Scalable Digital Holographic Displays

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Abstract

Zebra Imaging has recently developed and refined a new family of practical volumetric hardcopy displays, characterized by the company's Mosaic™ and Reflections™product lines. The development of this technology has led to the creation of the world's largest billboard-scale holographic images. This paper outlines some of the techniques used to create these digital, full-color, full-parallax holographic displays with scaleable resolution and size. Systems for tiling unit holograms together to form larger monolithic structures are presented. Issues associated with the optimal lighting and display of these holograms are discussed, as is the need for these displays to conform to predecessor graphic standards of color calibration, consistency, environmental stability and general quality. Unique capabilities of the displays, including presentation of limited angularly-multiplexed animation, are presented in comparison to other display media. The use of these holograms in a variety of display and light re-directing applications, including volumetric, spatial, and formal visualization, advertising and commercial mass deployment, and unique diffractive optical elements is outlined, and specific examples are described and demonstrated.

Introduction

Holographic stereogram displays have been in the public domain for the past thirty years. The earliest published work, by Pole, in 1967, has been followed on by many refinements and variations over the years, including advancements in recording materials, inclusion of computer graphic data, and manipulation of the size and shape of the hologram to create effective displays.[1] Of particular pertinence was work submitted by Yamaguchi, *et.al.*, in 1990, in which the authors demonstrated monochrome, full-parallax holographic stereograms of computer graphic data.[2]

Over the years, numerous applications for holographic displays have been proposed, promoted, and practiced. One of the more obvious applications has been to the field of advertising, which is constantly calling for new, engaging ways to transmit product information. There has been some success in entering this market, marked mostly by embossed holography and large scale rainbow holograms. Although these displays have advantages: bright, eye-catching images with good depth capabilities, their limitations are also well known, particularly their inability to reproduce true color, limited viewing angles, exhibition of prism-like color shift as the viewer changes vertical position, and cumbersome back-lit illumination requirements. A broader advertising market demands substantial reduction or elimination of these limitations and adoption of current graphic arts standards for color and general quality.

In consideration of alternative applications, the pursuit of holographic display development for the purpose of three-dimensional data visualization has also maintained high priority. Examples of displays and modalities have been demonstrated for many disciplines, including medical imaging, atomic structure visualization, and product design. In the latter, automobile design 3D pre-visualization has proven to retain the most potential for the digital hologram medium, due mainly to the large cost savings potential in that field, as well as the ability of the hologram to satisfy all requisite depth cues for demanding design engineers. In addition, the digital hologram can be composed of graphics generated directly from the CAD databases used to design and build the final automobile, thus eliminating the subjectivity and possibility for errors associated with hand-sculpted clay models. Finally, the holographic images can be easily stored, transported, and displayed unlike most of their physically sculpted counterparts. This is particularly advantageous when today's designs are often completed with input from around the world, and when approval must come from disparately-spaced locations prior to decision-making.

The demands and requirements of the product design and advertising communities have emphasized the need for certain characteristics in the holographic medium. These include full-parallax, scalability and capability to display life-size models in full-color, and with a wide viewing angle. In response to these requirements, a new system and process has been developed to enable automated production of high quality digital holograms directly from CAD data. This methodology has required the integration of unique computer graphic rendering algorithms, the construction of a novel optical printing system, the development of a scalable process for the conversion of the recorded images to workable displays and the acquisition and implementation of a number of lighting solutions. This paper will provide a technical introduction to the system, and address the validity of displays produced with the system in commercial markets.

Rendering

There are a number of variables associated with holographic stereogram image generation. They include camera track size and shape, angular resolution of the image set, and spatial resolution of each component image. These variables can be interchanged depending on the approach used for content generation, and the desired format for the final stereogram.

The most straightforward approach to stereogram image generation, widely used in the past, involves modeling a camera track in front of the scene that mimics the viewer's position when viewing the hologram. The images are generated from discreet positions on that track, usually at a spacing corresponding to an angular density of at least three per degree. In the case of a horizontal parallax-only (HPO) stereogram, the track is usually defined by a horizontal line, and the perspective images are collected or generated with a re-centered shear geometry, as has been documented previously.[3] Generally, for most stereogram techniques, between 100 and 150 images are adequate to meet these specifications, and are easily generated with standard computer graphics rendering packages. The images may be used directly for so-called two-step stereogram recording systems, or may be processed so as to create a set of masks for one-step hogel-based exposure. There are a number of references describing this procedure. Since the Zebra system utilizes a one-step approach, the focus here will be on one-step content creation.

