# Electronic display system for computational holography

Pierre St. Hilaire, Stephen A. Benton, Mark Lucente, Mary Lou Jepsen, Joel Kollin,
Hiroshi Yoshikawa, John Underkoffler

Spatial Imaging Group, MIT Media Laboratory
20 Ames Street, Room E15-416
Cambridge, MA 02139 USA

## ABSTRACT

We present an electro-optical apparatus capable of displaying a computer generated hologram (CGH) in real time. The CGH is calculated by a supercomputer, read from a fast frame buffer, and transmitted to a high-bandwidth acousto-optic modulator (AOM). Coherent light is modulated by the AOM and optically processed to produce a three-dimensional image with horizontal parallax.

## 1. INTRODUCTION

The display of three-dimensional information is central to progress in many fields, such as medical imaging, computer-aided design, and navigation. Typically, such information can be transformed into a holographic image, which facilitates rapid and accurate perception of complex structures in depth using the natural depth cues of stereopsis, motion parallax, and ocular accommodation. Although conventional display holograms can produce bright, full-color images of high resolution and a large range of depths, they are static, and cannot be altered electronically as can a typical two-dimensional display. Any use of three-dimensional data for interactive, animated, or real-time display is commonly limited to a two dimensional rendering and display on a cathode-ray tube (CRT). The possibility of a real-time holographic display has only recently emerged due to advances in computers and computational methods, which allow for the rapid (seemingly real-time) computing of a holographic representation of a given set of three-dimensional data, as well as new electro-optical technologies for their display.

## 2. THE BANDWIDTH PROBLEM

Progress toward real-time holography is handicapped by the limited information bandwidth available in present-day electronic, computing, and communication systems. The information content of a typical hologram is several orders of magnitude larger than that of a two-dimensional image, such as the image on a CRT display. For example, a hologram of dimensions 100 mm by 100 mm and a viewing angle of 30 degrees contains approximately 25 Gigabytes of information, or the equivalent of 25 billion samples of information - all for a single frame. In order to update such an image with 8-bit resolution at a rate of 60 frames/second, a data-rate of 12 Terabits/sec would be required for transmission of the hologram. This enormous bandwidth is well beyond the range of current technology.

We have taken several steps to reduce the information content of holograms to a level that can be realized with the existing technology. First, the vertical parallax has been eliminated from the CGH before computation, reducing the information content by several orders of magnitude. The resulting hologram is similar to the "rainbow hologram," which trades vertical look-around for ease of viewing[1]. Next, the field of view has been limited, allowing only a few standard eye spacings, limiting the range of viewing angles to 15 degrees. Third,the resolution of the image is reduced to the visual limit or the resolution of the data. The present holographic video system is capable of a horizontal-parallax-only holographic image, with 64 vertical lines of resolution. This corresponds to an information content of 2 megabytes per frame, or approximately 1□gigabit/second, which is well within the range of fast high-resolution frame-buffers that can be used to store the CGH while being read out to the display apparatus.

## 2. DISPLAY APPARATUS

The display apparatus consists of CGH generation and storage, data transmission, and electro-optical display subsystems. A synthetic three-dimensional object is constructed using standard three-dimensional graphics and animation editing methods. Data describing the object is transfered to the Thinking Machines Connection Machine model 2 (CM2) supercomputer, which contains 16,000 microprocessors in a massively parallel hypercube processing architecture. The CM2 calculates a single frame of the CGH, consisting of a complex series of sinusoidal variations, and loads this "fringe pattern" into its frame-buffer. The frame buffer is configured to store and read out the CGH as 64 horizontal lines, each of which consists of 32,000 data points (video pixels). Thus each line of holographic information will consist of 16 lines of 2K video pixels spliced together for a total of 2 megapixels. All commercially available framebuffers include a retrace interval between video lines during which the signal is blanked, so gaps will be included in the signal fed to the display. These gaps will reduce the resolution and signal to noise ratio of the image, and must be accounted for when computing the CGH.

