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Optics for full-parallax holographic stereograms

Michael A. Klug, Arno Klein*, Wendy Plesniak, Adam Kropp and Benjie Chen

MIT Media Laboratory, 20 Ames Street, Cambridge, MA 02139
*Computation and Neural Systems Program, 139-74 Caltech, Pasadena, CA

ABSTRACT

In the evolution of synthetic holography as a viable medium for industrial design and scientific visualization, the inclusion of full parallax represents a logical next step from the previous horizontal parallax-only approaches. The significant increase in full-parallax information content implies the need for high speed perspective view synthesis, optimized mechano-optical recording systems, and novel hologram illumination approaches.

This paper outlines recording techniques for producing full-parallax holographic stereograms of computer-synthesized and acquired data. We document on-the-fly high-speed rendering software that integrates the printing and image-synthesis steps. In the interest of hologram printer size control, approaches for optical image plane enlargement are highlighted, and successful examples of A4-size (30cm x 21 cm) full-parallax images are presented. We assess perspective-view array and image-plane pixel resolutions and their effect on overall image quality, in particular with respect to medium-size formats. Finally, we demonstrate optimized illumination techniques for controlling image clarity, including dispersion-compensated and edge-illuminated approaches.

1. INTRODUCTION

Holographic stereograms are a category of autostereoscopic volumetric hardcopy devices capable of producing unparalleled resolution, viewing angle, and image depth. Their ability to present the viewer with a vast amount of instantly accessible data make them excellent tools to help understand a three-dimensional volume completely and intuitively.

With a few exceptions, research in the development of holographic stereogram recording technologies has concentrated on the subcategory of horizontal parallax-only (HPO) displays. Preceded by Stephen Benton’s invention of the rainbow hologram, in which the vertical parallax information is exchanged for improved image sharpness, and based on the fact that collection and generation of component perspective views is much easier for a one-dimensional camera movement case, much progress has been made in the ability to produce very effective HPO holographic stereograms. Due to the horizontal orientation of the viewer’s eyes, horizontal parallax is adequate for understanding the shape of an object and its position in space for most cases.

In the field of industrial design, a greater understanding of an object’s surface is required in some cases, and the reduction or elimination of distortion artifacts that are inherent in HPO stereograms is desired. There is a need to be able to look over and under design forms, and vertical motion parallax cues are necessary to evaluate surface contours and the motion of specular reflections as well. The most complete vision of the object must be obtained so that the hologram can come as close as possible to simulating the properties of an actual physical model. In short, vertical as well as horizontal parallax should be included in the holographic stereogram in order to obtain the best feedback to understanding surface shape and form.

The main production barriers for practical full-parallax holographic stereograms in the past have included: 1) the amount of rendering time required for production of extremely large perspective image sequences, 2) the amount of memory needed to store those frames, 3) the amount of time needed to holographically record the requisite integral holograms, and 4) the adequate means of displaying the images clearly. The recent advent of very high speed computer graphic rendering hardware has been a major catalyst for practical investigations into full parallax holographic stereogram generation. The ability to produce and manipulate large image sequences in a reasonable time, and the ability to store those sequences on a single disk drive have made these and future investigations into full parallax a practical reality.

2. BACKGROUND

The earliest experiments in full parallax holographic stereograms were conducted by R. V. Pole at IBM in 1966[1]. Pole's original experiments involved the recording of a two-dimensional array of photographs using a fly's eye lenslet array, followed by a volume reflection holographic "transfer" of these perspectives. The processed plate reconstructed each perspective for its individual viewing position in space as a series of virtual images, or, in phase-conjugate illumination, as real images. Pole reported that the resulting holographic stereograms exhibited "full three-dimensionality" like ordinary holograms, but that the large inactive area between the lenslets contributed some image degradation akin to viewing an ordinary hologram through a coarse grid structure. Pole concluded that optimum lenslet sizing would be on par with the diameter of the human eye to best accommodate the sampling and depth of field compromise inherent in the new display.

