

# Anamorphic Raytracing For Synthetic Alcove Holographic Stereograms

by

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## **Abstract**

An anamorphic ray tracing technique is discussed as it relates to distortion correction for synthetic holographic stereograms. This technique considers each sub-hologram of the area-segmented alcove hologram individually. If each sub-hologram reconstructs the correct information the whole alcove hologram will be undistorted. This research is a part of the development of the alcove format for holographic hardcopy of computer aided design being conducted by the Spatial Imaging Group at the MIT Media Lab.

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# Chapter 1

## Introduction

### 1.1 An Overview

A hologram can reproduce all of the light it “sees” when it is created. Computer graphic ray tracing can determine what light rays are coming from an imaginary object. Computer graphic raytracing has produced some amazingly realistic 2-D images which are begging to be extended into 3 dimensions. It is natural to merge holography and ray tracing to reproduce the three dimensional scene of your imagination.

I will describe the combination of a modified computer graphic ray tracer and a one-step holographic stereogram printer to form a holographic hardcopy system for computer graphics. The raytracing system is modified to carefully model the anamorphic optics of the hologram system.

Although the raytracing system is an extremely general system which can be used to form holograms of arbitrary shape, I will examine it in the context of the alcove holographic system. The alcove hologram is being developed at the MIT Media Lab by the Spatial Imaging Group for the

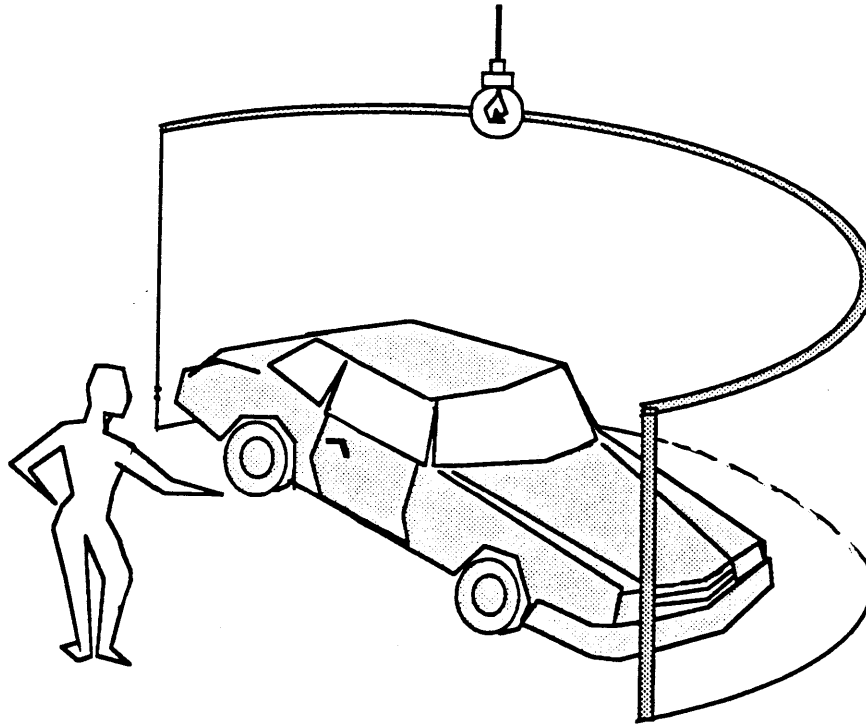


Figure 1.1: The alcove hologram

display of computer aided design data.

The *alcove hologram* is a new type of synthetic holographic stereogram. It's reconstructed image is displayed in a concave half-cylinder which has an angle of view of nearly  $180^\circ$ .

One unique feature of the alcove hologram is that there is no barrier between the the viewer and the image. The image rests in front of the holographic film and can extend behind it as well. The alcove hologram allows the exploitation of strong foreground-background relationships in 3-D imagery.

The alcove hologram is made in one step so that an automated computer peripheral can make it quickly. Video projection systems (such as liquid crystal displays) will be used in the place of the 35mm movie film we currently use to make each sub-hologram.

Reflection holography will be used to make the white light viewable versions of the alcove hologram. This will exploit the color stability of reflection holograms. This stability allows us to make images that do not change color with viewer height.

Large 3-D images can be made using the alcove techniques. In area-segmented holographic stereograms the hologram is made up of many small "sub-holograms." Each sub-hologram can be made with limited laser power. Because the alcove hologram is made up of many sub-holograms, low-power lasers can be used. Available laser power has in the past limited the size of holographic displays to about one square meter. Using the alcove format, available film sizes limit the size of the hologram instead of laser power.

Crossing the hologram surface has been a goal for many one-step holographic systems. Only one previous system has successfully achieved this. (sec. 2.3) Unfortunately, this system has not proven practical due to the size of the optics needed. Here, because the scenes we wish to image are not real, but are computer models of the scene, the "optics" needed to produce the 2-D perspective views can be imaginary. The requirement that the holographic image spans from the center of the alcove to behind the hologram surface *without distortions* motivates much of the current research.

Two concurrent but different approaches to distortion correction of the alcove hologram have evolved within our Spatial Imaging Group at MIT

One school of thought (to which I subscribe) is that if each sub-hologram reconstructs the appropriate image information, the entire image will be undistorted. The other approach [11,12,15] depends on the fact that if each view of the whole hologram is known, the information in it can be put into the correct sub-hologram. Both approaches lead to careful matching of the 2-D frames from which the hologram is made to the holographic systems.

In order to achieve these goals, a system consisting of a one-step reflection holographic printer and carefully matched computer graphics is being designed.

## **1.2 Organization**

This thesis discusses the anamorphic computer graphic techniques needed to produce distortion-free alcove holograms. It also discusses the optical systems to which the computer graphics are carefully matched.

I describe the anamorphic distortion correction techniques of Benton [1] on which my computer graphic raytracing system is based. Next I give a brief description of computer graphic raytracing before showing its application to perspective distortion correction. I then outline an extension to this system which corrects for misconjugation distortions. Finally I discuss a succession of holographic systems leading toward reflection alcove holograms for which these distortion corrected images are being prepared. I briefly touch on the slice and dice technique employed by Mark Holzbach. (For a full description of the slice and dice technique see [1].)



## Chapter 2

# Distortions In Holographic Stereograms

Area-segmented holographic stereograms generally exhibit three classes of image distortion. *Perspective distortion* and *time smear* are the result of the viewer seeing many sub-holograms at the same time. The third class of image distortion arises from non-ideal illumination of the hologram and is called *misconjugation distortion*.

*Perspective distortion* arises when the viewer sees different parts of the image rendered as photographed from different camera locations, only one of which corresponds to the viewer's location at that moment. This distortion becomes severe as images approach the hologram's surface. Because the hologram surface must not be an impenetrable barrier in the alcove format, perspective distortion must be corrected.

*Misconjugation distortion* arises because often it is impossible to recon-



Figure 2.1: Perspective distortion is manifested as curvature of the image of the car in “Banana-Cam”

struct the hologram with a perfect phase conjugate of the original reference beam. When either the reconstruction wavelength or convergence do not match, the reference source distortions are visible in the hologram. Authors such as Benton [3] and Welford [17] discuss the consequences of imperfect conjugate reconstruction.