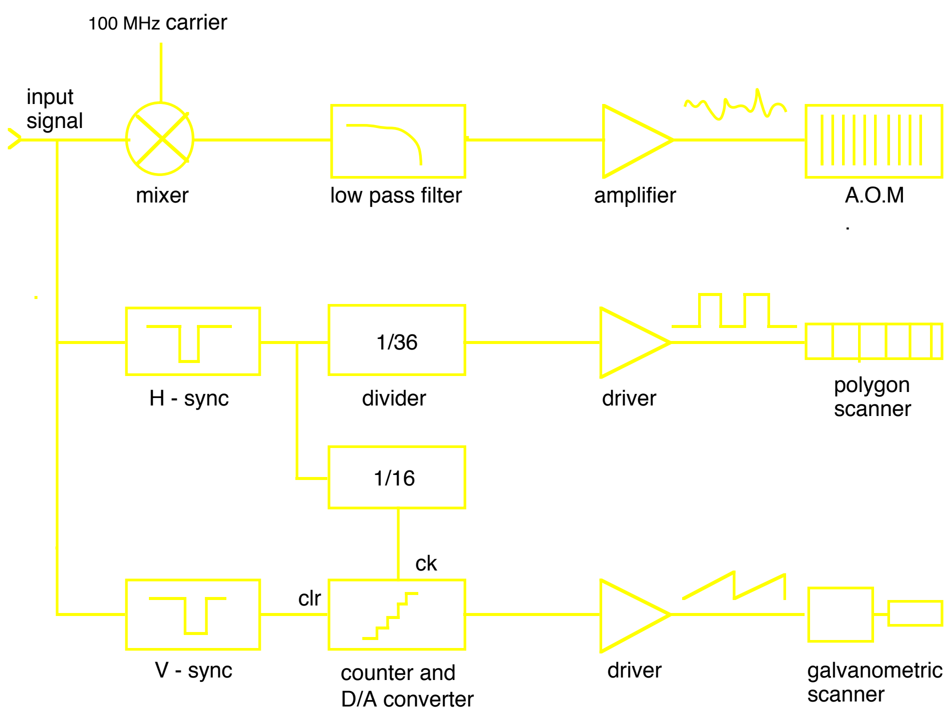


Figure 1. Block diagram of display electronics

The fringe pattern is transmitted from the frame-buffer to the display as a 55 MHz bandwidth video signal that propagates over an optical fiber link. An optical receiver sends the video signal to the display electronics (Fig. 1). The link also transmits the necessary synchronization signals, which are separated by the display electronics and processed into control signals for the opto-mechanical scanning portion of the display apparatus. The video signal is then mixed with a 100 MHz carrier and filtered to keep only the lower sideband. This up-converts it to the 45 - 100 MHz operating range of the acousto-optic modulator. The signal is then amplified and used to drive the acousto-optic modulator (AOM), which is at the heart of the display apparatus.

The AOM consists of a single transparent $TeO_2$ crystal operated in the slow shear mode. At one end of the crystal is an ultrasonic transducer, which converts the amplified video signal to an acoustic wave that is launched down the crystal. As the acoustic wave propagates, the regions of elastic shear present a modulated index of refraction to the optical beam, which passes perpendicular to the acoustic wave. The optical beam thus emerges from the crystal with a relative phase-difference pattern across its 35□mm width that is proportional to the instantaneous amplitude of the acoustic wave along the length of the crystal[2]. This complex fringe pattern transfers the CGH data to the optical beam. The crystal has an aperture time of 40 microseconds and a space bandwidth product of 2000. Its operating RF spectrum ranges from 45 to 95 MHz. Because its total angle of diffraction is only 3 degrees, a demagnification of 5 is needed to bring the viewing angle to 15 degrees. The 100 MHz carrier is also present in the diffracted beam and needs to be removed by spatial filtering.

Figures 3 and 4 show the electro-optical portion of the display, which exhibits many similarities with the Scophony system introduced in the 1930's for the display of television images[3,4]. A widened beam of coherent light is phase modulated by the input CGH data-stream in the AOM, and assembled into the image of the CGH by the scanning system. We will now explain how the coherent light emitted by the holographic display behaves as if transmitted through a hard-copy hologram printed from the CGH data.

A 10mW HeNe laser is used as a coherent source of monochromatic red light ( 632.8 nm wavelength). The beam is spatially filtered, expanded, and collimated using a microscope objective, a pinhole, and a collimating lens. A horizontal slit-shaped portion of this beam passes through the AOM, producing a diffracted order, which represents a portion of one line of the hologram. In the AOM, the fringes propagate at a rate of 617 meters/second, which is the speed of shear waves in the $TeO_2$ crystal. Therefore, the diffracted image also moves (from left to right) at this rapid rate. In order to make the image appear stationary, a spinning 18-sided polygonal mirror is used to scan horizontally in the opposite direction. The horizontal scan also acts to multiplex the image of the crystal, creating a virtual crystal that is exactly as long as one line of the CGH. This multiplexing is necessary because the crystal can hold only 2000 fringes at a time, whereas 32,000 pixels make up a horizontal scan line.