Subsequent to Pole's pioneering work, holographic stereogram research moved toward horizontal-parallax-only (HPO) approaches, favored for their extreme reduction of information and ease of acquiring or generating perspective images. The demonstration of the ability of Benton's "Rainbow" hologram to convincingly display depth with only a single vertical perspective was contemporaneous with work in what would become known as the "Multiplex™" hologram by Lloyd Cross,[2] and a host of other stereographic techniques that employed cylindrical lenses, track cameras and turntables for image acquisition and recording. DiBitetto's spatially-multiplexed sequential exposure of a masked holographic plate provided an alternative to the white-light resolution limitations of Poles original lenslet array approach.[3] In the DeBitetto experiment, the integral holographic exposures could be spaced with virtually no inactive area between them, and the resolution of each was limited only by the high resolution holographic emulsion. Subsequent work by King, Noll and Berry[4] involved producing a white light-viewable transfer image from a DeBitetto-type master. The sequential exposure of integral holograms required significantly more recording time than Pole's "parallel" technique, and so subsequent elimination of vertical parallax information was incorporated to reduce the number of necessary exposures and to improve white-light viewability. With the advent of computer graphic image synthesis for holographic stereograms, the need to generate only a single horizontal sequence was advantageous, because rendering required costly cycles of computer time. HPO approaches have become the basis for most research and production of holographic stereograms based on the minimal amount of information required for their production and their ability to present clear, sharp images.

In 1988, Honda and Yamaguchi at Tokyo Institute of Technology revisited the full parallax regime with their one-step holographic stereogram experiment.[5] In this system, a two-dimensional perspective sequence array was generated and later image-processed to form a new array of mask frames. These were recorded on video tape and downloaded one-by-one to a liquid-crystal screen in a system that sequentially recorded Fourier Transform volume reflection holograms of each mask in a two-dimensional array on holographic film. The resulting hologram reconstructed an accurate full parallax view of the scene. The process was promising, but the 320-by-240 Fourier transform hologram array required many hours for recording, and the perspective image and Fourier transform mask generation times were also prohibitive for practical application.

In 1991, Halle, *et.al.* outlined a method and demonstrated examples of HPO holographic stereograms with reduced geometrical constraints.[6] The "Ultragram" process enabled arbitrary placement of the master and transfer planes of a two-step system by carefully controlling the component image rendering camera, and post-processing the original views to produce new images to fit the desired recording geometry. Both one- and two-step holographic stereograms were demonstrated using various versions of the Ultragram process, thus demonstrating its versatility and usefulness. Although investigations were limited to the horizontal parallax-only regime, Halle's techniques provided an approach to investigating stereograms that was no longer restricted by strict geometrical constraints.

This paper documents recent investigations into full-parallax holographic stereogram recording approaches. Both standard camera rendering and optical pre-distortion approaches related to the Ultragram work have been adapted to full-parallax. Emphasis has been placed on providing the necessary additional information in the holographic stereogram without unreasonable increases in generation times. Examples of several presentation formats show an productive evolution from horizontal parallax-only approaches to the more complex full-parallax recording systems.

3. RECORDING SYSTEM

Our experiments with full-parallax holographic stereograms were conducted using a variation of the King, Noll and Berry/

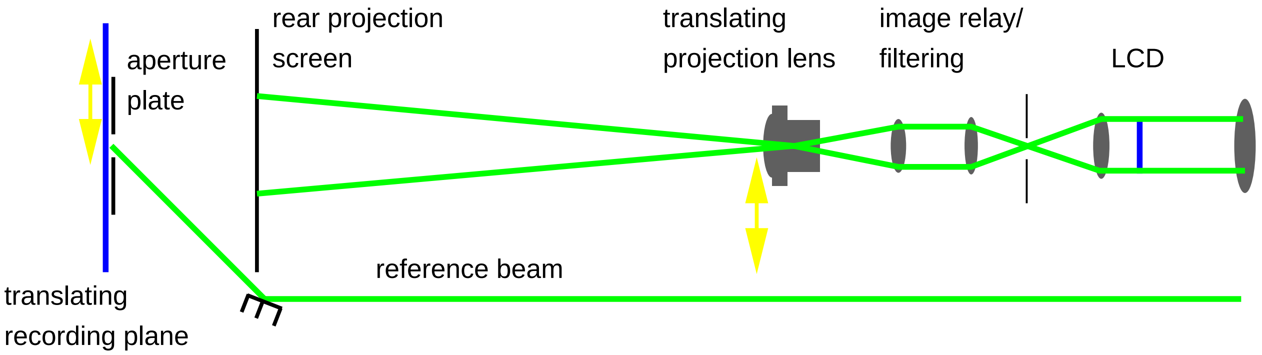

Figure 1: Optical path schematic for full parallax holographic stereogram printer

