Real-time holographic display: Improvements using a multichannel acousto-optic modulator and holographic optical elements

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ABSTRACT

Any practical holographic display device relying on the MIT synthetic aperture approach will require time-bandwith products far exceeding those available with single channel acousto-optic modulators (AOMs). A solution to this problem is to use a multichannel AOM, thus making use of the parallelism inherent in optical systems. It is now technically feasible to accomodate a large number of acoustic channels on a single crystal with a corresponding improvement in image characteristics.

The vertical view zone also becomes a significant problem for any large size display since each horizontal scan line line is visible only from a narrow angle in the vertical direction. Using holographic optical elements (HOEs) alleviates this limitation in two ways: First, the interline spacing can be adjusted easily with HOEs. Second, it is possible to manufacture an HOE which will act as a one-dimensional diffuser. Placing such an HOE in the vertical focus plane of the display increases the view zone by diffusing each line in the vertical direction, but leaves the horizontal image content unaltered.

1. INTRODUCTION

Holography has long been recognized as a powerful medium for the display of complex three dimensional information but until recently progress in the real time display of holographic data had been hampered by the large amount of calculations required as well as the lack of a suitable display device. Recent research at the MIT Media Laboratory has permited us to overcome some of those limitations and has resulted in the production of animated images that, though of a small size, offer all the depth cues found in holography[1]. The operation of the display has been described in a previous publication[1] and will be briefly summarized as follows:

The fundamental idea behind the MIT holo-video display is the use of an acousto-optic modulator (AOM) as the medium in which the holograms are written[1,2]. 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 electrical holographic information 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 perpendicularly to the acoustic wave. The optical beam thus emerges from the crystal with a relative phase-difference pattern across its width that is proportional to the instantaneous amplitude of the acoustic wave along the length of the crystal. This complex fringe pattern transfers the CGH data to the optical beam. The crystal has an aperture time (width / sound speed) of 40 microseconds and a space bandwidth product (max cycles / mm x aperture width) of 2000. Its operating RF spectrum ranges from 45 to 95 MHz. Because its total angle of diffraction range is only 3 degrees, a demagnification factor is needed to bring the viewing angle to a more acceptable value (typically 15 degrees).

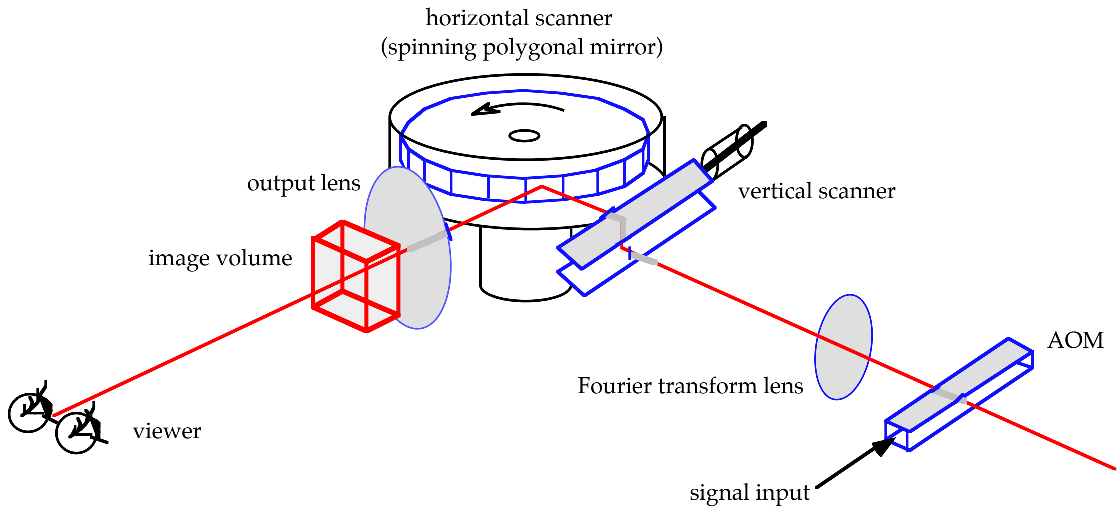

Figure 1.1 Electro-optical section of the MIT holographic display.
The vertical scan lenses have been omitted for clarity

Figure 1 shows the electro-optical portion of the display. 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. A 10mW HeNe laser is used as a coherent source of monochromatic red light. 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 polygonal mirror is used to scan horizontally the image of the AOM 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 a small fraction of the total number of fringes at a time. The vertical deflection is provided by a closed loop galvanometric scanner.