Synchronisation and multiplexing are central to the operation of the system. In the simplest case (Fig. 2), the relationship relating the angular speed of the polygon $\omega$, the speed of sound on the crystal v and the focal distance $f$ of the focusing lens $L_1$ is given by :

$$\omega = v / 2f \ . \tag{1}$$

$\omega$ is determined by the relation:

$$\omega = 2\pi / N P \tau \ , \tag{2}$$

where N is the number of video lines included in one holographic line, P is the number of polygon facets, and $\tau$ the scan time of a single video line, including the retrace interval.

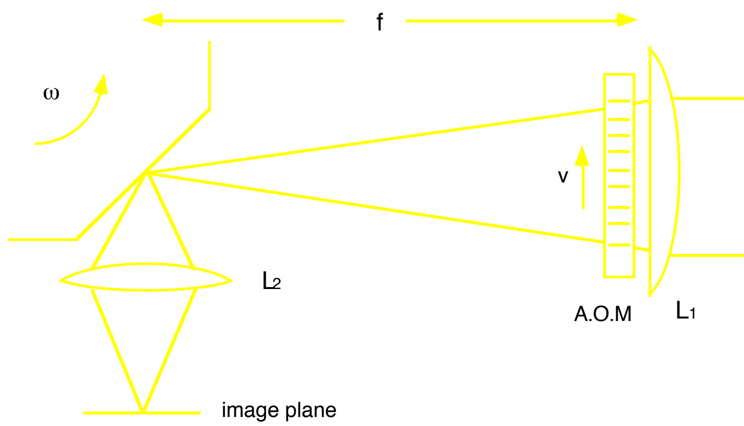


Figure 2. Matching the polygon's angular speed with the velocity of sound on the A.O.M. crystal

In the more general case where the holographic image is focused at a plane different from the scanning plane, the condition to be satisfied becomes:

$$f\,v / 2\omega + L\,(f + h) - f\,h = 0 \ , \tag{3}$$

where L is the distance between the AOM and the polygon's facets and h is the distance between the hologram plane and the AOM (Fig. 3). Focusing the diffracted beam in front of the scanning polygon simplifies the spatial filtering of the 100 MHz carrier without the need of an additional relay lens. It introduces, however, a slight motion blur for deep objects since (3) is satisfied for only one value of h.

The last component in the horizontal scanning plane is the ouput lens $L_3$. The function of that lens is to re-image the now steady holographic image with the correct magnification (1/5 in the present system). For this purpose we use a 55 mm f/1.2 camera lens. The resulting field curvature is small enough to be hardly noticeable given the size of our images. The holographic image will now seem to float a few centimeters in front of the output lens.

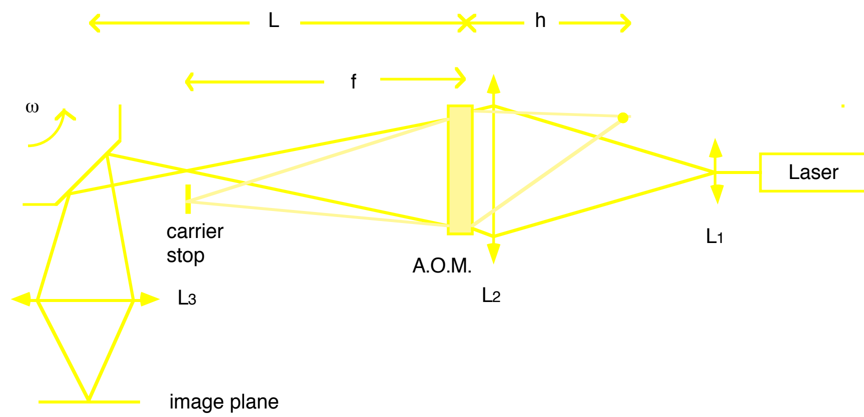


Figure 3. Horizontal scanning part of the system. The galvanometer mirror and the other vertical scanning optics are omitted for clarity.

Vertical deflection is provided by a closed loop galvanometric scanner used in a telecentric configuration with lenses $L_6$ and $L_3$ (Fig. 4). Lens $L_5$ acts to increase the vertical field of view. The vertical focus is ajusted so that it will coincide with the middle plane of the image to reduce astigmatism. Of course, image planes away from the vertical focus will still be slightly astigmatic (as in any rainbow hologram), but this astigmatism is well within the range of ocular accomodation and remains virtually unnoticeable.