DeBitetto-style two-step system. The optical system, illustrated in Figure 1, is comprised of an object beam path including a VGA-resolution liquid crystal display (LCD) spatial light modulator, image relay, filtering, and projection optics, and a rear-projection diffusion screen. As in previous horizontal parallax-only systems, the projected image is translated between exposures in compliance with the recentered-shearing rendering geometry of the component perspective images.[11] This configuration maximizes the available resolution of the holographic stereogram, and enables simplification of the reference beam optical system. An aperture placed in intimate contact with the holographic emulsion provides the necessary masking for each integral hologram. The reference beam is introduced from below at the desired angle, usually 45^o. The projection screen is placed 300mm from the hologram recording plane. The holographic plate is mounted on a coupled X-Y translation stage and, like the projection lens, is moved in a plane parallel to the diffusion screen between exposures, in keeping with the recentered-shearing configuration.

The simple DeBitetto-derivative configuration ensures minimization of optical distortions and enables construction of a relatively compact, efficient recording system. A stationary mask aperture implies that a small-diameter reference beam may be used, in contrast with moving mask systems requiring reference beam diameters at least as large as the master plate itself. The distance between the diffusion screen and the recording plane can be changed very easily in this configuration as well, since the reference beam angle remains fixed with respect to the recording aperture. These characteristics have enabled us to maximize the number of experiments we have been able to perform with the same basic system.

4. IMAGE RENDERING

A challenge to producing full parallax stereograms is the need for considerably more rendered perspective views than in the horizontal parallax-only case. A typical two-step HPO image may consist of approximately 100 images, rendered at a resolution of 1000 x 1000 pixels. This image sequence requires 100 megabytes of disk memory if it is generated off-line prior to exposure. The equivalent full-parallax image, consisting of a matrix of 100 vertical views by 100 horizontal, requires approximately 10 *gigabytes* of storage, and proportionally longer rendering time. Early experiments using the present system made use of pre-rendered perspective images sets. These sequences, composed of images of medium complexity and resolution, required an average of 5 minutes rendering time per frame using standard commercial graphics rendering software. Although this software produced very high quality results, the speed made quick turnaround of a given image impractical.

A more recent approach to rendering, documented in detail by Halle and Kropp,[7] involves taking full advantage of state-of-the-art image generation hardware to produce images much more rapidly than more general commercial systems. In addition to incorporating fast rendering hardware, an effort has been made to limit the complexity of the scene and reduce the amount of environmental modeling needed to produce esthetically-acceptable imagery. This includes minimizing the number of light sources in a scene, limiting the number of environment maps, and reducing the polygon count of the model itself. As a result of implementing this strategy, perspective images of reasonable complexity can be generated in less than one second per image, making the goal of high-speed recording of full-parallax holographic stereograms achievable.

As implemented, the full-parallax printer system records component holographic views as they are rendered in “real-time”.

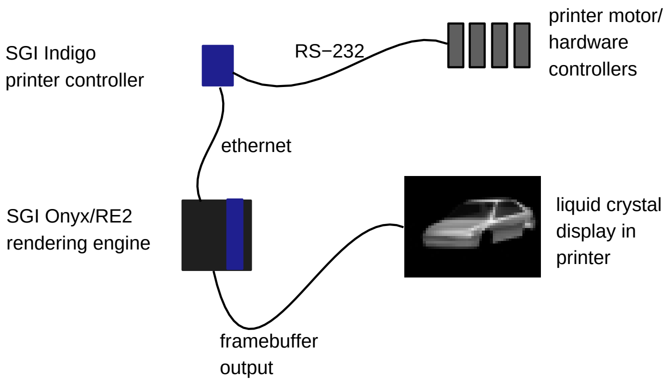

Figure 2: Client-server configuration and control diagram for full parallax holographic stereogram printer.

