

A Low Cost Holographic Display

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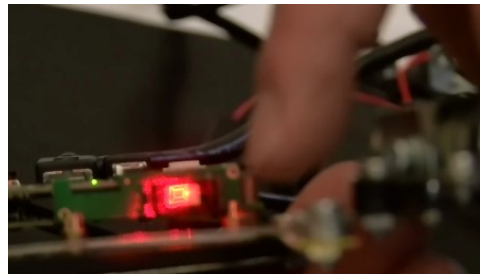
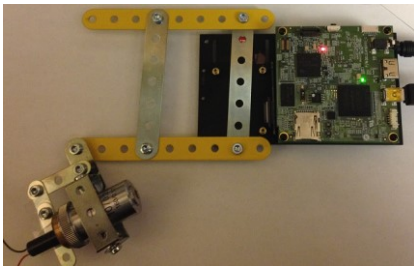


Figure 1: (a) Prototype holographic display (left), (b) Image of wireframe truncated pyramid as displayed in the prototype display

Abstract

Holography can be viewed as the ultimate display technology since it correctly duplicates all the cues used by our visual system. In the graphics community this technology has largely been ignored in the past due to its computational cost, but this is changing as more powerful parallel processors are becoming available. One of the main challenges in this area is the lack of a commercially available display device at a reasonable cost that can be used for testing and evaluating algorithms. This paper describes a low cost holographic display device that can easily be constructed from standard parts as a solution to this problem. This paper discusses the design considerations for such a device, its construction and an overview of how holograms can be computed for it. It is our hope that this device will stimulate further research on holography within the computer graphics community.

Keywords: 3D display, holography

Concepts: • **Hardware~Displays and imagers**
• **Computing methodologies~Virtual reality**

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1 Introduction

In many ways holography is the ultimate display device capturing all aspects of the light energy that is reflected or emitted by the environment. This includes all the cues that our visual system expects. This differs from other display technologies, such as head mounted displays (HMDs) that present conflicting cues to the viewer. In the case of an HMD the images are displayed on a fixed plane producing focus and accommodation cues suggesting that all the objects are at the same depth, while the stereo and projection cues suggest they are at different depths. This causes fatigue and other visual problems. Light field displays are a step forward, but only provide correct 3D cues over a limited depth range [Yamaguchi 2011]

Recently, holography has become a marketing term that has been associated with any type of 3D display. In this paper holography refers to the optical phenomena where an interference pattern is generated when a coherent light source (for example, a laser) illuminates both an object and the recording medium [Goodman 2005, Saxby and Zacharovas 2016].

There have been very few papers on holography in the graphics literature since it has been viewed as too computationally expensive to be a practical display medium. This is rapidly changing as powerful parallel architectures are now becoming readily available even on consumer class devices. It is now possible to compute simple holograms on consumer devices in a matter of seconds while in the past this would have taken many hours or days.

Holography is based on the interference of two wave fronts that are produced by a coherent light source, a light source with a single frequency. The most common source of coherent light is a laser. In its simplest form a single wave front from a laser is split into two beams with one beam aimed at the object to be recorded and the other at the recording medium. The two beams meet at the surface of the recording medium and form an interference pattern. If the same light source illuminates the interference pattern the original wave front from the object is produced resulting in the same visual stimulus as the original object.

Optical holograms have been produced for many decades and they are typically recorded on film which then must be developed before the hologram can be viewed. Once the film has been developed a laser can then be used to reconstruct the hologram. The physics of holography is well known so it can be simulated numerically resulting in a computer generated hologram. In this case the interference pattern for the hologram is stored as an image. To reconstruct the hologram this image must be displayed and illuminated by a laser. A large number of algorithms have been developed for computing holograms and digital holograms have a wide range of applications [Goodman 2005].

Figure 2 shows the interference pattern computed for a wire frame truncated pyramid like the one shown in figure 1b. Clearly it is impossible to determine that this interference pattern represents a truncated pyramid just by looking at it, so it is impossible to debug or evaluate computational holography algorithms without a holographic display device. Unfortunately, holographic display devices that can be used in computer graphics research are not commercially available.

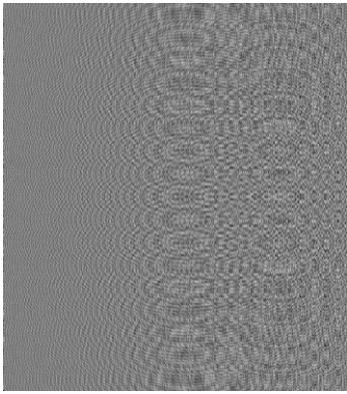


Figure 2 *Interference pattern for truncated pyramid*

This paper presents the design of a low cost holographic display that can be used to test and evaluate holographic display algorithms. Our goal was to produce a display for under \$1000 that can be constructed from readily available components. A graduate student should be able to construct the display in less than a day once the components have been purchased. Since this is a research prototype flexibility and cost are more important than image quality

The next section of this paper describes the design considerations that drove the design of our holographic display. The third section describes the construction of the holographic display and the fourth section briefly describes the software that can be used to compute interference patterns. The final section presents results and discusses possible extensions to the design.