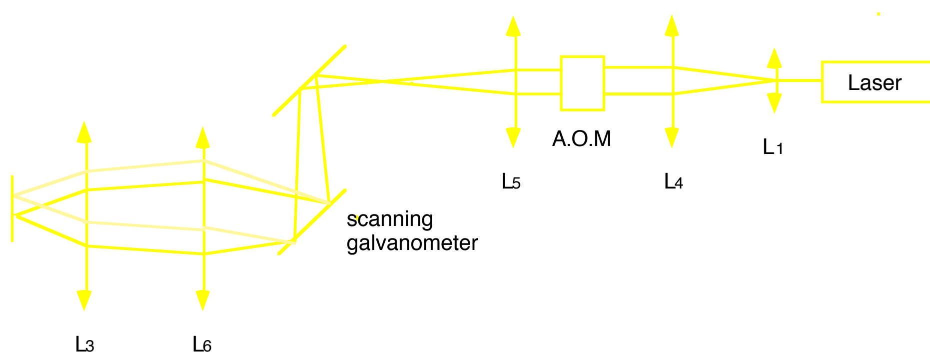


Figure 4. Vertical scanning optics. The polygonal mirror is omitted for clarity

## 4. HOLOGRAM COMPUTATION

Many methods have been published concerning the computer generation of holograms[2,3]. The method used here is very straightforward in the sense that it simulates the actual physical phenomenon underlying holography.

Previous methods of calculating holographic fringe patterns have relied on approximate techniques to reduce computation time; most notably, by constraining the "object" to a single plane parallel to and far behind the hologram plane one may approximate the actual wavefront as the Fourier transform of the input distribution. By modifying this procedure to concatenate several such planes with appropriate quadratic phase factors, one could achieve three-dimensional images of a kind, but these were still required to lie behind the hologram plane. Further, for the most part these techniques were designed to produce fringe patterns of on-axis holograms, those with reference beams normal to the hologram.

The intent of the MIT Holographic Video system is to produce images reconstructed with an off-axis reference beam which represent objects both behind and in front of the hologram plane. Thus, the computation of fringe patterns for this system proceeds directly from an optical description of physical holographic recording: at each sampled hologram point a summation of complex amplitude contributions from all parts of the object is performed, and, after the addition of a term representing a reference beam, the magnitude of this summed amplitude is squared to yield an intensity value. This non-negative value is then scaled and rounded to fit a dynamic range appropriate to the device.

Thus far, all the images computed for the MIT system have been composed of distinct, self-luminous point sources. This object representation was chosen because it results in the simplest possible summation computation. A straightforward fringe calculation based on this model generates "transparent" objects, since each points source used to represent them have no width and thus cannot preclude light originating behind it from reaching the hologram plane. However, the incorporation of occlusion effects into the simulation greatly enhances the understandability and the perceived reality of the images. (Occlusion is, of course, an important depth cue.) This can be done by assigning a width or "absorptive cross section" to each point source so that it occludes other sources behind it over some small range. Alternately, the notion of an object can be extended beyond simple edge-defining points to a polygonal scheme in which point sources lie along polygon-bounding edges, so that a point may be obscured by a polygon nearer to the viewer.

The issue of aliasing is of primary importance to the fringe calculation process: because the acousto-optic crystal is being fed by an essentially digital stream of computed data, there is an inherent resolution to the medium ("lines per millimeter"). Whereas real film, which also has a maximum resolution, turns an incident pattern with an excessive spatial frequency into average-valued noise, a computed (and therefore inherently sampled) hologram cannot effectively reject extreme spatial frequencies. The solution used with the MIT system is to limit the hologram range over which a point source contributes to the interference pattern; in other words, a point source is ignored over any portion of the hologram for which it would produce an aliased pattern. Thus, for each point source, bounds on the hologram beyond which aliasing would occur are calculated; the contribution of that source is then considered only within these bounds.

## 5. CURRENT RESULTS

To date, several three-dimensional images have been displayed (Figs. 6 and 7). The images exhibit high contrast and an excellent signal-to-noise ratio. The horizontal resolution of imaged points is almost diffraction limited to well below human perception in the plane of the hologram. Objects of size up to 30 x 30 x 30 mm can be displayed with 64 lines of vertical resolution. The 40 Hz refresh rate makes for an almost ficker-free image. The characteristics of a holographic display are immediately apparent to the viewer: Depth is readily perceived due to the natural combination of depth cues of binocular convergence, motion (side-to-side) parallax, and ocular accommodation.

Animation is achieved using two methods. In the first, the object is animated using standard computer graphics techniques, and the result is fed to the CM2 for rapid "on the fly "computation. The computation time of a simple CGH frame has been reduced to under 5 seconds. Therefore, this method results in honest real-time holography.

The second alternative is to pre-calculate a series of CGH frames in an animated sequence, which are then stored in the read/write memory of the CM2. The frames can then be simply read out of the CM2 in sequence and transmitted to the display at rates of more than 16 frames per second. This method, though not truly real-time holography, does provide a dynamic holographic animation after an initial computation time of only minutes.