Figure 2 illustrates the technique in which a client-server protocol is established to retain printer mechanical control by the local hardware, an SGI Indigo, while taking advantage of the faster rendering hardware of a remote render server, an SGI Onyx Reality Engine^2 system. The two machines communicate via ethernet to synchronize the rendering and exposure processes. Simple command-line calls from the local host trigger nearly instantaneous rendering of the images by the render server. The framebuffer of the server directly drives the liquid crystal spatial light modulator located in the printer, eliminating the need for costly network image transfer alternatives.

The ability to quickly render perspective image sequences has three main advantages: 1) a full parallax master can be produced within a few hours, 2) large amounts of disk space are no longer necessary for recording holographic stereograms, and 3) a more direct conduit now exists between the computer graphics model and the hologram, as the rendering time is “abstracted out” in the exposure time. Making use of this basic system, a number of experiments have been conducted to develop useful formats for full-parallax holographic stereograms, and to better study ways to increase printing speed, size, image quality and presentation.

For an initial experiment, a two-step holographic stereogram with image dimensions of 100mm-square was produced using the system. The hologram-projection screen distance was 300mm, and the reference beam was collimated, and intersected the plate at 45^o. The master plate was composed of 6,600 perspective views rendered in “real-time,” and requiring a recording time of approximately 5 hours. A image-plane transfer hologram, made using DuPont HRF 750X-181-20 photopolymer, was used for mass replication with favorable results.

The basic printer was used as a test bed for a number of experiments in scaling and alternative pseudoscopic printing, as well as for stereograms exposed in the above documented “standard mode”. The remainder of this paper documents these experiments and alternative illumination systems.

5. EXPERIMENT: IMAGE SCALING VIA OPTICAL MAGNIFICATION

In order to generate larger scale full-parallax images, an optical magnification technique was implemented. In this case, the goal was 2X magnification of the component perspectives between recording and replay for transfer recording. Magnification would enable the printer, originally designed to produce output at 100 by 150mm on the image plane, to produce 200 x 300mm output, without significant physical scaling of the optical system.

Magnification of the reconstructed real images was accomplished by recording each perspective view with a diverging reference beam. Subsequent replay using a broad collimated illumination beam for full coverage of the master plate produces the requisite magnification of each perspective image. The optical magnification is directly related to the relative object recording and image replay distances by the equation:

$$M_{lat} = m \frac{\lambda_2}{\lambda_1} \frac{d_{\mathrm{img}}}{d_{\mathrm{obj}}}$$

Recording and replay wavelengths were both 514nm. For a replay distance of 300mm, as was desired for this experiment, and a magnification of 2X, between the rear-projection screen and the recording plane is calculated to be 150mm. The relationship between the recording reference beam wavefront and the replay wavefront is given by the standard horizontal focusing equation:

$$\frac{1}{d_{\mathrm{img}}} = m \frac{\lambda_2}{\lambda_1} \left(\frac{1}{d_{\mathrm{obj}}} - \frac{1}{d_{\mathrm{ref}}} \right) + \frac{1}{d_{\mathrm{ill}}}$$

In the collimated, same-wavelength illumination case ($d_{\mathrm{ill}} = \infty,\ \lambda_2 = \lambda_1$), this reduces to

$$\frac{1}{d_{\mathrm{img}}} = \frac{1}{d_{\mathrm{ref}}} - \frac{1}{d_{\mathrm{obj}}}$$

for the real image case, ($m = -1$). Finally, d_{ref} can be found to be 300mm by simple substitution of the known values for d_{img} and d_{obj} .