*Time smear* arises from the viewer looking at many 2-D images all recorded at different moments in time. This can produce effects such as arms appearing to be made of rubber as seen in many Multiplex(tm) holograms. Because the computer can record all the 2-D perspective views necessary to make the alcove hologram at the same instant in time, we can ignore time smear in computer generated stereograms.

## 2.1 Perspective Distortion

Glaser [7,8] describes the perspective distortions, which he terms *anamorphic distortion*, inherent in area-segmented holographic stereograms. This distortion can show itself as curvature in the final hologram (fig 2.1). He showed that if the viewer's eye is located at the plane of the hologram, no perspective distortion will occur.

Two techniques have been proposed for avoiding perspective distortions. Benton [1] shows that if a scaled version of the optical system used to produce the hologram is used to record the original 2-D views, distortions in the hologram will be exactly compensated. Huff and Fusek [12] show that if a set of 2-D perspective views are separated into many vertical strips and carefully rearranged, Benton's cylindrical optical system can be mimicked.

This method I refer to as *slice-and-dice*.

## 2.2 Misconjugation Distortion

Misconjugation distortion occurs because holograms are diffractive elements. As diffractive elements holograms are sensitive to both the wavelength and curvature of the reconstruction wavefront. A hologram can only exactly reconstruct the object wave with which it was made if both the wavelength and curvature of the reconstruction and reference sources match. If both sources do not match, the image will be displaced angularly and magnified. Benton [3] describes these distortions in terms of “miss angles” (i.e., angles by which reconstructed ray misses the object location). Welford [17] uses vector notation to predict the direction of the reconstructed ray. If the vector from the object, reference, and reconstruction source are known, Welford’s isoplanism theory can predict the reconstructed ray vector.

## 2.3 Anamorphic Optical Compensation

Benton reminds us that, as in any autostereoscopic display, the hologram must recreate the intensity and the direction of all light rays visible in the image. Thus the image contained on each individual 2-D photographic frame must exactly correspond to the image reconstructed by each sub-hologram. Benton acquired the 2-D images for the Multiplex(tm) format holograms he created by building a scaled version of the Multiplex(tm)

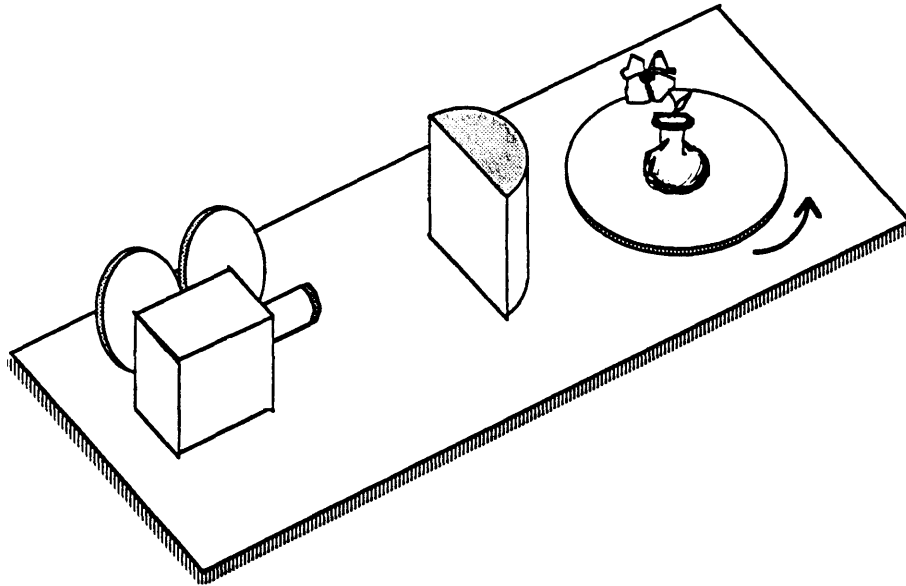


Figure 2.2: System used by Benton to collect distortion corrected images.

printer's optical system. He then shot the 1080 movie frames needed for the 360° multiplex hologram through this camera (fig. 2.2).

These holograms were the first one-step area-segmented holographic stereograms in which the images penetrated the hologram plane. Unfortunately, this method for collecting the 2-D perspective views necessary to make a hologram the size of a person, for example, requires an  $f/1$  cylindrical lens the size of a person. Lenses of this size are prone to severe aberrations and are not practical to build.

A close look at the optical ~~system~~ (see sec.4.1) shows that the holo-

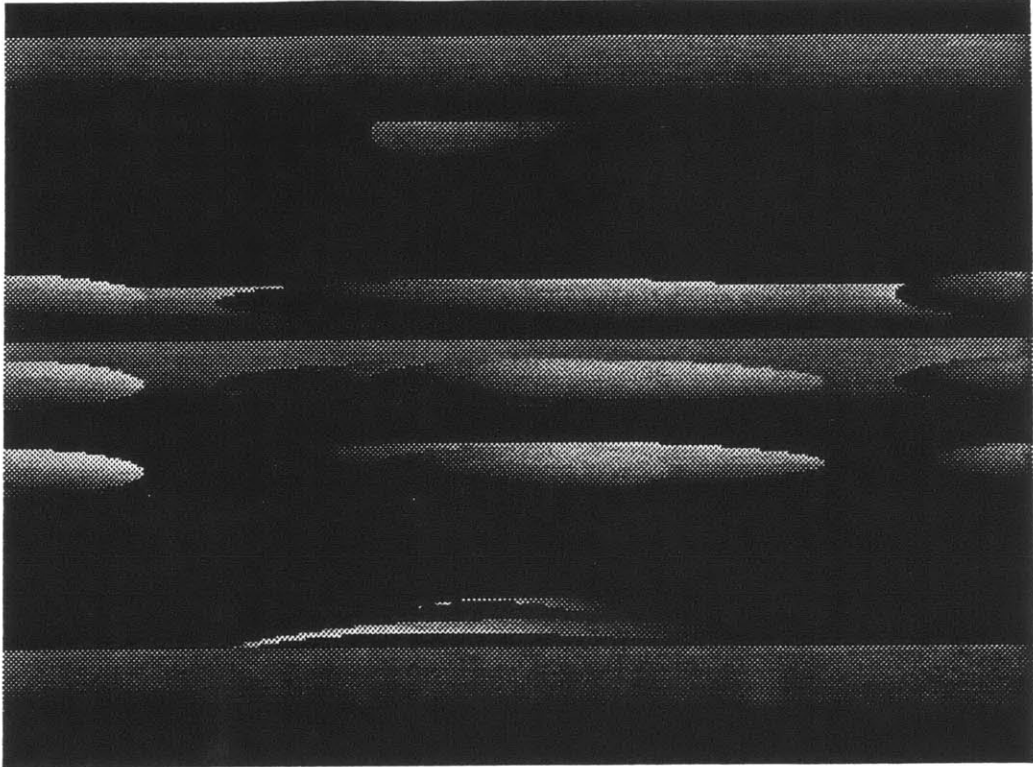


Figure 2.3: Photograph of one distortion compensated frame used to produce "Spheres"

gram is located at the focal point of a large cylindrical lens. The desired viewer locations are located at the horizontal stripe image of the spherical projection/exposing lens as seen through the cylindrical field lens.