After computation on a Thinking Machines CM2 supercomputer the holographic information is sent to a high resolution frame buffer and converted to a signal having the same bandwidth as the AOM. This signal is then upconverted to the AOM operating frequency range by mixing it with a 100 MHz carrier and filtered to keep only the lower sideband. It is then amplified and used to drive the AOM.

The scheme employed is very similar to the synthetic aperture radar case where a narrow antenna is linearly scanned to give an effective aperture equal to the scan length, the main difference being that we are generating a wavefront instead of recording it. Thus the name Synthetic Aperture Holography is sometimes used to refer to that type of display.

II USE OF MULTICHANNEL AOM'S

Synthetic holography requires large amounts of information[3]. For example, a hologram having an horizontal size d = 100 mm and an angle of diffraction θ = 30 degrees would require:

$$N = \frac{2 \cdot d \cdot \sin \theta}{\lambda} = 158\,000 \qquad (1)$$

samples per scan line for a HeNe laser. Assuming a 50 MHz RF bandwidth (a typical figure for shear mode TeO_2 AOMs) and a 60 Hz refresh rate results in a display having less than 11 lines of resolution. This figure is clearly unreasonable for any practical application.

Increasing the number of lines while keeping the refresh rate, view angle and horizontal size constant requires a proportionally larger number of samples per unit time. For a single acoustic channel this translates into a higher operating bandwidth for both the AOM and the associated electronics. Many factors, however, impose a practical upper bound on the maximum bandwidth. In the case of shear mode TeO_2 this limit comes from the relatively high acoustic attenuation of the material, which is a quadratic function of the operating frequency[4] (this quadratic dependence is a general property of AO materials). This attenuation limits the useful range of the material to less than 75 MHz if we want to keep a space-bandwidth product larger than 1000. The use of other materials such as Lithium Niobate ($LiNbO_3$) or Gallium Phosphide (GaP) can extend the bandwidth into the gigahertz range, but once again it is very difficult to attain high space-bandwidth products at those frequencies[4,5]. Moreover, the electronics associated with the synthesis and signal processing parts of the system become impractical or prohibitively expensive at such high frequencies.

A more elegant approach is to use a multichannel AOM, thus making use of the parallelism available to optical systems (Fig. 2). Such an approach has been extensively researched by the signal processing community[6,7] and devices having low crosstalk between channels and high space-bandwidth products are readily available. In our previous example, using 40 acoustic channels would result in a vertical resolution of 440 lines, a figure comparable to NTSC television. The number of acoustic channels, however, is itself constrained by the spreading of the acoustic waves across the length of the AO material. This effect, similar to the diffractive spreading of a light beam propagating in free space, is further compounded in the case of shear mode TeO_2 by the high anisotropy in the acoustic properties of the material. The acoustic beam spread results in some crosstalk between adjacent channels as well as in a reduced AOM space bandwidth product. Minimum transducer dimensions and spacing are thus necessary to prevent excessive interchannel crosstalk.

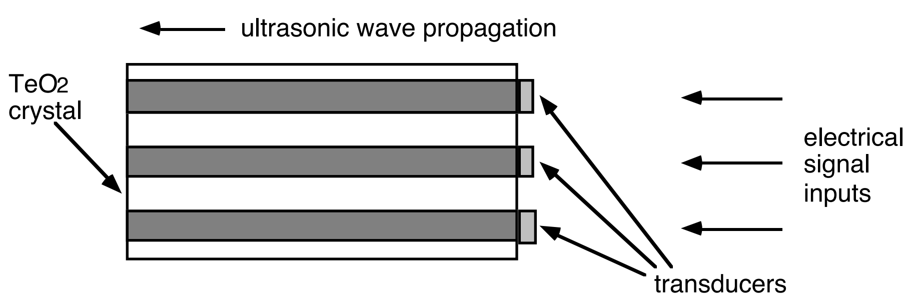

Figure 2. Multichannel AOM, front view

The acoustic spreading and interchannel crosstalk can be reduced by using apodized transducer electrodes and holographic compensation techniques[6,7] . Such holographic techniques have been experimented with by Vanderlugt and hold great promises for future generations of the display, but they have not been investigated in the course of the present research. In some other materials, such as longitudinal mode TeO_2, the anisotropy in the speed of sound results in a reduction of the acoustic beam spread. This effect and the fact that longitudinal mode TeO_2 can be operated over a wide bandwidth (typically 200 MHz) make this material very attractive for future research.