In the vertical direction, the recording and replay distances are governed by the vertical focusing equation:

$$\frac{\cos^2\theta_{\mathrm{img}}}{d_{\mathrm{img\text{-}v}}} = m \frac{\lambda_2}{\lambda_1} \left(\frac{\cos^2\theta_{\mathrm{obj}}}{d_{\mathrm{obj\text{-}v}}} - \frac{\cos^2\theta_{\mathrm{ref}}}{d_{\mathrm{ref\text{-}v}}} \right) + \frac{\cos^2\theta_{\mathrm{ill}}}{d_{\mathrm{ill\text{-}v}}}$$

For these experiments, $d_{\mathrm{ref\text{-}v}}$ was calculated to be 113.7mm for 2X image magnification in replay with collimated illumination. The resulting astigmatic reference beam was realized using two cylindrical lenses inserted into the reference beam, as diagrammed in Figure 3. The recording plate was composed of 133 columns by 100 rows of integral holographic exposures, 13,300 in all. Master hologram generation time, including rendering and exposing, was approximately 7 hours.

The transfer hologram was made by illuminating the master with a large diameter collimated beam in phase-conjugate mode. The resultant image replayed with the desired 2X magnification, at the designed 300mm distance. Off-axis volumetric transfer holograms were recorded on both Agfa Millimask silver-halide plates, and on DuPont HRF 700X-071-20 and HRF 750X-232-20, with good results. Figure 4 shows a photograph of an automobile CAD design display as recorded and transferred using the magnification approach.

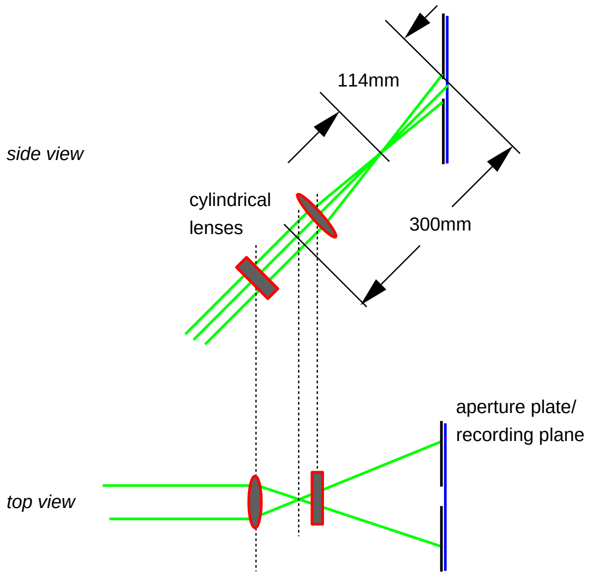

Figure 3: Astigmatic reference beam used to produce 2X magnification of the real image.

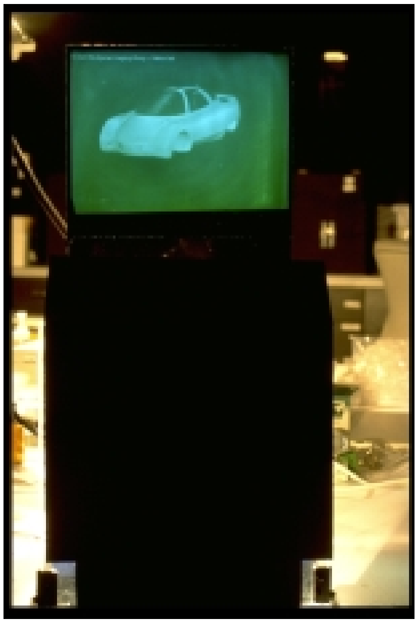

Figure 4: Full parallax image plane holographic stereogram transfer made using the 2X optical magnification. Image size is A4 standard (297mm x 210) and is displayed in a dispersion compensation viewstation.

6. EXPERIMENT: PSEUDOSCOPIC MASTERING

The image rendering software used for these experiments has the capability of rendering image sequences that can produce an orthoscopic real image when illuminated by the reference beam phase-conjugate[7]. Figure 5 illustrates the concept of this "pseudoscopic mastering" process. A transfer hologram made from a master recorded in this manner could be illuminated with light from the same direction and with exactly the same divergence as the reference beam used to make that hologram. Such replay eliminates distortions caused by incorrect illumination, since the transfer system can be customized to exactly fit the final illumination geometry. Examples of similar configurations recorded in the horizontal parallax-only "Ultragram" system have been successfully demonstrated previously.[6]