Images recorded using this optical system have a different appearance from ordinary perspective views. Objects forward as far as the cylindrical lens surface will appear normal: A circular object at the cylindrical lens surface will appear circular on the film. As the circle moves away the vertical size of its photographic image decreases, as in a photograph, but its horizontal size increases. When the circle reaches the hologram plane (the focus of the cylindrical lens) its width becomes infinite and its image fills the width of the film, or the cylindrical lens. As the object withdraws further, its image reverses from right to left and becomes circular again only at infinitely large distances behind the hologram.[16]

The anamorphic imaging approach considers each sub-hologram individually, in contrast to the slice-and-dice approach of Huff et. al. [12,13], considers each allowed view point individually. The slice-and-dice system begins with a set of 2-D perspective views of the scene, which are then broken up into individual vertical slices. These vertical slices are then shuffled into the appropriate 2-D images required to form a hologram (as described in detail by Holzbach [11]). The final 2-D images generated by this technique closely resemble the images formed by Benton's technique. Although developed for Multiplex(tm) holograms, both of these models for distortion correction in area-segmented holographic stereograms are valid for the alcove format.

# Chapter 3

## Computer Graphic Techniques

### 3.1 Computer Graphic Raytracing

Computer graphic ray tracing is a technique that models the propagation of light in order to render images of 3-D scenes.

The equation of a light ray beginning at a view point and passing through a pixel on the “film plane” is intersected with a mathematical description of each image element (an image element is an object, or part thereof, in the picture.) If this ray intersects an element, the intensity at the nearest intersection point is calculated from its surface characteristics and the light source(s) characteristics and position(s) in order to get a realistic surface appearance. The intensities of the reflected and refracted rays may be calculated so that their contributions can be added to the intensity of the spot.

Many refinements of this technique are used in practice. For example, rays are often cast to each light source in order to determine if the point on an element is in shadow. Extensions to the basic algorithm have been



described to more accurately model real camera optics [5].

Refinements in the modeling of the 3-D scene can increase the efficiency of the algorithm. Current models are often quadric surfaces (spheres, ellipsoids, cylinders etc.). Quadric surface patches and planar polygons can also be used to describe scenes. Sophisticated groupings of objects [9] can also be used to greatly reduce the number of calculations needed to determine if the light ray hits an image element.

## 3.2 Anamorphic Ray Tracing

In order to implement Benton's distortion correction techniques, we must consider each pixel on the 2-D composite view from which each sub-hologram is made and calculate the source of the light hitting this spot on the film. Remembering that each ray of light reconstructed by each sub-hologram must carry the image modulation appropriate for that ray's direction, we realize that each spot on the film must also contain a recording of the light emerging from that sub-hologram and traveling through the holographic recording optical system. Computer graphic ray tracing is used to calculate the appropriate intensity for each pixel of our 2-D composite image.

A naive and inefficient way to solve this problem is to use ray tracing to follow a ray through the mathematical description of each refracting surface in the optical system until an object is hit. We would have to calculate several intersections and refractions at each pixel (one for each optical surface) just to get through the optical system. This would also

limit our allowable image space to the space beyond the last optic, but the large cylindrical lens is in the center of the alcove, where we wish to place objects. Some other method for describing the rays must be found.

A sub-hologram cannot “know” what the optical system behind the large cylindrical lens looks like. All that a sub-hologram “sees” when it is made is the set of light rays coming from a horizontal line at the viewing distance. This line is the horizontal image of the projection optics formed by the cylindrical field lens (see fig. 4.1).

This anamorphic optical system can be modeled as a pinhole camera with two crossed slits instead of a pinhole. One of the slits corresponds to the vertical strip of the sub-hologram. The other slit corresponds to the horizontal allowed viewer locations.

From the viewpoint of the sub-hologram, each ray of light is coming from the direction that the last optic sends it. This leads us to a model of the optical system in which all rays pass through the vertical line described by the sub-hologram and the horizontal line at the desired viewing distance.

This raytracer, based on the *crossed slit* model, is used to produce the anamorphic images from which we make some of our holograms. This raytracer is shown in a programming example in Appendix A.

### 3.3 Misconjugate Distortion Correction

Modifications to the raytracing program can be made to exactly compensate for non-perfect conjugate illumination. This is important because the final alcove holograms will be three color separations. Each of the three

colors will be recorded using the same laser. Thus at least two of the colors will not be reconstructed with perfect conjugate illumination.

Until this point we have insured that the object and reconstruction ray directions for each pixel of the 2-D frame are equal. When the reconstruction beam's wavelength or curvature do not match the reference beam (imperfect conjugate illumination), distortions occur in the final hologram. In order to precompensate for these distortions, we must calculate the reconstructed ray direction from the known object, reference, and illumination ray directions and wavelengths.

Holloway and Ferrante [10] describe a method based on Welford's [17] isoplanism theory to predict these distortions in holographic optical elements. We can use this method to modify our raytracing system by the addition of a subroutine which calculates  $\hat{r}'_o$  in the equation:

$$\hat{n} \times (\hat{r}'_o - \hat{r}'_r) = m(\lambda'/\lambda)[\hat{n} \times (\hat{r}_o - \hat{r}_r)],$$

where:  $\hat{n}$  = hologram normal

$\hat{r}_o$  = ray from object

$\hat{r}_r$  = ray from reference

$\hat{r}'_r$  = reconstruction ray

$\hat{r}'_o$  = reconstructed ray

$m$  = diffraction order

$\lambda$  = recording wavelength

$\lambda'$  = reconstruction wavelength

This subroutine should be used to calculate the reconstructed ray direction so that we can raytrace using the conjugate of the reconstructed wave instead of the object wave. With this addition to the raytracing system, the 2-D frames needed to produce undistorted full-color alcove holograms can be created.

### **3.4 From Sub-hologram to Hologram**

Now that we can make the 2-D frame needed for one sub-hologram, a sequence of such frames is needed for the whole hologram. In the case of the flat format stereogram, after one frame is calculated, the “camera” is moved horizontally the width of the sub-hologram before calculating the next frame (fig. 3.1). This is repeated until a frame has been calculated for each sub-hologram.

In the case of the alcove hologram, the camera must be rotated around a point in the center of the alcove such that the vertical line which represents the sub-hologram moves along the surface of the hologram one sub-hologram width.(fig. 3.2) Using this camera motion, the normal to the sub-hologram always points directly at the center of the imaginary optical system.