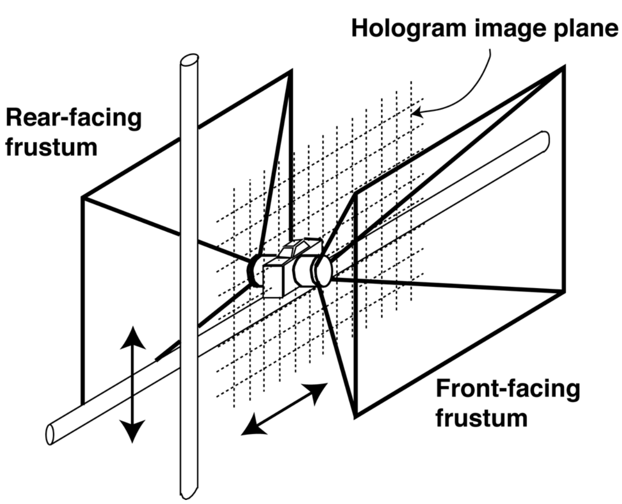

Figure 1. Hologram-centric double-frustum camera

An unconventional "image plane-based" camera may be modeled in order to generate the proper masks needed for one-step recording. In the HPO case, this requires an anamorphic optical system composed of crossed cylindrical lenses that serve to introduce two planes of focus into the recording frustum--one at the viewer's (camera) position, and the other at the hologram position. This has been described in the literature by Teitel.[4] For full-parallax one-step mask generation, using computer-graphic models only, a more conventional, though still unique camera model may be employed. In this case, diagrammed in Figure 1, the plane of camera positions is placed nearly coincident with the eventual holographic plane with respect to the scene. A camera model is adapted that is analogous to a camera with a pair of wide angle lenses, one on each side of the film plane. Image information is collected from the two resulting view frusta and composited to form a single mask image. As documented previously, this so-called "double frustum" approach, is advantageous, in that it makes use of standard computer-graphic camera models with minimal modifications, and thus can be implemented in hardware, increasing the speed of image generation.[5]

Since hologram recording time depends in part on the speed at which hogel-masks are generated, using a high speed approach is advantageous. Another advantage of the double-frustum approach is that only the three-dimensional model need be permanently stored, since the masks are generated in real time as the hologram is recorded. The same model can be used for a variety of different size holograms just by changing the camera specifications prior to recording.

The Zebra rendering system has implemented a highly optimized double-frustum rendering approach. For the standard case, a total of 90,000 masks are generated per hologram, each with a resolution as high as 1280 x 1024 ray directions, resulting in hologram data content of approximately 360 gigabytes. Using a dedicated Silicon Graphics Onyx workstation equipped with an Infinite Reality Engine graphics pipeline, hogel masks can be generated rapidly in hardware using OpenGL library calls. The rendering time for each mask image is approximately one second for moderately-complex scenes. One second timing is used as a delimiter since this approximately matches the maximum hogel print rate for the optical printer's mechanical system. Polygon counts of up to 300,000 can be accommodated at this rate, but rendering time is highly dependent on other scene variables, including environment maps, textures, transparency, and lighting. Generally, a wide variety of scenes can be accommodated with this limitation, and polygon count is often traded off for enhanced environmental mapping, lighting effects, and multi-channel image set generation.

Although the software for mask rendering uses a proprietary three-dimensional data format, conversion from a variety of commercial formats is routinely accomplished. The most direct pipeline is available through 3D Studio Max, the modeling and rendering package with the most commercial seats currently, and broadest application. Successful conversions have also been achieved from Alias Autostudio, Maya, AutoCad and Electric Image, FormZ, Opticore, VRML, and Open Inventor.

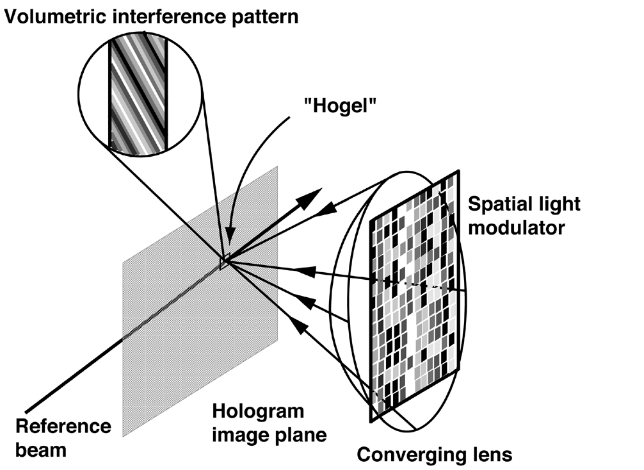

Figure 2. General one-step, full-parallax holographic stereogram recording schematic.