III VERTICAL SCAN OPTICS AND VIEW ZONE

Combining the holographic scan lines coming from a multichannel AOM into a single final image is not a simple problem, however. To see how it can be done, let us first examine the vertical imaging optics in the case of a single channel AOM (Fig 3).

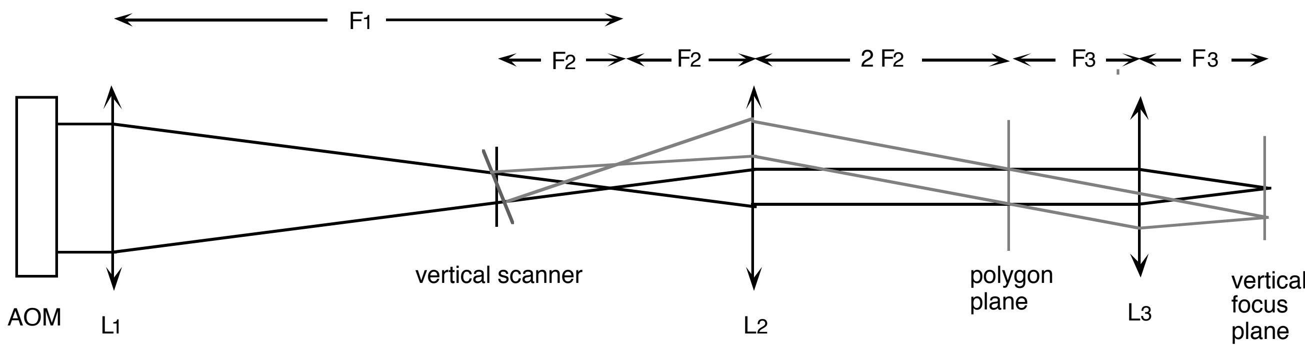

Figure 3. Vertical scanning optics. L_1 and L_2 are cylindrical lenses.

The MIT display does not exhibit vertical parallax and so its vertical focus is fixed. In that respect it is equivalent to the rainbow or Benton hologram. The resulting images are thus necessarily astigmatic, and the overall astigmatism is at a minimum where the vertical focus intersects the center of the image plane. A desirable feature of the vertical scanning system is that the output beam be normal to the image plane throughout the field. This condition, called telecentricity, assures that the displayed image will not appear vertically distorted as the horizontal focus is moved away from the vertical focus plane. A telecentric system converts an angular beam deflection to a linear translation by having the scanning element at the front focal length of the output lens[8]. This causes a problem in our system since this space is usually occupied by the horizontal scanning polygon. The solution is to put the vertical scanner away from the polygon and re-image it at the required plane using a relay lens L_2. We can then use the same lens L_3 both as a horizontal and vertical output lens. In the geometry of Fig.3 the vertical focus is at the focal plane of L_3, but this can be changed if necessary by moving the focal plane of L_1 away from the focal plane of L_2.

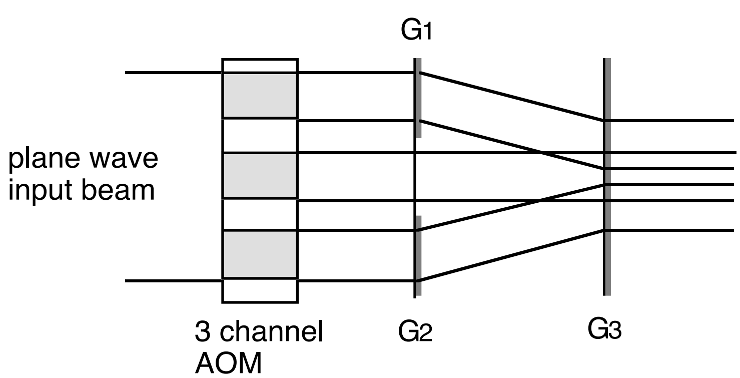

Figure 4. Holographic beam multiplexer

Simply inserting the multichannel AOM at the position previously occupied by A_1 on Fig. 3 would not give any meaningful results since the light diffracted by the channels would be focused at the same position at the output plane. There are many solutions to this problem, and the one adopted in our case was to use a holographic beam combiner. This HOE, shown in Fig. 4, was made in house using standard silver halide plates. It consists of three gratings G_1, G_2 and G_3 having the same spatial frequencies. The first two gratings G_1 and G_2 diffract the outer lines in the +1 and -1 orders respectively while the effect of G_3 is to recombine the beams (the extraneous diffracted orders are not shown on Fig. 4 for clarity). If we now place the HOE just after L_1 each diffracted channel becomes focused at a different location of the output plane (Fig. 5). The interline spacing can be easily adjusted by changing the distance separating G3 from G1 and G2 without any other modification in the system geometry. The HOE has an overall efficiency of 30%. The strategy adopted here obviously becomes difficult to use if we try to multiplex more than three channels. In that case, solutions such as lenticular arrays or cylindrical prismatic lenses might prove easier to apply.