Frames for a hologram of arbitrary shape can be calculated using the anamorphic raytracing system. If images for another format hologram are to be calculated, then our imaginary camera must be translated such that

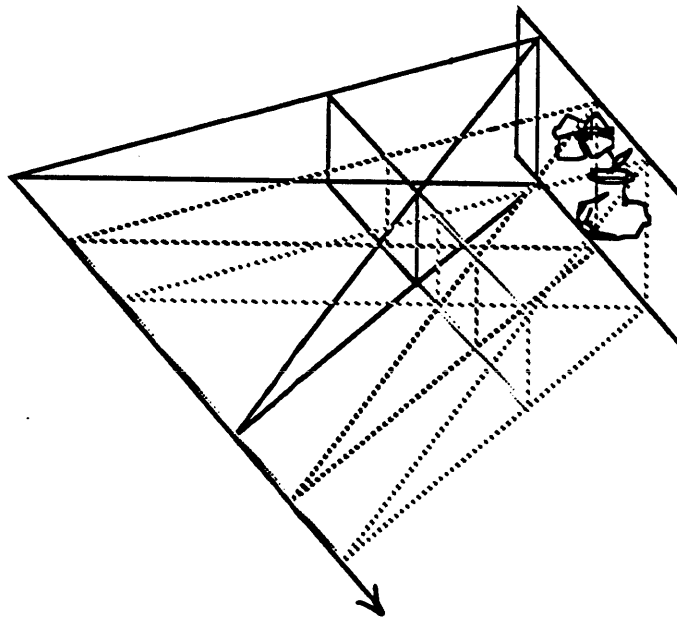


Figure 3.1: Camera motion for distortion compensated flat holograms

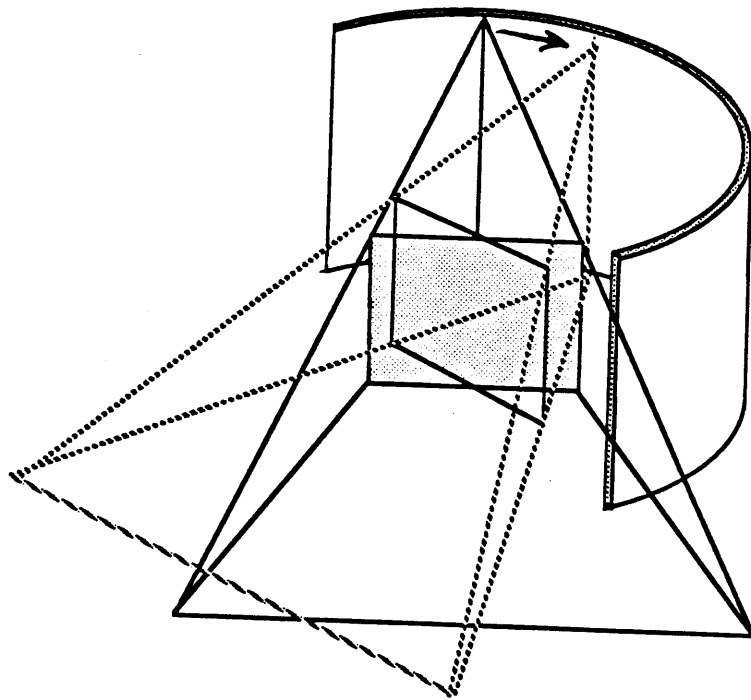


Figure 3.2: Camera motion for distortion compensated alcove holograms

its focus stays on the hologram plane and its center is always at the normal to the sub-hologram for which it is calculating the image.

### 3.5 Experimental Results

In our experiments, 200 raytraced frames were calculated using the anamorphic raytracer outlined in Appendix A. This raytracer, although modified to simulate the anamorphic optical system, did not employ any optimizations to reduce the computational load. The test scene consisted of an array of 47 spheres arranged in two 3 x 3 x 3 grid patterns. One sphere was left out of each layer of the grids in order to check orientation. Between each frame the "optical system" was moved horizontally relative to the scene description by 1mm (fig. 3.1). Perfect conjugate reconstruction was assumed.

Each frame took 11.9 cpu minutes to render on a VAX 11/785 for a total of 40 cpu hours for the whole image. Each 2-D anamorphic composite frame was then transferred to 35mm motion picture film using a Mitchell/Dunn Instruments film recording system. Each frame was then printed as a hologram (fig. 3.3) using the modified rainbow Multiplex(tm) system described in section 4.2.

A second image was calculated using the same system. This image showed a chess set made out of spheres and planar polygons. (fig 3.4) In this image we allowed three levels of reflection and had two light sources.

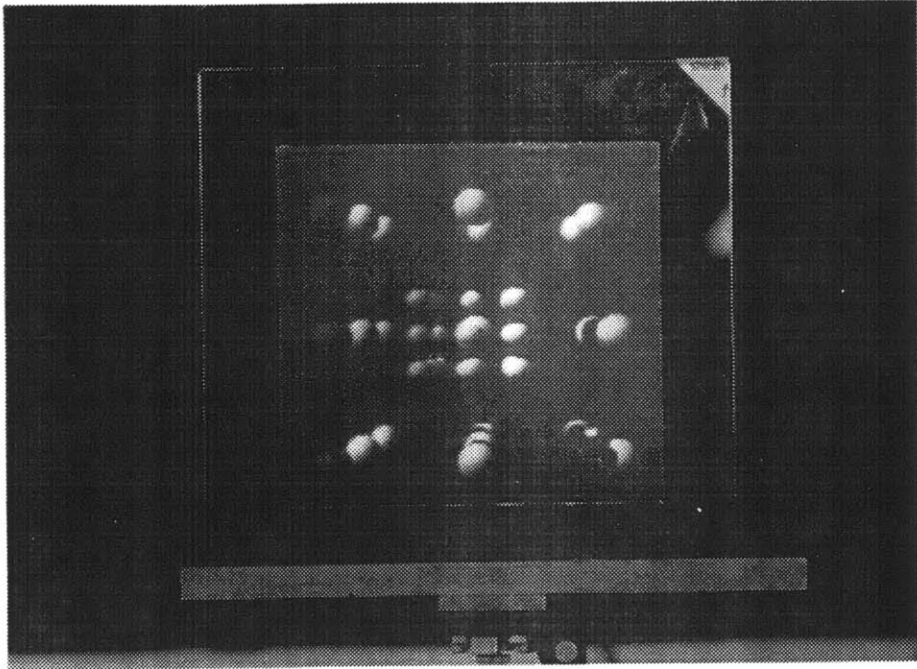


Figure 3.3: "Spheres"