2 Design Considerations

Flexibility was one of our main design considerations, allowing us to rapidly explore different device configurations to determine the ones that produce the best display. Better packaging can be considered once the final device configuration has been determined. The design uses off the shelf components since we wanted to avoid the use of specialized optical and mechanical shops. The design will be accessible to a wider range of researchers if specialized facilities are not required to produce it.

One of the most important design consideration is the device that is used to display the interference pattern. The size of the display device's pixels must be close to the wavelength of the light and the pixel array must have a large fill factor. The fill factor is the proportion of the device surface that is covered by pixels. This pretty much eliminates LCD panels from consideration since they have a low fill factor and in most panels the pixels are considerably larger than the wavelength of the light that we are using.

There are two display technologies that meet our requirements. The one that is the closest fit is LCOS (Liquid Crystal on Silicon), but unfortunately it is too expensive for our purposes with chips starting in the \$4000 range in small quantities. The other technology that fits our requirements is the Texas Instruments DMD display. These displays have larger pixels than LCOS, but they are small enough to work. The cheapest DMD is the DLP3000 which has a pixel size of 10.8 μm and a fill factor of 92%. A red laser which has a wavelength of 650 nm, so the pixel size is roughly an order of magnitude greater than this wavelength. Texas Instruments has a LightCrafter™ evaluation module that includes the DLP3000 along with the electronics and microprocessor required to drive the DMD. This provided a good starting point for the development of our prototype.

3 Holographic Display Prototype

The three main components of our prototype are the Texas Instruments LightCrafter™ evaluation module, a semiconductor laser and a lens for increasing the size of the laser beam so it completely covers the surface of the DMD. A bit of Meccano is used to assemble all of the components as shown in figure 1a.

The LightCrafter™ comes with an optics system that allows the device to be used as a projector. This system consists of three LEDs plus a number of lens and half silvered mirrors. To get access to the DMD this optics system must first be removed. Instructions for doing this are on the Texas Instruments website. You should check that the LightCrafter™ works correctly before you remove the optics system, since this is hard test later. A good set of precision screw drivers makes this a lot easier.

The next component is a laser. As shown in figure 1b the user looks into the device to see the hologram, therefore, a low power laser must be used to avoid eye damage. On the other hand, we want to be able to use the device in a room environment, so the laser cannot be too dim. A good compromise is a 10mw laser (Egismos Technology model S8365010D) which is bright enough for the room environment. This laser requires 3V power which is supplied by two AA batteries.

The beam produced by the laser is too narrow to illuminate the whole DMD; therefore a lens assembly is used to spread the beam. In the prototype the 10x microscope objective (Edmund Optics part number 43905) is used for this purpose.

The final step is to assemble all of the components. This could be done on an optical bench, but then again this exceeds our budget for the project. Instead parts from a basic Meccano set were used to mount the lens and laser on the LightCrafter™ module. The metal parts from the Meccano set provide a rigid support for the components and at the same time are easy to work with. A more refined system would use custom designed parts produced by a 3D printer, but the use of Meccano allowed for very rapid prototyping of different lens and laser configurations. A good quality glue is used to attach the laser to a piece of Meccano. Figure 1a shows the

assembled unit.

The total cost of our prototype is:

LightCrafter™	\$610.98
Laser	10.00
Microscope Objective	65.00
Meccano Set	50.00
Total	\$735.98

A graduate student, or motivate undergraduate, should be able to assemble the whole system in a single day.

4 Software

There are many ways of computing interference patterns for holographic displays, some of them are summarized in [Poon 2006]. A particularly simple way of doing this is describing by Lucente [Lucente 1993]. This approach is based on viewing the object to be displayed as a collection of point light sources, computing the hologram for each light source and then summing the holograms. Most of the objects that we would like to display are solid, so at first this doesn't appear to be a good choice. Our holograms have a fixed resolution, so as long as the points are placed close enough together the object will be viewed as solid. The number of points required can be determined from the physics of the device [Goodman 2005], or it can be experimentally determined. For our device both the theoretical calculations and the experiment produced similar results, which is used as the default resolution in our software. This technique is not particularly suitable for complex models, but is good enough for testing the device and illustrating the basic process. This will be discussed in more detail in section 5.

The computation assumes that the plane where the interference pattern is produced is normal to the z axis and is located at $z=0$. The coordinates on this plane are x and y. In the computations x and y correspond to the physical locations of the pixels on the display surface. The points on the object are (x_p, y_p, z_p) and the location of the reference beam (the laser) used to create the hologram is (x_R, y_R, z_R) . The intensity of the light $I(x,y)$ at (x,y) is computed in the following way:

$$I(x,y) = \sum \cos(\Phi(x,y) - \Phi_R(x,y))$$

Where:

$$\Phi(x,y) = k \sqrt{(x - x_p)^2 + (y - y_p)^2 + z_p^2}$$

$$\Phi_R(x,y) = k \sqrt{(x - x_R)^2 + (y - y_R)^2 + z_R^2}$$

The summation in these equations is over the number of points light sources p.