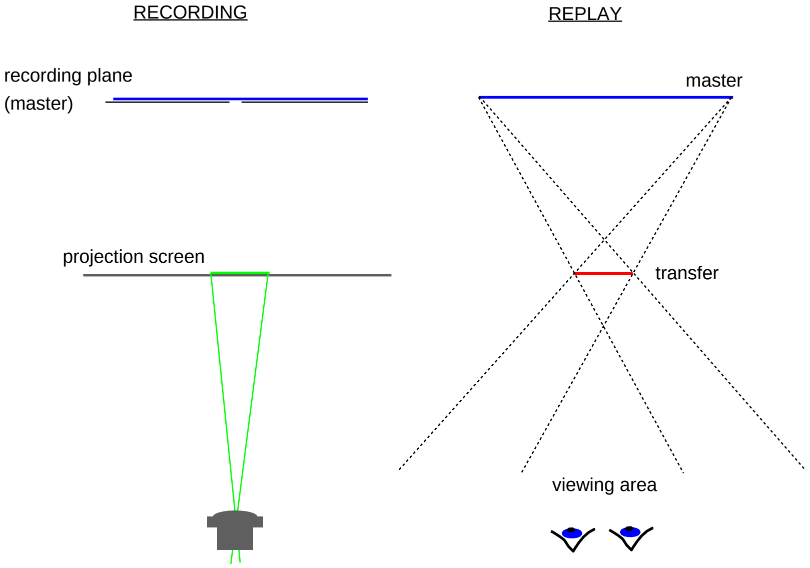

Figure 5: Recording and viewing orientations for display of pseudoscopically-recorded master plate.

An exemplary configuration for which pseudoscopic mastering is optimal is in master recording for edge-illuminated transfer holograms. One version of the edge-illuminated or "edge-lit" hologram, documented more fully by Farmer,[8] is recorded by first attaching the holographic film to a thick glass plinth using an index-matching fluid or, in the case of DuPont photopolymer, using the film's own adhesion qualities. The reference beam is introduced into the system through the orthogonal edge of the plinth at a very steep internal angle, usually less than 15 degrees. In order to simplify the recording and replay of edge-illuminated holograms, and to keep the illumination system compact, it is optimal to use a simple diverging point source for the reference and replay beams. A master that reconstructs a real, orthoscopic image with phase-conjugate illumination is necessary for this type of edge-illuminated hologram transfer recording.

Examples of horizontal parallax-only pseudoscopically-mastered edge-illuminated transfers have been demonstrated previously.[8] In that case, the master was recorded after the perspective images were generated and image-processed to produce an orthoscopic real image. Utilizing the new Halle/Kropp renderer, we have the capability of generating the pseudoscopic component images directly and in "real time", eliminating the need for costly postprocessing steps.

The optical configuration for recording the pseudoscopic master is nearly identical to that used for standard formats. The rendering software was initiated with a special flag to produce the proper pseudoscopic component images. The images were sequentially projected onto the rear-projection screen placed 300mm from the hologram plane, and 15,000 integral holograms, each 3 x 3 mm square, were recorded in a step-and-repeat fashion on a holographic plate with dimensions of 450mm by 300mm. The master recording time was approximately 7.5 hours. Conjugate illumination of the master produced an orthoscopic real image. An edge-illuminated hologram was made with the image shearing plane placed at the transfer film

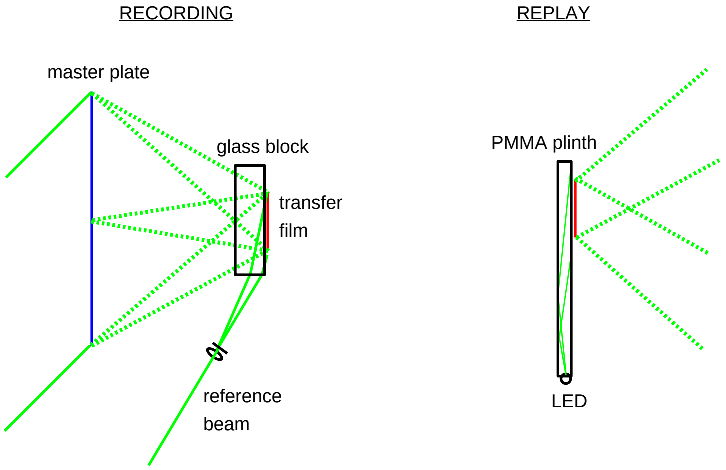

Figure 6: Recording and replay of edge-illuminated full-parallax holographic stereogram recorded using the pseudoscopic mastering technique.