Recording

General one-step, full-parallax optical printer design follows some basic parameters, as noted schematically in Figure 2. The laser beam is split, and one beam is directed through a spatial light modulator and subsequently converged onto the recording medium. A reference beam is directed onto the same spot, but from the opposite side, thus forming a volumetric interference pattern within the bulk of the emulsion. The medium and the spatial light modulator content are indexed, so as to record a sequence of volumetric Fourier-transform holograms in a two dimensional array. Using this fundamental model, we have built an optical printer that is designed to serve the specific markets with perceived demand.

Optical Printer Design

The design visualization and point-of-purchase advertising markets require a number of display characteristics that have significant implications for optical printer design. These include: full color, full-parallax, a wide viewing angle, ease of illumination and display, high brightness, high contrast, and large/scalable size. Variables associated with optical printer design include choice of recording medium, laser sources and optical configuration. Large size images have implications for angular resolution, since we can expect these images to be viewed from a variety of different distances.

Figure 3 schematically illustrates the optical printer mask beam. The system makes use of a SXGA-resolution large-area (approximately 200 x 250mm) RGB liquid crystal display as a spatial light modulator. The LCD is connected directly to the SGI frame buffer to optimize image transfer rates. A transmissive holographic optical element sandwiched in intimate contact with the SLM provides the requisite high numerical aperture convergence of the mask beam and the appropriate hogel shaping at the focus. A third element, an infinite-conjugate doublet, is placed in close proximity to the film in order to provide nearly parallel converging light rays to the recording medium and thus retain nearly constant spatial resolution throughout the usable volume of the display.

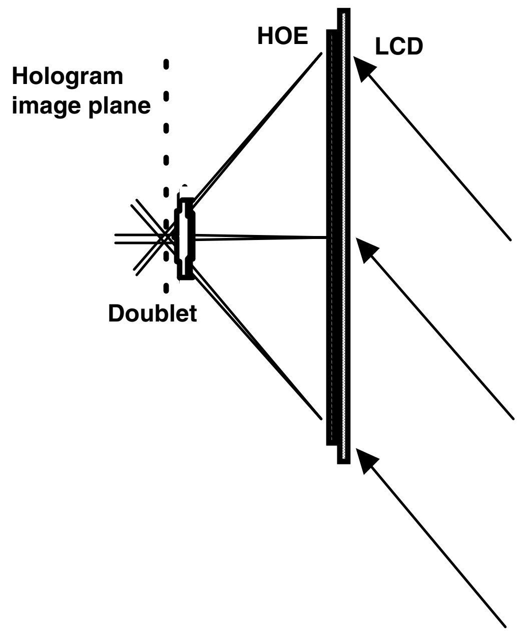

Figure 3. Optical printer mask beam elements.

The reference beam for the first generation system is directed through an optical system designed to enable manipulation of the impingement angle of the beam on the media within a fairly broad range (see Figure 4). Thus, any hogel may be recorded with a different angle compared to its neighbor. This “beam-steering” methodology was adopted in order to enable illumination of the complete matrix of holographic exposures from a single point source at a specific position in space. This is especially necessary in cases where the resultant composite hologram is quite large, and illumination approximating a collimated beam is impossible. Since each hogel is recorded with a collimated “pencil reference beam” the system can be programmed to create a virtual intersection point in space for all of these beams. This also has implications for replaying each hogel’s image with maximum efficiency, because of better Bragg angle matching between recording and replay. An aperture in close proximity to the film plane provides the necessary masking to prevent reference beam exposure into neighboring hogel areas.

The optical printer is designed to record using Dupont OmniDex 801 holographic recording film, due to its availability in large sizes, its near-panchromaticity, low-scatter, high diffraction efficiency and dry processing. The relatively low sensitivity of the Dupont material in comparison to silver-halide emulsions requires significant laser intensity at the plane of exposure, hence the incorporation of large frame Krypton and Argon ion lasers for red and blue sources at 647nm and 476nm, respectively. Both ion laser systems incorporate active feedback mechanisms in order to maintain extremely constant power output over the many hours required for hologram recording. The green beam, at 532nm, is produced by a frequency-doubled Nd:YAG laser that also has good power stability over long time periods. Exposure energies at the film plane with all three beams enable individual hogel exposure times of approximately 150 milliseconds for maximum diffraction efficiency. Total cycle time for each exposure is approximately one second, including exposure, indexing, and settling time, required for vibration elimination.