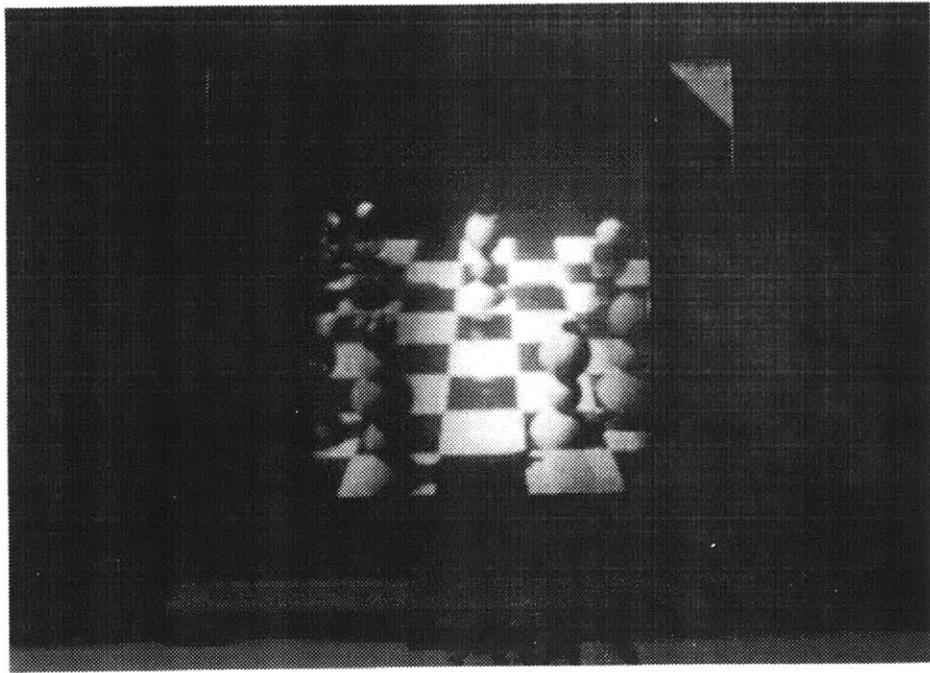


Figure 3.4: "Chess Set"

## 3.6 Computational Optimization

Using the optical system described in section 4.2 the raytraced, distortion-compensated images "Chess Set" (fig. 3.4) and "Spheres" (fig. 3.3) were recorded holographically. In the test grid image both the cubical array of spheres in front and behind the hologram plane showed no noticeable distortion. This hologram showed that the ray tracing method can be successfully used to prepare 3-D data bases for holographic display. The chess set image shows that the model for reflections and shadows in computer graphic raytracing is consistent with the 3-D needs of holographic display. Careful consideration of each sub-image used to form a holographic stereogram can lead to high quality holographic stereograms without limits to the depth, forward or back, imposed by distortion.

As is evident by the total cpu time consumed for each of our raytraced scenes, raytracing uses a lot of cpu time. At each pixel the computer must solve the quadratic equation for each object to check for an intersection. Using this algorithm, if an object is hit a ray must be traced to each light source to check if the point of interest is in shadow. Then if the object is reflective or transparent another ray must be traced in the reflected or transmitted direction. Raytracing is a problem naturally suited for an array processor because it is dominated heavily by the intersection calculations.

We implemented the intersection calculation part of the raytracing code on a Weitek Matrix Transformation Processor board. This array processor was installed on a Sun I by Sun Microsystems. The performance of the Sun/Weitek combination could be further improved by moving the illumi-

nation calculations to the array processor instead of letting the Sun system make these calculations.

Parallel computers such as the Connection Machine by Thinking Machines Corp. can also be used to calculate ray traced images. This machine, with its single instruction multiple data architecture, could calculate the intersection of many rays with each object simultaneously.

Even with the computational expense of anamorphic raytracing for one-step holographic stereograms, the versatility of this technique will keep it viable as a method to produce the 2-D images needed for holographic display of computer-aided design.

# Chapter 4

## Holographic Optical Systems

To make the alcove hologram, a one-step reflection area-segmented holographic stereogram technique was chosen. We feel that the hologram must be made in one step so that an automated computer peripheral can make holograms with wide viewing angles in reasonable time using low power lasers.

As an area-segmented holographic stereogram, the whole large hologram is composed of a series of many sub-holograms. Each of these sub holograms can be made with limited laser power so a small laser can be used to make a large complete hologram. Available laser power has in the past limited the size of holographic displays to about one square meter. Alcove format holographic stereograms that are one meter by three meters can be made using relatively low power lasers.

We plan to use reflection holography to make the white light viewable versions of the alcove holograms. Reflection holography is well suited to the alcove format due to the requirements that the holograms be full color and

easy to display. Emulsion swelling techniques can be used in order to control color for the three color separations needed to produce full color holograms. Unlike color control methods for transmission holography, methods for color control of reflection holograms create images with stable color over wide ranges of viewer height.

The next sections describe four different stages leading toward reflection alcove holograms. These stages are rainbow flat holograms, laser transmission flat holograms, laser transmission alcove holograms, and reflection alcove holograms. First we will describe in detail Cross's [6] Multiplex(tm) system. Because our systems all build on this basic setup, a thorough understanding of the Multiplex(tm) system is necessary.

## 4.1 Cross Multiplex System

In Cross's Multiplex(tm) system [6] perspective views are collected by a standard movie camera. The subject is usually placed on a turntable and three movie frames are recorded for each degree of rotation. In practice 1080 different perspective views are collected for a 360° hologram.

Each view is recorded holographically using an optical system as pictured in fig. 4.1. In the figure you can see that each frame is projected using a spherical projection lens into a spherical field lens followed by a cylindrical field lens before reaching the holographic film where the hologram is formed. The large spherical field lens serves to form an image of

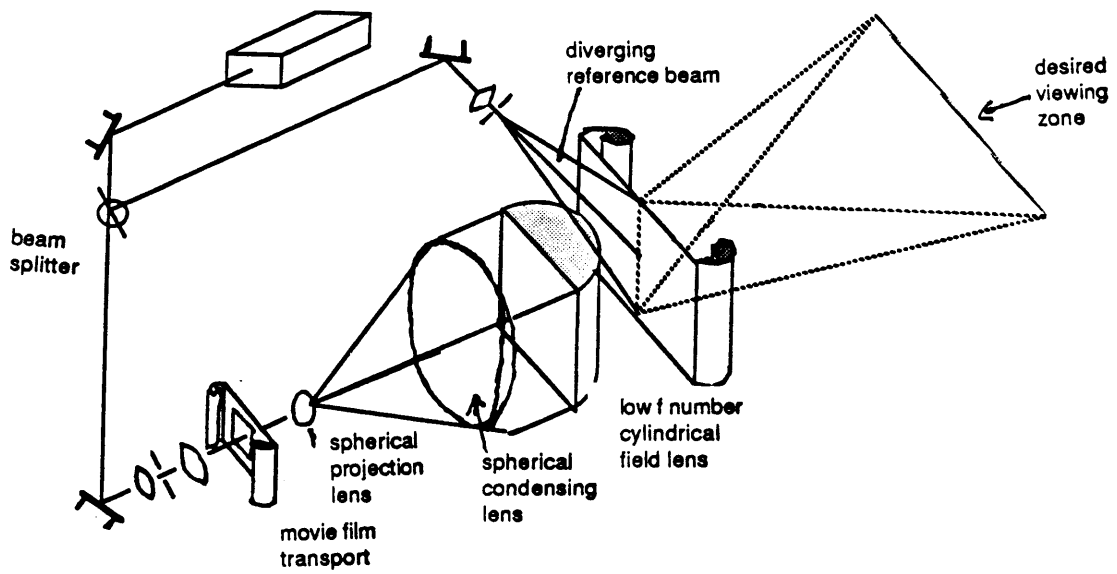


Figure 4.1: Multiplex(tm) holographic optical system

the projection lens at the desired viewing distance beyond the hologram plane. This vertical focusing serves to form the horizontal slit needed for single color viewing of the rainbow hologram.