plane, and with a diverging point source introduced from the image bottom, as diagrammed in Figure 6. The hologram was recorded using DuPont HRF 700X-071-15 photopolymer with an exposure time of approximately 20 seconds. After processing, the hologram was fixed to a 1/2 inch thick clear acrylic plinth and illuminated using a single light-emitting diode with a center wavelength of 520nm. A bright, undistorted image is produced, with a viewing angles of 50 degrees horizontally by 30 degrees vertically.

7. HOLOGRAM PRESENTATION ISSUES

Full-parallax holograms often lack the ability to reconstruct sharp image details in the vertical direction (image components with strong horizontal components) in white light illumination. A major artifact seen is blur caused by chromatic dispersion, which has more magnitude in the vertical direction due to the higher spatial frequencies and the off-axis nature of the reference beam in that direction. Work-arounds for this problem include elimination of vertical parallax altogether, as in the case of the rainbow hologram, or recording of a volume hologram that narrows the bandwidth of the illumination light sufficiently as to retain adequate sharpness of horizontally-oriented details, as in the Denisyuk hologram. In the case of data visualization using holograms, however, the user must be able to interact with the entire image volume without blocking the illumination. Standard off-axis volumetric reflection holograms inadequately address this issue since they are usually made with the image volume entirely behind or bisecting the holographic plate, and they are illuminated from above and in front, making it nearly impossible to avoid blocking the illumination while probing the image volume with an opaque stylus or finger. Two solutions are presented here to address these problems: narrow-band edge-illumination, and dispersion-compensated illumination.

Some components of a two-step edge-illuminated full-parallax holographic stereogram have already been described here. This hologram configuration, diagrammed in Figure 7, was used as subject matter for palpability experiments by Plesniak.[9] Plesniak's experiments required a compact image presentation system in which the illumination beam could not be blocked in any way by a force-feedback probe used to “feel” the holographic image. The edge-illuminated format produced with a pseudoscopically-rendered master image provided a favorable solution. The hologram was mounted onto a 1/2 inch-thick acrylic plinth and was illuminated by a single LED. Although edge-illuminated holograms are made with a high angle between the reference and object beams, they still retain some significant chromatic dispersion characteristics. Consequently, best illumination results were achieved by narrowing the bandwidth of the illumination LED using an interference filter or forgoing LED illumination altogether in favor of laser illumination. Laser illumination and filtered LED illumination provided adequate sharpness in the palpable edge-illuminated hologram image, while removing the illumination beam from the image space in a compact configuration. For laser illumination, frequency-doubled Nd:YAG with wavelength of 532nm was used, due to this

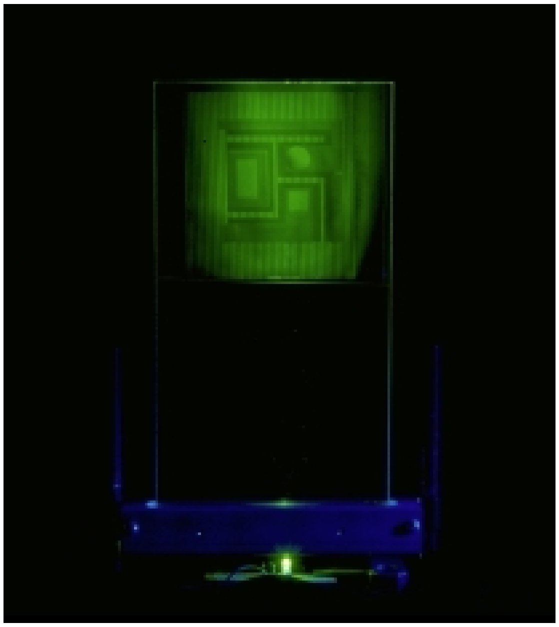

Figure 7: Edge-illuminated full-parallax holographic stereogram.

laser's small size and high efficiency. The beam was rapidly diverged using a ball lens placed at the bottom of the acrylic plinth. Undesirable laser speckle was reduced by placing an active random phase modulator in the beam prior to the lens. The hologram produced adequate brightness and sharpness throughout the entire image volume, enhancing the perceived realism of the image.