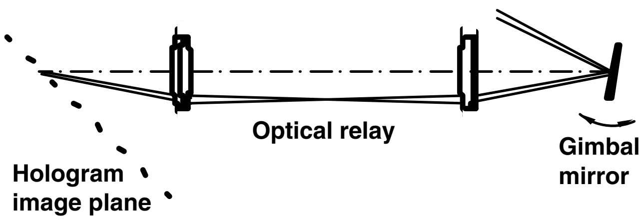

Figure 4. Reference beam-steering configuration.

Hogel size on the printer is variable, ranging from 3 mm to 1mm, depending on the size of the reference beam aperture. Best results are obtained with the smaller aperture, resulting in a higher image-plane resolution of the image. However, larger hogels are advantageous for extremely large images where speed of recording outweighs individual tile resolution. The standard exposure area is approximately 600 x 600 mm, resulting in a matrix of 90,000 hogels (at 2mm). Total recording time for an image of this size is approximately 24 hours. A section of a typical hologram recorded on the system is shown in Figure 5.

Recording Procedure

Recording proceeds as follows: Film is first laminated (through the polymer's natural tackiness) to a glass support plate. The plate is then installed into a frame on the indexer. A computer controls the loading, exposure indexing, and unloading sequences, as well as the generation and downloading of the individual mask frames. Subprograms monitor various feedback systems, including lasers, shutters, and actuator systems in order to maintain consistency and warn operators remotely of any problems. This enables the printer to be in operation 24 hours per day, 7 days per week.

The system is vary reliable, and has run nearly constantly for over 2 years. Periodic maintenance is required for the mechanical and limited-lifetime parts, particularly for shutters and laser tubes. The system operates in a dark room, but computer networks allow constant monitoring and alarm systems warn operators of potential problems.

Figure 5. Hologram recorded on the Zebra optical printer.

Converting

After exposure, the film is processed using DuPont standard techniques, including flood exposure with long-wave ultraviolet light, and heat processing for one hour at 120º C. The film is then laminated to a scratch-resistant transparent PET layer. This composite is then laminated to a rigid substrate, usually acrylic or glass. Good results have been obtained laminating to aluminum honeycomb composite materials, which retain excellent rigidity, but with a significantly reduced thickness to weight ratio as compared to glass or acrylic.

Tiling

Scalability is achieved, despite film width limitations, through tiling 600 x 600 mm unit holograms together. In monolithic holographic exposures, this is usually not feasible due to quasi-Gaussian diffraction efficiency falloff from center to edge of the hologram. Since each hogel exposure made in the Zebra system is indentical with respect to potential efficiency, there is no such falloff in brightness at the edges of each tile. Thus, tiling techniques are naturally adaptable to this process.

Although the uniformity in diffraction efficiency of Zebra holograms is high, the continuity of multi-tile images is affected by the following other factors, including mechanical abutment tolerances, mechanical angular orientation tolerances and tile-to-tile color consistency.

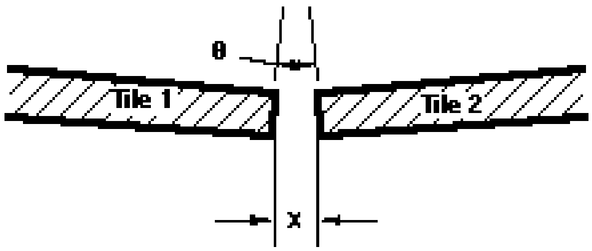

Figure 6. Tile-to-tile abutment and angular relationship.

A mechanical abutment and angular orientation model is presented in Figure 6. Mechanical abutment, or inter-tile spacing (variable x in the figure) has been minimized through careful control of tile substrate and mounting mechanism tolerances. Through mechanical tolerancing, the gap between tiles is kept to 0.5 millimeters or less, which is usually adequate for most images. The tolerance for inter-tile spaces is relaxed depending on the relative size of the final multi-tile hologram, and on the viewer's distance from the hologram.

