV are required to bias the material [1, 11, 12]. The current study employs samples with dimensions 2 in. x 2 in.
2.3. Automation and Control
NI LabVIEW 2011 is used for automation and control of SSDP laser, spatial light modulator, translation stage, and DC power supply.

3. Current Results
At the time of this writing, we have built-up a testbed for direct fringe writing experiments with the photorefractive material and have gathered preliminary results.

3.1. Validation Results

Table 1. Writing parameters for HPO teacup stereogram.

| Parameter                                      | Value         |
|------------------------------------------------|---------------|
| PR Polymer Bias Voltage                        | 5.0 kV        |
| Overall Fringe Pattern Resolution              | 48000 x 1080  |
| Exposure Time per Elemental                    | 10 s          |
| Maximum Irradiance per Elemental               | 1.25 W/cm²    |
| Total Writing Time                             | 300 s         |
| Estimated Persistence per Elemental            | 300 s         |

Figure 8. Teacup model used for RIP stereogram fringe generation.

Figure 9. Resulting holographic image of teacup model.

Initial validation tests of the system were carried out using pre-computed fringes generated using an earlier diffraction specific stereogram algorithm – the Reconfigurable Image Projection (RIP) approach [13]. Fringes were computed using a model of a teacup (depicted in Fig. 8). Writing parameters and persistence observations are depicted in Table 1. The resulting holographic image in the PR material due to the direct fringe writing of these computed fringes is shown in Fig. 9.

3.2. HPO DSCP Results
Tests of the system with the DSCP algorithm were carried out using computed fringes from the Stanford Bunny model (depicted in Fig. 10). Writing parameters and persistence observations are depicted in Table 2. The resulting holographic image in the PR material due to the direct fringe writing of these computed fringes is shown in Fig. 11.
Table 2. Writing parameters for HPO Stanford Bunny Diffraction Specific Coherent Panoramagram.

| Parameter                                | Value          |
|------------------------------------------|----------------|
| PR Polymer Bias Voltage                  | 5.0 kV         |
| Overall Fringe Pattern Resolution        | 51840 x 1080   |
| Exposure Time per Elemental              | 10 s           |
| Maximum Irradiance per Elemental         | 1.25 W/cm²     |
| Total Writing Time                       | 350 s          |
| Estimated Persistence per Elemental      | 300 s          |

Figure 10. Stanford Bunny model used for DSCP fringe generation.

Figure 11. Resulting holographic image of Stanford Bunny model.

3.3. Observations
While the current results do indicate that holographic images can be formed via single-beam direct fringe writing as well as via optical interference, there remains much room for improvement of the display quality. At the present time, diffraction efficiency of the resulting images is poor and the images suffer from low contrast, low discriminability, and low persistence – all of which pose problems for direct viewing.

4. Future Work
4.1. Improvement of Image Quality
In order to make direct writing more practicable as a replacement for interference-based recording schemes, future work needs to address several performance issues.

4.1.1. Diffraction Efficiency
Diffraction efficiency is linked to a number of factors, including fringe visibility (i.e., modulation efficiency in the resulting refractive index distribution from recording), exposing parameters (i.e., incident irradiance and exposure time), and applied electric field strength. Improvements are likely with characterization and refinement of the imaging system MTF (up to the maximal spatial frequency indicated by its demagnification), further optimization of exposing parameters, and further characterization and optimization of the effect of the applied bias voltage.

4.1.2. Image Persistence
Image persistence is largely a function of applied electric field strength but has also been observed
to vary based on the particular sample of photorefractive material being used. Improvements are expected with the use of newer samples with longer grating holding times and optimization of the applied bias voltage.

4.1.3. Image Discriminability
Image discriminability is largely related to both diffraction efficiency and image persistence and improvements in these two areas will likely yield improvements in discriminability as well.

4.2. Extensions

![Diagram of the Microsoft Kinect pipeline](image)

Figure 12. Pipeline for real-time generation of DSCP fringe patterns using the Microsoft Kinect peripheral.

It should be noted that while the current implementation of the DSCP fringe computation algorithm only produces “pre-rendered” fringes for recording at a later time, the algorithm can easily be integrated into the control system for real-time computation (with the caveat that such real-time computation will only be beneficial in the case of a fast writing scheme to take advantage of the fast computation). Furthermore, the authors’ research group has previously demonstrated generation of DSCP fringe patterns of real scenes in real-time using consumer rangefinding cameras (Fig. 12 depicts this process). This capability can be exploited in a future holographic telepresence scheme using a direct fringe writing approach.

Direct fringe imaging for full-parallax images is a plausible extension but will require the adaptation of the DSCP algorithm, telecentric optical imaging using standard spherical optics, and spatial multiplexing in two dimensions. Alternatively, massively parallel direct writing schemes can be employed in which several areas of the overall multiplexed hologram are written simultaneously.

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