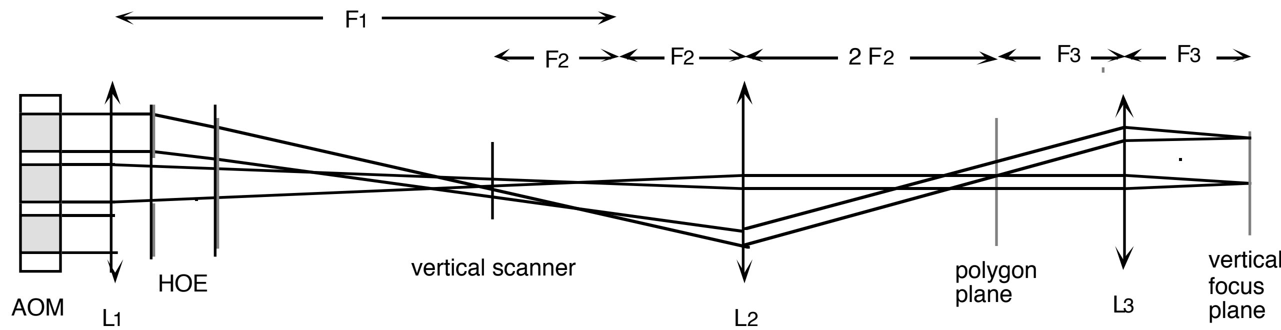

Figure 5. Vertical scanning using a three channel AOM

III USE OF A VERTICAL DIFFUSER

Another problem arises when we multiplex many thin acoustic lines: the vertical view zone becomes narrow to the point that the eye might not be able to perceive the whole image at once. This situation is easy to explain if we refer once again to Fig. 3. Deriving the vertical view angle θ by using simple geometrical optics gives the result:

$$\theta = 2 \tan^{-1}\left(\frac{d \cdot f_2}{2 \cdot f_1 \cdot f_3}\right) \qquad (1)$$

where d is the width of the acoustic channel. For example, typical values in our system are d = 3.2 mm, f_1 = 400 mm, f_2 = 100 mm and f_3 = 55 mm. Using (1) with those numbers gives us a vertical view zone of 0.83 deg., which is clearly unacceptable. Diminishing f_1 to increase θ is not practical because electromechanical considerations severely constrain the sizes of the galvanometer and polygon scanning mirrors.

The solution to this problem is to vertically diffuse the light in the output plane while leaving the horizontal component of the image unaltered. A fine pitched cylindrical lenslet array can be used to that purpose, but in keeping with the spirit of this research we decided to manufacture a one dimensional diffusing HOE.

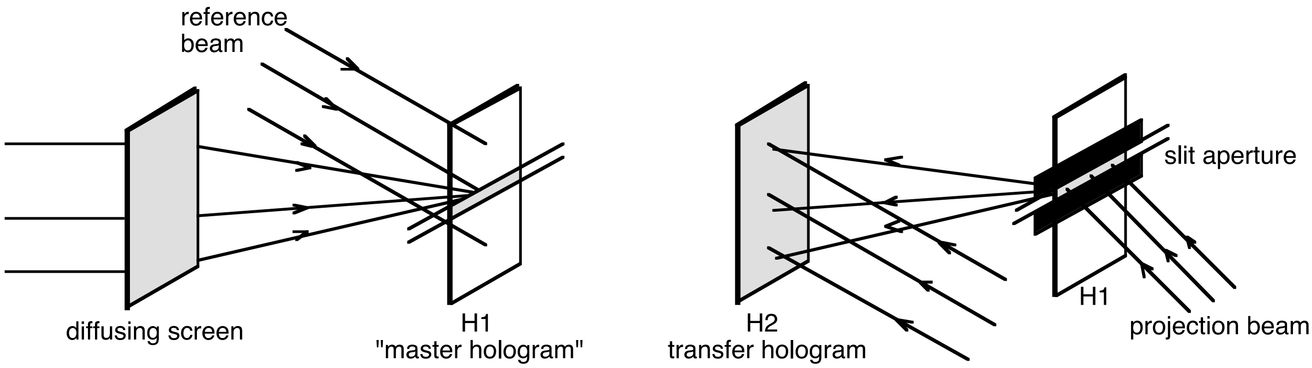

Figure 6. HOE master recording (left) and transfer (right)