Mechanical angular orientation (variable θ in Figure 6) from tile to tile can also adversely affect the quality of the full image. It is useful to model the tiles as individual mirrors in order to understand the tolerance requirements for angular orientation. In this model, an object is placed at a distance from the mirrors corresponding to the maximum depth of the final hologram. Virtual images formed in adjacent mirrors of this object must be superimposed to within the angular resolution limit of the eye. For very deep images, even a small θ can quickly exceed the eye's tolerance. The Zebra mounting system was designed to accommodate image depths of up to 2 meters without tile-to-tile blurring of extreme depth image points. This resulted in a tolerance specification for θ of approximately 0.25°. Three adjustable kinematic mounting points make it straightforward to manipulate adjacent tiles to be co-planar within this tolerance (see Figure 7). Zebra's patented system makes use of button snaps mounted on fine threaded inserts in order to facilitate both angular orientation adjustment and ease of multi-tile image assembly.[6]

For images composed of 3 x 3 tiles (1.8 meters square) or smaller, a less adjustable, but lighter and less complicated mounting system has been adapted. This system incorporates preparation of an aluminum-honeycomb backplane, that retains flatness and stiffness specifications well within the tolerances required. Tile component holograms are laminated to 0.0625" thick acrylic panels, which are carefully trimmed so as to fit tightly together. The thin acrylic retains adequate flexibility to enable lamination, in turn, to the rigid backplane, using re-positionable adhesive to allow for minimizing inter-tile distance prior to permanent attachment. This method has proven to be reliable and adequate for all but the largest images produced by the system.

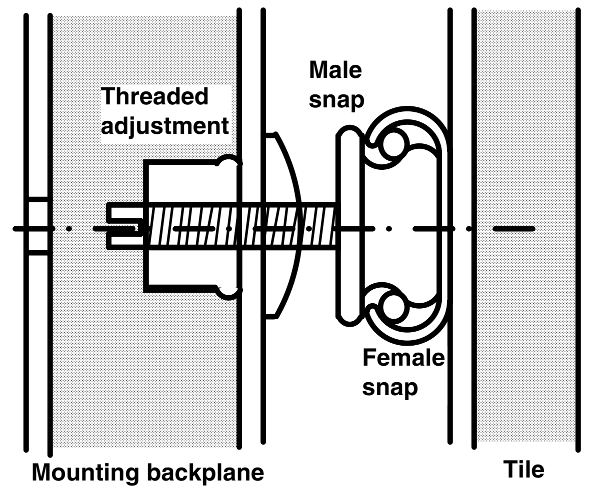

Figure 7. Adjustable tile mounting point.

Tile to tile color consistency is perhaps the most challenging issue for multi-tile images. This variable depends on control feedback within the printer itself, careful documentation of chromatic component laser intensity levels before and after each tile exposure, and maintenance of a thermally- and humidity-controlled environment to minimize or prevent laser intensity drift at the hogel exposure point.

Mastering

Images produced by the Zebra system can be used as masters for replication, with some changes in the final mounting. For this application, the recorded film is mounted on a glass substrate. Contact copies can then be made through lamination of a holographic film layer, and exposure with a point laser source, effectively making a hologram of the original hologram. These replication images can be made much more quickly and less expensively than the master image, and can be used for a variety of applications, particularly advertising.

Lighting

Proper lighting angle, distance, color temperature, and source size are critical for the effective display of all holographic images. This is especially true for full-color images with extreme depth, since color rendition and maximum sharpness are of paramount importance. Zebra has developed a number of solutions for hologram lighting.

Figure 8. Integrated frame, light and hologram.

For single tile images, an integrated light and frame solution has been developed, in order to provide a “plug and play” solution to a market that is wary of technical complexity. This system, shown in Figure 8, incorporates a simple frame with a detachable gooseneck, onto which the bulb is attached. The gooseneck snaps directly into a receptacle on the frame, automatically placing the light at the correct (45º) angle and 1-meter distance from the hologram. Adjustment is easily made to swivel the light in order to center the beam vertically on the image. A specially-chosen low-voltage 65 Watt halogen source is used, with a color temperature of approximately 3100ºK. All color calibration is done to provide proper chromatic display at this color temperature. The image is recorded on the optical printer specifically for the 1 meter illumination distance, so as to eliminate the potential for image distortion and inefficient replay. The integrated frame and light unit are easily installed by the customer, a critical issue for commercial viability.