The large cylindrical field lens condenses the object beam in the horizontal direction. A hologram is formed at the focus of this cylindrical lens by interference with a reference beam which diverges from a point directly over the cylindrical field lens. The sub-hologram will have a viewing angle related to the  $f$ -number of the cylindrical field lens.

A step-and-repeat process is used to advance the movie and holographic frames into position until each frame is recorded holographically. The holographic film is then processed and wrapped around a cylinder. An illumination source located below the center of the cylinder is then used to reconstruct the virtual image of the hologram.

## 4.2 Rainbow Flat Holographic System

Two modifications were made to the Multiplex(tm) system in order to produce rainbow flat holographic stereograms ( fig. 4.2). The reference beam was collimated and the large spherical condensing lens was removed from the object beam. Minor modifications to the projection optics were also made to account for the aspect ratio of the cylindrical field lens that was available.

The diverging reference source was collimated in order to match the horizontal and vertical divergence of the reconstruction source. From the

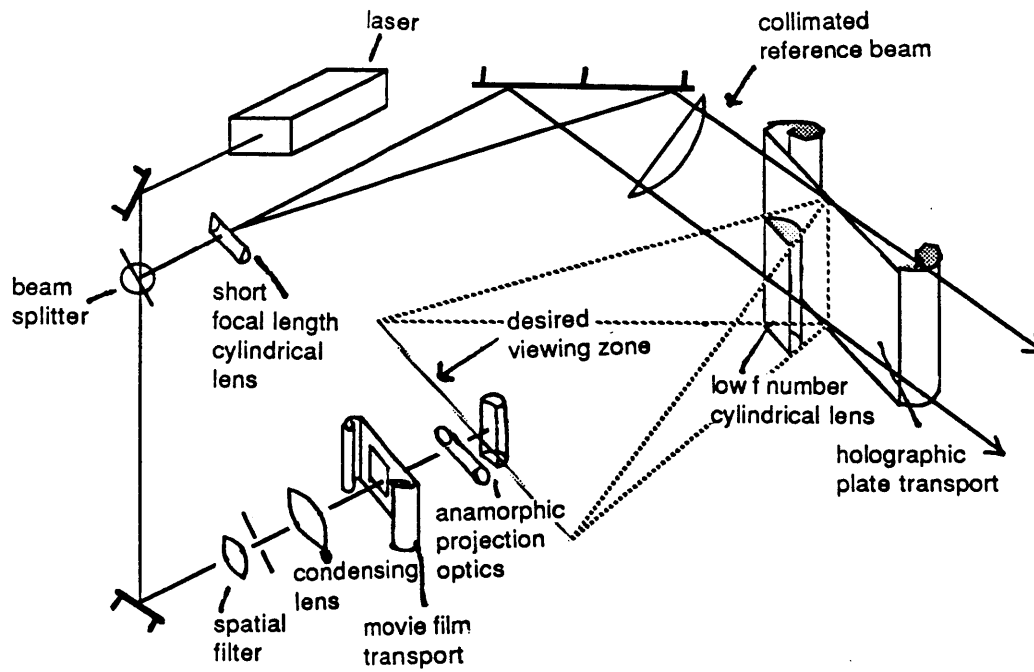


Figure 4.2: Holographic system for rainbow flat holograms



geometry of the system, we see that the reconstruction source must diverge horizontally from the center of curvature of the hologram when it is displayed. If the reference beam is collimated vertically when the hologram is made, the need for a large cylindrical optic in the display is avoided. This also allows the choice of reconstructing the hologram with the original reference source or its phase conjugate.

Reconstruction with the phase conjugate of the reference source was chosen because a large spherical condensing lens was not available to converge the object beam to the desired viewing distance. This places the desired viewing location at the focus of the projection optics. Unfortunately this forced us to sacrifice a few degrees of viewing angle by not moving the focus of  $f/2$  cylindrical field lens away from the lens.

Because we did not have a large oil-filled Plexiglas cylindrical lens as used in most Multiplex(tm) printers, we used a rectangular plastic Fresnel cylindrical lens as the cylindrical field lens in our system. This necessitated the use of an anamorphic projection system in order to correct for the non-square aspect ratio of the cylindrical field lens. We were also able to focus the horizontal and vertical components of our 2-D distortion-compensated movie frames in differing locations. The horizontal component was focused at the rear surface of the cylindrical field lens while the vertical component was focused at the hologram surface.

## 4.3 Laser Transmission Flat Holographic System

In preparation for the move to reflection format, we prepared a series of laser transmission stereograms. Because reflection holograms can be modeled as a combination of a laser transmission hologram and an interference filter [4], the laser transmission format was chosen as a prototype format in which the distortion correction techniques could be studied without the additional problems imposed by reflection holography.

For the first experiment using laser transmission holography, the plastic Fresnel lens from the previous rainbow transmission hologram setup was replaced by a diffusion screen. A laser transmission hologram of “spheres” was produced. As expected, this image looked very similar to the rainbow version in its horizontal parallax direction. In the vertical direction this laser transmission hologram differed greatly from its white light cousin. Looking at the holographic recording setup for each of these hologram types we see that the inherent vertical parallax location differs. In the laser transmission case, the vertical parallax inherent to the hologram system is located at the hologram plane. In the laser transmission case the inherent vertical parallax location is at the diffusion screen upon which each 2-D image was projected.

The laser transmission test grid image was extremely difficult to look at because of difference in the location of the horizontal and vertical parallax. Psychologically, the astigmatism of this image does not allow the viewer to believe that the object is solid.

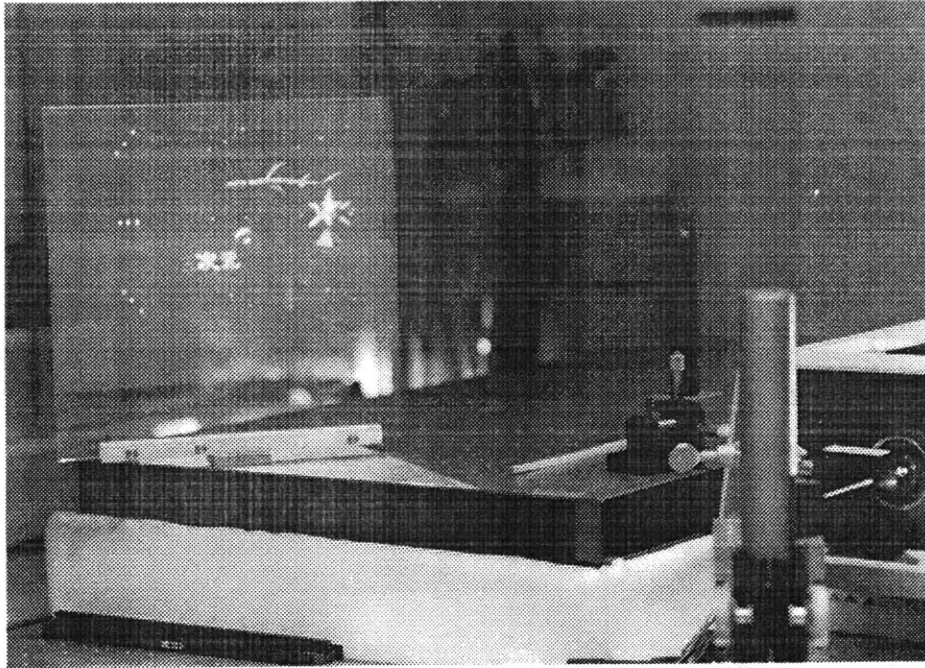


Figure 4.3: “Sangigen”

A new set of images was prepared for transfer as laser transmission flat holograms. These images, “Shark Sushi” and “Sangigen”, were prepared using the slice and dice technique implemented by Mark Holzbach. In order to overcome the astigmatism problem of the previous laser transmission image, their central object was placed at the so called *sweet spot*, which is centered at the location of the diffusion screen.