The manufacture of a one dimensional diffuser HOE is straightforward and uses precisely the same geometry as a rainbow hologram. We first make a H1 master of a ground glass screen using the setup of Fig.6. This master is then illuminated by a narrow slit of light and the real image of the ground glass is transfered to a second plate in a rainbow fashion (Fig. 6). A laser beam hitting the final hologram as shown in Fig. 7 will project a real image of the slit in front of it. The HOE can thus be modeled as a strong diffuser in the vertical direction while in the horizontal axis it acts as a combination of a very weak diffuser combined with a lens of focal length D, where D is the distance between H2 and H1. The vertical and horizontal diffusion angles are respectively given by:

$$\theta_{vert} = 2\tan^{-1}\left(\frac{Y}{2\square D}\right) \tag{2}$$

$$\theta_{hor} = 2\tan^{-1}\left(\frac{X}{2\square D}\right) \tag{3}$$

where X and Y are the horizontal and vertical dimensions of the slit. As an example, with X = 0.7 mm, Y = 120 mm and D = 300 mm we get $\theta_{hor} =$ 0.13 deg. and $\theta_{vert} =$ 23 deg.

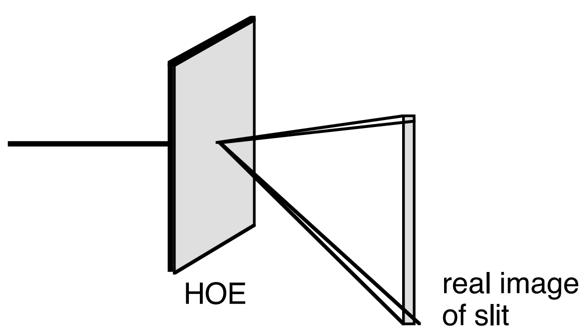

Figure 7. HOE playback as a vertical diffuser. The hologram

has been rotated by 90 degrees with respect to Figure 6.

The diffuser is placed in the vertical output plane. Obviously, the narrower the slit, the more our HOE will approximate a perfectly one dimensional diffuser. Diffraction effects, however, become significant for very narrow slit widths. Another point worth mentioning is that the HOE works off-axis, thus requiring the viewer to look at the display from an angle. On-axis operation and much higher performance diffusers could probably be acheived by using binary optics technology.

IV RESULTS

We tested the multichannel AOM scheme using the line multiplexer described in Section II and the diffuser of Section III. The AOM uses TeO_2 in the shear mode and consists of three acoustic columns having an individual width of 3.2 mm and an interchannel spacing of 1.5 mm. The crosstalk is specified to be less than -25 dB across an aperture of 20 μs. The AOM operates between 50 MHz and 100 MHz and receives its information from the Red, Green and Blue outputs of the CM2 framebuffer. The resulting image is 40 mm on a side, has a horizontal view zone of 12 degrees and a refresh rate of 40 Hz (Figs. 9 and 10). The use of the three channel AOM gives a vertical resolution of 192 lines which correspond to a total of 6 Mbytes of data per frame. The 1-D diffuser in the vertical focus plane results in a comfortable vertical view zone of 23 degrees. The final images are bright, reasonably sharp and are strikingly three dimensional. The vertical diffuser, however, introduces a some speckle noise which is most visible on large rendered surfaces. The fact that the display has to be observed off axis is also slightly annoying for some viewers.

Figures 9 and 10. Images displayed by the MIT holographic display.

V CONCLUSION

Electronic holography is clearly still in its infancy. Many questions need to be answered before we can ascertain whether it represents a viable display technology. The primary focus should obviously be on increasing the size, resolution and view zone of the holograms. We have demonstrated that the use of holographic optical elements and multichannel AOMs represents a significant first step towards achieving those goals. Later versions of the display will certainly feature a much larger number of active channels and specially designed high bandwidth electronics. The use of binary optics HOEs[9] will likely become a important topic in the next few years, along with the investigation of different scanning technologies. The present system is already very successful in evaluating new algorithms for a faster and better rendition of images but large displays represent a major challenge from a computational and data transfer wiewpoint. However, the authors express their opinion that interactive holography will become a significant display technology in the forseable future.

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