Figures 6. and 7. Holograms displayed by the MIT system.

## 6. FUTURE RESEARCH

Future research includes the use of higher bandwidth crystals and electronics to generate a larger image, a larger viewing zone, and more horizontal scan lines. The use of diffractive optics, multichannel crystals, and the display of full color images are also being considered.

The system is now almost capable of interactive holographic display. Thus, the three-dimensional image can be drawn and edited by the user in real-time. In addition, use of the display to image data from real-world sources is being explored. This will enable the visualization of, among others, medical imaging or computer-aided design data.

The present status of the system makes it highly valuable for the development of CGH algorithms. The results of a particular algorithm can now be visualized in a matter of seconds instead of the much longer times required for other methods such as laser printing or e-beam writing. Thus we are concurrently investigating better and faster methods of CGH computation.

Improving the display by the two orders of magnitude necessary for any practical display application will require major advances in computer and signal processing technology because of the huge bandwidth required. The computational answer to real time holography undoubtedly lies in the use of massively parallel architectures. Optical computers are particularly attractive in this respect since they often reproduce in their architectures the algorithmic principles (such as Fourier transforms) necessary for the computation of holograms .

## 7. CONCLUSION

Work by members of the MIT Spatial Imaging Group has produced a new system capable of presenting moving monochromatic three-dimensional holographic images measuring a few tens of millimeters in size and depth. Simple computer generated holograms can be calculated in under five seconds, and flicker-free animation can be achieved by pre-calculating and storing a sequence of holographic frames. Although these images are small, they are bright, have high resolution, and exhibit all of the depth cues found in holography. These early results show that the promise of real-time holography is becoming a reality.

## 8. APPENDIX 1: INFORMATION CONTENT OF A HOLOGRAPHIC IMAGE

The angle of view $\theta$ of a hologram is determined by the grating equation:

$$f_h \lambda = \sin\theta \ , \tag{4}$$

Where $f_h$ is the maximum spatial frequency of the hologram fringes and $\lambda$ is the wavelength of the diffracted light.

According to the sampling theorem, the minimum sampling frequency $f_s$ required to generate or digitally transmit the hologram is:

$$f_s = 2 f_h \ , \tag{5}$$

so the number N of samples required for a 1-dimentional hologram of size d is:

$$N = 2 d f_s = 2 d \sin\theta / \lambda \ . \tag{6}$$

The total number $N_t$ of samples required for a horizontal parallax hologram with a vertical resolution of l lines is thus:

$$N_t = l N_s = 2 d l \sin\theta / \lambda \tag{7}$$

and for a full parallax hologram of vertical size w we have :

$$N_t = 4 d w \sin^2\theta / \lambda^2 \ . \tag{8}$$

## 9. ACKNOWLEDGMENTS

The authors wish to acknowledge the generous support of our sponsors. Early parts of this work were supported by US West Advanced Technology, Inc. Research on high-speed computation and animation was supported by Rome Air Development Center (RADC) of the the Air Force System Command and the Defense Advanced Research Projects Agency (DARPA). We also wish to thank John Earls, Jim Salem and David Shepard of Thinking Machines Corporation for their help in adapting the CM2 framebuffer to our purposes and Henry Holtzman for his contribution to the animation software.

The views and conclusions in this document are those of the authors, and should not be interpreted as necessarily representing the official policy, expressed or implied, of the Rome Air Development Center (RADC) of the the Air Force System Command, the Defense Advanced Research Projects Agency (DARPA), or the United States Government.

## 10. REFERENCES

1. S.A. Benton, "The Mathematical Optics of White Light Transmission Holograms", *Proceedings of the First International Symposium on Display Holography*, Lake forest College, July 1982, T.H. Jeong, editor.

2. I. C. Chang, "Acoustooptic Devices and Applications", *IEEE transactions on sonics and ultrasonics,* vol. su-23, No. 1, January 1976.

3. L. M Myers, "The Scophony system: an analysis of its possibilities.", *TV and Shortwave World*, pp 201-294, April 1936.

4. A. Korpel *et. al.*, "A Television Display Using Acoustic Deflection and Modulation of Coherent Light", *Applied Optics*, vol. 5, pp 1667-1682, October 1966.

5. W. J. Dallas, "Computer Generated Holograms", *The Computer in Optical Research*, B. R. Frieden editor, chapter 6, pp 291-366, Springer Verlag, 1980.

6. D. Leseberg and O. Bringdahl, "Computer Generated Rainbow Holograms", *Applied Optics*, vol. 23, October 1987.