This is clearly a computation that can be parallelized over (x,y) suggesting a GPU based implementation. This would be quite efficient as long as the number of points is small enough to be efficiently packed into GPU memory.

In the case of the DLP 3000 there is one complication in this computation, the pixels are diamond shaped and alternating rows of pixels are offset by half the width of a pixel. This slightly complicates the computation of the x coordinate of the pixels.

A simple graphics package has been built on top of this computation for drawing wire frame objects. The main primitive in this package is a line specified by its end points. A simple line drawing algorithm is used to convert the lines into points which become the light sources for the algorithm. A similar approach could be used to convert polygons into light points. Again this package is sufficient for testing the device and evaluating different holography algorithms, but a more sophisticated package would be required for production graphics.

When loading the images onto the LightCrafter™ the image load and video functions can't be used. These functions apparently process the images in a way that destroys the interference pattern. Instead the pattern load function must be used. The image can be loaded as a pattern sequence of length one, with the image as the only pattern in the sequence. This function only supports 8 bit images, so colour must be handled by three images.

5 Results and Future Work

The accompanying video has two clips that show the display in action. The first clip shows a truncated pyramid with the camera moving to simulate how a user would view the hologram. This shows that the object floats in space as would be expected with a hologram. The second clip shows an animation of the truncated pyramid and was shot with an iPhone camera.

These clips shows two type of artifacts that appear in the display. The first clip shows a bright spot that is to the right of the hologram. This spot is produced by the interaction between the laser and the DMD. It could be caused by the diamond shaped pixels that are used in this particular DMD. The impact of this artifact can be minimized by moving the position of the hologram.

The second artifact is illustrated by the second clip where the hologram is repeated multiple times at regular intervals. This is expected based on the physics of holograms [Goodman 2005] and is further evidence that the device is operating correctly. This artifact can be removed by placing an aperture between the DMD and viewer that selects just one of the hologram images.

On an Intel i7 based laptop the interference pattern shown in figure 2 can be computed in several seconds without using any form of optimization. Taking advantage of the GPU on this laptop would considerably improve the performance of this algorithm. This is an interesting area for future research.

One of the restrictions with this device is the size of the hologram that can be produced. In the current configuration the size of the hologram is restricted by the size of the DMD which is 6.5718 mm by 3.699 mm. A larger hologram could be produced by using projection. This requires a lens to focus the hologram on the projection screen. We have tried placing a lens in front of the DMD and have observed a projected image on a screen placed approximately 30 cm in front of the display. This indicates that it is possible to use our device is a projection configuration as well.

The resolution of the DMD also has an impact on the quality of the holograms. The current device has a resolution of 608x684 pixels which is good enough for the wireframe holograms that we are producing but may not be sufficient for more complex algorithms. Again, this can be solved by using a higher resolution DMD at extra cost.

The two main future refinements to the current design are better packaging and color holograms. A desktop enclosure for the device would make it easier to use. It would allow the user to quickly glance at the holograms and opens the possibility for interaction. The enclosure could include a lens and aperture for projection which would produce a larger hologram image. We are using a 3D printer to prototype this type of enclosure.

Color holograms can be supported by using three interference patterns, one for red, green and blue, instead of the single pattern. This would require the addition of green and blue lasers along with their lens. These lasers are considerably more expensive, but units in the \$100 range can be found. The mounting of multiple lasers would require a considerable reworking of our design, but it could be done. The lasers would need to be synchronized with the display of the corresponding interference patterns. The evaluation module provides pulses that can be used for this synchronization and this would probably require an additional circuit to drive the lasers.

Currently the interference patterns are loaded using the GUI that is provided with the evaluation module. In this mode of operation the evaluation module has a limited amount of storage for patterns, so it couldn't be used for animation or interaction. This GUI can be bypassed by using a program that runs on a host computer and interacts directly with the evaluation module over a USB connection. This is something that we are currently working on and will allow us to interact with the device in real-time.

The software that we have produced was designed to test and evaluate the hardware and is far from efficient. The technique described in section 4 could easily be parallelized on a GPU to give much better performance. Previous work on this technique have used lookup tables to improve performance [Lucente 1993; Masuda et al. 2006; Xu et al. 2008], but it is not clear whether this would be faster than a straight GPU implementation.

We are currently working on a higher level software package that is closer to existing graphics APIs. Geometry descriptions and transformations are essentially the same as other graphics packages, facilitating the porting of the model portion of applications. The main difference is in image generation, where a very different pipeline is used. The device model is also different from that of a typical graphics package. In our design we are attempting to make these as close as possible to other graphics packages reducing the learning curve associated with using this new type of display technology.

6 Conclusions and Acknowledgments

This paper has presented a low cost holographic display device that can be constructed from standard components in about a day. It can be used to test and evaluate algorithms and techniques for producing holograms and will hopefully stimulate research on this topic within computer graphics.

The software packages that we have developed, a more detailed description of the construction process and some of the display's properties can be found at <http://graphics.science.uoit.ca/holography/>.

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