For larger images, other light sources have been identified as having the proper characteristics to display the hologram optimally. Multi-tile images up to 1.2 x 3 meters are illuminated with a reasonably-priced commercially-available theatrical framing projector, with a 3100ºK color temperature, a high quality optical system, and minimal source size. As in the single-tile case, the hologram is carefully recorded for the intended illumination distance, in order to minimize image distortion and maximize image brightness.

For extremely large images, custom lighting solutions have been developed and employed. In these cases, minimizing source size is critical, due to the extreme depth of the images. It is also often useful to narrow the spectrum for each chromatic component, in order to minimize scatter and boost sharpness as well. Laser illumination is most advantageous for ameliorating these latter issues, due to its extreme monochromaticity, and nearly infinitesimal apparent source size. Unfortunately, laser sources retain the unwanted artifact of speckle, and so their utility is limited. A better, cheaper alternative are Xenon “Cermax” arc lamps, which have an extremely high photonic output, minimal source size, and a limited spectrum. Zebra Imaging has developed a custom lamp utilizing a 1KW Cermax source, that incorporates UV and IR filtration, optics for proper angular divergence and optional spectral filtering and recombination. This source has been used to light a 1.8 by 5.4 meter hologram, with adequate brightness and image sharpness.

Other Examples

Figure 9 depicts the world’s largest holographic image, produced using the system documented here. The image, of a prototype automobile, was produced for Ford motor company, and consists of 27 tiles, with a total size of 5.4 meters wide by 1.8 meters tall. It is illuminated with a 1 KW Xenon point light source from a distance of 10 meters.

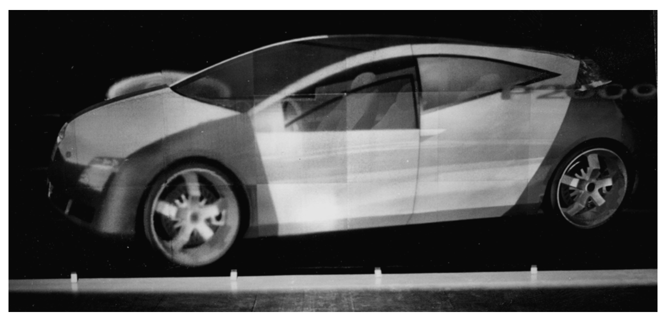

Figure 9. World’s largest hologram: 5.4 meters by 1.8 meters

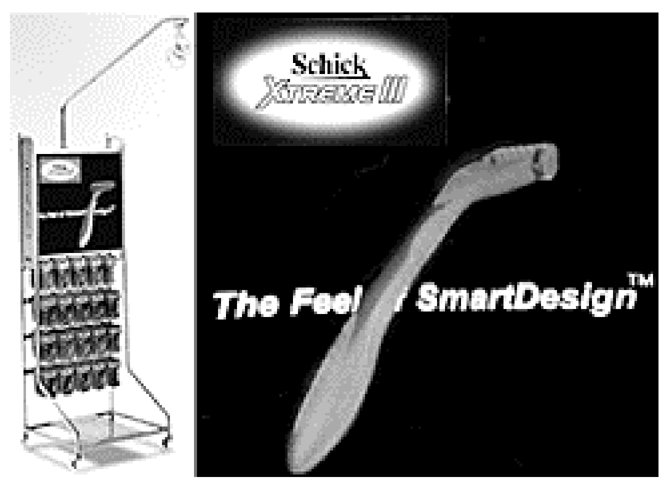

Figure 10. Point of purchase application.

Figure 10 shows a point-of-purchase display, in this case an advertisement that was replicated using a master hologram produced on the Zebra system. These images were successfully deployed in retail establishments across Japan.

Conclusion

The first commercially viable scalable holographic optical printing system has been described. Technical details associated with the generation of image content, the printing process, and the conversion of completed images have been detailed, as have lighting and presentation issues. The system has created the world's largest holographic image, measuring 1.8 x 5.4 meters, as well as masters for replication. Examples of typical output have been shown. The system continues to be improved, and new features and capabilities added.

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Biography

Michael Klug received his Bachelor's Degree from MIT in 1989, and his Master of Science degree from the MIT Media Laboratory in 1991. He continued on, over the following six years, as a Research Scientist with the Media Lab, further developing holographic displays for use in industrial design visualization and graphic arts applications. In 1996, he and two fellow Media Lab alumni co-founded Zebra Imaging, Inc., in Austin, Texas, with the express purpose of commercializing and further developing practical three-dimensional display technologies and products. He currently holds the post of Chief Technology Officer at Zebra Imaging.