“Shark Sushi” and “Sangigen” were also used to test a new holographic setup in which the ground glass diffusion screen used in the previous setup was replaced by a high-efficiency holographic diffusion screen [2]. The square aspect ratio of the holographic diffusion screen allowed us to use

a high-quality spherical projection lens to project the 2-D sub-images. A wider ( $f/1$ ) angle of view is also provided for in the design of the holographic diffusion screen.

## 4.4 Laser Transmission Alcove Holographic System

Several images were prepared using the slice and dice technique for holographic recording as alcove holograms using the holographic setup of fig 4.4. For each alcove hologram a total of 950 sub-holograms (one per running mm of the final hologram) was made. A vertically converging reference source was used in order to match the requirement that the reconstruction source diverge from the center of curvature of the hologram when reconstructed with conjugate illumination.

Five alcove holograms were produced. First a set of perspective views (not slice and diced) of a computer graphic Camaro (an American automobile) was made into an alcove hologram. This image was confined to the area near the center of the alcove. Although the image was not obliterated by perspective distortion, it was later dubbed "Banana Cam" because of the marked curvature seen in the image. This image, produced before the slice and dice computer program was completed, not only served to debug the holographic setup but also served as a useful control image.

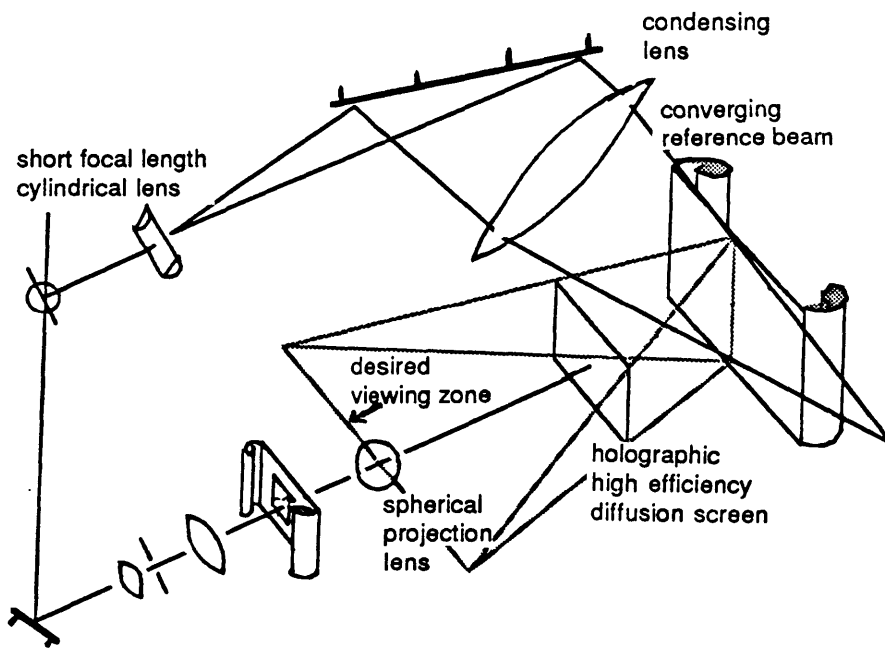


Figure 4.4: Laser transmission alcove setup

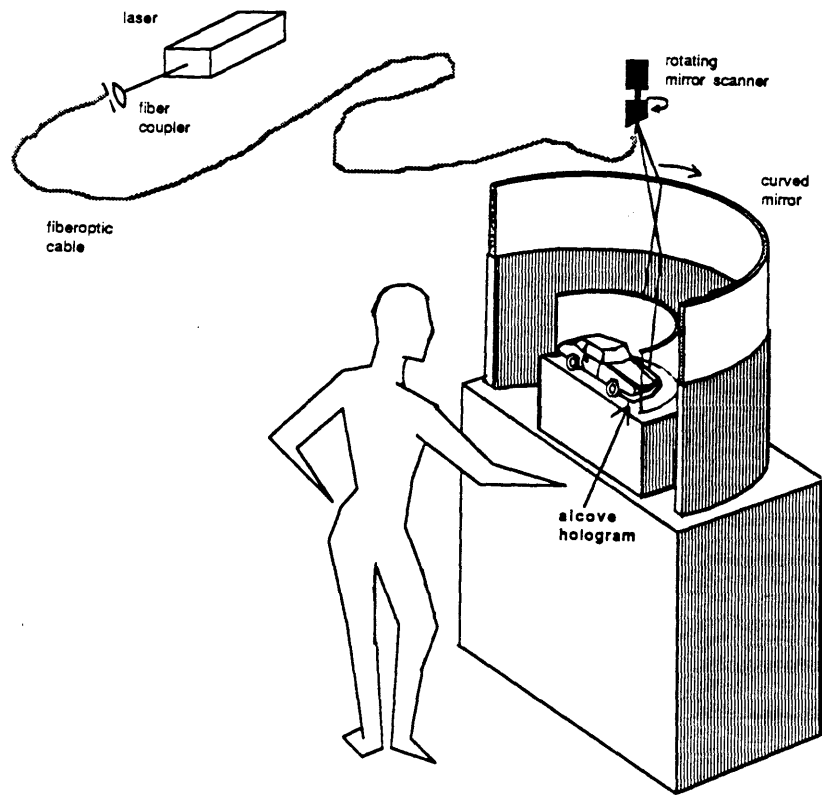


Figure 4.5: "The laser transmission alcove display"