The presentation of large scale full parallax images presents a significant challenge, since the amount of blurring due to chromatic dispersion scales for proportionally deep image points. Also, in order to avoid distortion, the illumination source must produce approximately the same wavefront as the reference beam used to record the transfer image. In order to solve both problems simultaneously, we produced a holographic optical element to collimate a diverging white-light illumination source, and filter and reverse-disperse the illumination spectrum in order to produce a sharp image.

Dispersion compensation has been investigated by a number of researchers. In the approach used here, detailed by Klein,[10] a volume reflection hologram was recorded with the same average spatial frequency as the holographic stereogram. DuPont HRF 750X-232-20 was used, primarily due to its high efficiency and relatively narrow bandwidth. The HOE was recorded with a diverging beam at 0^o inclination and 300mm distance, and a collimated beam at 45^o inclination with respect to the plate normal. After processing, the HOE was illuminated with a diverging white light source placed 300mm away at 0^o inclination. A collimated beam was reconstructed, and the HOE exhibited nearly 100% efficiency at the peak wavelength of 512nm. Figure 8 illustrates the replay configuration for this display as incorporated into a compact "viewstation". The reconstructed beam was directed toward a bottom-lit full-parallax holographic stereogram that was precisely positioned with respect to the illuminating grating. Chromatic dispersion blurring for rays emanating at 0^o from all points on the stereogram plate is theoretically eliminated due to the perfect reverse dispersion occurring at those points. For off-axis points some reverse dispersion occurs, although the approximation deteriorates as the rays continue to deviate from on-axis. Klein has explicitly documented the nature of the approximation and its effect on the image sharpness for all points[10]. The resultant image exhibits a high degree of sharpness, especially when the white point source illuminator diameter is minimized, as with a arc-fed fiber system. This has enabled us to produce extremely deep images that are resolvable when viewed in this dispersion compensation viewstation.

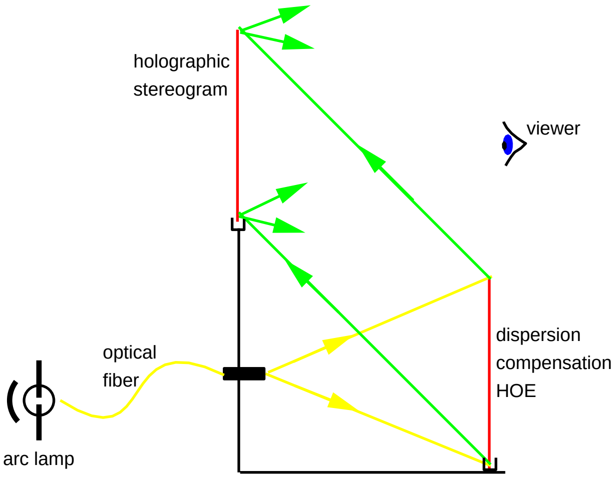

Figure 8: Configuration of a dispersion compensation viewstation for full parallax holographic stereograms

8. CONCLUSION

The advent of faster computer graphics hardware, and the development of high-speed, high quality image rendering software has made it possible to produce practical, scalable full-parallax holographic stereograms. The resulting images are significantly more realistic and solid than their horizontal parallax--only counterparts, exhibiting less distortion and much more information than their HPO predecessors. The application of special image rendering techniques and optical magnification approaches has helped to demonstrate the feasibility of clear image presentation in the full-parallax regime. Adaptation of integrated viewstations has increased the image clarity and the usable image volume. Future work will concentrate on increasing resolution and image contrast, increasing the image size, and improving integrated illumination systems. Initial feedback from industrial designers has been very favorable, and we are encouraged that full-parallax holographic stereograms present interesting new opportunities to the field of display holography.

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