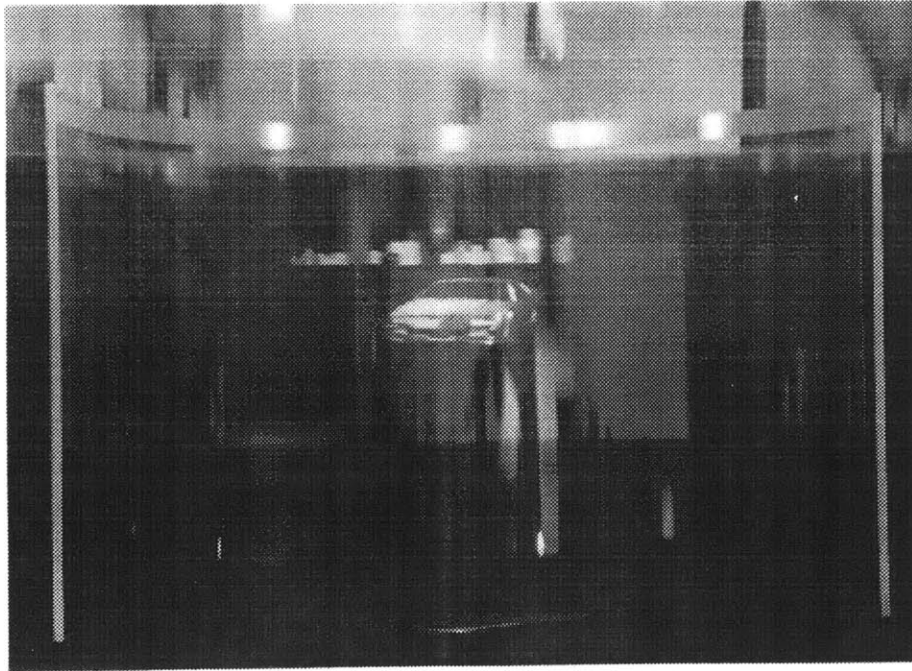


Figure 4.6: "Bos-Cam"

A test pattern dubbed "Target" consisting of an array of wire frame cubes and a concentric circle pattern was calculated in order to test the slice and dice distortion correction technique for the alcove format. This image spanned from about one foot in front of the center of the two foot diameter alcove to about one foot behind its surface. Although this image crosses the hologram plane without distortion, its width suffers from the limited angle of view of each sub-hologram.

After we tested the slice and dice distortion compensation technique with the target image, we produced three new images. The "Banana Cam"

was straightened out and an image dubbed "Bos-Cam" of the Camaro with the Boston skyline in the background were produced as examples of the alcove hologram for automotive design applications. An image which began as a computer aided tomography scan of a dislocated artificial hip implant was also made, in order to explore the use of the alcove hologram for medical imaging applications.

## 4.5 Reflection Alcove Holograms

After our successes with the laser transmission system we made a reflection hologram using the seemingly simple method of bringing the reference beam in from the opposite side of the holographic plate. Unfortunately this hologram suffered severely from spectral blurring problems. The image was unrecognizable when reconstructed with white light. However when reconstructed with laser light the image was sharp and clear.

Reflection holograms can be reconstructed in white light because the hologram structure includes an interference mirror. If the reflection bandwidth of this interference mirror is small, reflection holograms of great depth can be made. Our reflection alcove hologram showed spectral blur because the bandwidth of reflection holograms made in silver halide emulsions is relatively large.

One way to reduce the bandwidth of the hologram is to increase the emulsion thickness, thereby increasing the number of layers in the interference mirror. Another way to reduce the bandwidth is to increase the



refractive index modulation of each layer of the interference mirror. Using 15 micron dichromated gelatin emulsions, Ishii and Murata [14] showed that the smallest resolvable point we can expect to resolve at 300mm is 4mm across. Because the silver halide emulsions we use are only five microns thick, we cannot attain even that modest resolution.

Another way to reduce the reconstructed bandwidth of the hologram is to limit the bandwidth of the reconstruction source, which can be achieved by reconstructing the hologram using a laser or a gas discharge lamp. Because the hologram contains its own wide bandwidth interference filter, the gas discharge lamp can have many spectral lines as long as only one falls within the reconstruction band of the hologram. A full color hologram can be made using this technique if the three colors reconstructed by the hologram match three spectral lines in the discharge lamp. Unfortunately such a lamp is not easily available or very bright.

# Chapter 5

## Conclusions

I have shown an anamorphic raytracing system for preparing 2-D computer graphic images for 3-D display as alcove holograms. This system considers each sub-hologram of an area-segmented hologram separately in order to correct distortions in the whole hologram. This method for distortion correction of area-segmented holographic stereograms depends upon a close match between the holographic system and the 2-D frames from which each sub hologram is made. A crossed-slit model for the holographic optical system is used to determine the direction and origin of the rays of light from which each sub-hologram is made. Using this information, the direction and intensity of each ray of light reconstructed by the sub-hologram is calculated. Because all sub-holograms carry the appropriate image information the combination of all sub-holograms will be undistorted.

The alcove hologram is a new display format. In the alcove format, holograms are displayed as concave half-cylinders. Their images can have

almost 180° fields of view. The anamorphic distortion correction technique makes it possible to place images in the center of the alcove or behind the film plane.

The holographic film has been a barrier in previous one-step holographic stereogram systems. The alcove hologram breaks the physical barrier separating the viewer's space from the image space. It also breaks the limit on depth previously imposed by the holographic film.

The anamorphic raytracing system can also account for misconjugation distortion by applying Welford's isoplanism theories to the computer graphic raytracing. This is important when preparing images for color holograms where the reconstruction and recording wavelengths will not match.

Although anamorphic raytracing is computationally more expensive than other methods for distortion correction of alcove holograms, I feel that its generality justifies its expense. New and faster computer graphic hardware and software are rapidly reducing the computational cost. Unlike the slice-and-dice method, anamorphic raytracing has a short lag time between the time the computation is begun and the time that holographic printing can begin. Once the first 2-D frame is calculated, the first sub-hologram can be made. Using the slice-and-dice method most of the computation must be completed before the hologram production can be begun. The massive data storage required for the slice and dice is also not necessary using anamorphic raytracing because each sub-hologram is considered separately.

A series of holographic systems has also been described. These holographic systems, beginning with a system for one-step rainbow flat stereograms, begin the trail toward reflection alcove stereograms. In preparation

for the move to reflection holography we made laser transmission alcove holograms wich allowed us to debug the distortion correction techniques without the additional problems of reflection holography.

## Chapter 6

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# Appendix A

## Programing Example

```
dotrace()                                dotrace
{
    /* hologrampt, viewpt, dir are point triplets */
    /* pixel is a triplet in rgb space. */
    /* struct object contains the object definition */
    holoh = 24.5 * 12; /* 12" square hologram */
    hologrampt.x = hologrampt.z = 0;
    hologrampt.y = holoh/2;
    viewpt.y = 0;
    viewpt.z = viewdist = 3 * holoh;
    dx = -2 * (-holoh/2)/hortres;
    dy = holoh/vertres;
    for(i = 0; i < vertres; i++) {
        viewpt.x = -holoh/2;
        for(j = 0; j < hortres; j++){
            dir.x = hologrampt.x - viewpt.x ;
            dir.y = hologrampt.y - viewpt.y ;
            dir.z = hologrampt.z - viewpt.z ;
            raytrace(&viewpt,&dir,&pixel,
                (struct object *) NULL);
            /* struct object contains
                the object definition */
            outpixel(&pixel); /* write pixel to file*/
        }
    }
}
```

```
        viewpt.x += dx;
    } /* End for */
    hologrampt.y -= dy;
} /* End for */
}
```

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