Three-Dimensional Image Processing for Synthetic Holographic Stereograms

by

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Abstract

A digital image processing technique is presented that allows conventionally produced images to be prepared for undistorted printing in one-step holographic stereograms. This technique effectively predistorts the source 2D image set for a holographic stereogram to compensate for the distorting effects of its display geometry. The resulting stereograms can have undistorted images that occupy space in front, back, and through the hologram surface. This technique is much more convenient that the current alternatives which either require unusual large optics, or much more intensive use of computer resources. It should therefore facilitate the fast and convenient production of one-step stereograms which are excellent 3D hardcopy displays with potential for applications that require fast visual communication of complex 3D information.

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Chapter 1

Introduction

The potential for holographic stereograms to facilitate visual communications is great. Some types of holographic stereograms have already proven to be an effective way of presenting 3D information from many sources, and greatly aid in its comprehension and interpretation. The further development of the technology calls for faster and more convenient methods for both image generation and production of the final holographic display. One-step methods for printing holographic stereograms are known, but the use of conventional perspective images (either photo-optically recorded or computer-generated) results in a final output with strong geometric distortions. This thesis presents methods by which the geometric distortions can be eliminated with the help of digital image processing.

1.1 Brief Background of Problem

Holographic stereograms are a class of 3D holographic display styles that are composited from many[1] 2D images[4,5,9,2]. The display presents the binocular viewer with a range of 2D stereo-pairs of a scene at appropriate locations in space to give the illusion of a 3D scene.

A recognized problem of Multiplex™ type one-step stereograms has been the distortion caused by the mismatch between the standard perspective projection for generating images (photo-optically or computer-generated) and the non-standard anamorphic projection required by the hologram printer. The exact understanding of this distortion requires close analysis of the holographic printing and display geometry which will be discussed in the next chapter.

Let it suffice now to say that the 2D images of the scene required by the stereogram printer discussed in the next chapter are the anamorphic projections through a cylindrical lens with an f-number determined by the geometry of the stereogram printer[1]. For photo-optical recordings, or for ray-traced computer-graphic renderings, acquisition of images through a real or computer simulated cylindrical lens with the proper f-number is a technique which works in principle for any type of image. However, there are significant practical problems working with actual large cylindrical lenses or with computer-graphic ray-tracing simulated cylindrical lenses.

Cylindrical lenses for recording real scenes must have a size approaching

[1] usually ranging between 10^2 to 10^4

that of the subject. For people-sized subjects this is difficult, for building-sized images or larger, impossible. In general, the production of good-quality, low-f-number, large cylindrical lenses is very expensive and time-consuming. The practical problems of actually employing a large cylindrical lens, after it is made, are also significant because strict positioning and motion-control would require large-scale special equipment for the big lens. For a computer simulated cylindrical lens, the problems are much less severe. The major practical problem is the exorbitant time required for most computers today to generate even moderately complex ray-traced scenes.

1.2 Digital solutions

1.2.1 Anamorphic ray-tracing

Ray-traced computer graphics is an extremely powerful graphics method that simulates sampled light rays that can reflect and refract off and through a synthetic world of analytic surfaces. Because it approaches a physically correct simulation of the real world, the results of this technique can be very realistic. The tradeoff is that ray-surface intersections must be computed for each pixel many times, depending on the number and extent of the analytically defined surfaces and the number of reflections each ray is allowed. For moderately complex synthetic scenes with moderate resolution, this is a very time-consuming method. However, the definition and inclusion of a simulated cylindrical lens is straightforward in the ray-tracing context.

1.2.2 Digital Remapping

The remapping solutions that are presented in this thesis take standard perspective images as input and produce the required type of anamorphic perspective images as output. Each standard image is decomposed into vertical strips and recomposited with other strips from other images in a manner determined by the final viewing geometry. In the final display geometry, the original standard images become visible again as the display reverses this mapping process.

1.3 Comparison of Digital Solutions

The ray-tracing method is the most desirable one for synthetic scenes that require very realistic lighting effects such as complex reflections and refractions. The computational resources for rendering all the images will be great for most moderately complex images; this means that either the computation will take a very long time to complete, or one must gain access to special supercomputing resources to accomplish the job in less time. However, the realism produced by this technique is difficult to match for many kinds of images.

In contrast, the remapping solution has the advantages that one can see the images the way they should appear in the display before processing begins. This is valuable for previsualizing the results. Also, photo-optically recorded images can be used, and even combined with synthetic images for whatever purpose. Computer-graphic images can be computed with less resource-intensive, methods such as polygon-based shaded rendering techniques. These methods work very well for many types of effects and scenes, and are far faster or less resource intensive than ray-tracing methods. Real-time flight-simulators exist today that can render moderately complex scenes in one thirtieth of a second at 24-bit color NTSC resolution (640 x 480) pixels.

1.4 Motivation for this work

The digital remapping solution is of great importance to the development of holographic stereograms. For computer-graphic images, this method allows more resource-efficient techniques to be used. For real scenes, it allows recordings from standard-perspective cameras to be processed for one-step holographic displays; the alternative is to record with an unwieldy large and expensive cylindrical lens. This method also allows image designers to previsualize the results. And it allows more types of scenes to be created because images from different sources can be more easily combined with this technique than with most.

Chapter 2

Distortion Analysis

2.1 Printer and Display Geometry

The design of a holographic stereogram must allow a binocular viewer to see correct stereo-pairs of images over a range of viewing positions. Figure 2.1 illustrates a binocular viewer correctly positioned in front of a holographic stereogram. In this figure, different 2D images are seen by each eye. The stereo-pair for the binocular viewer in this viewing position can be carefully produced so that it creates the illusion of a 3D scene. Other images can be similarly projected to neighboring locations in the viewing zone so that if a viewer moves to the right or to the left in the zone, the illusion of the 3D scene is further perpetuated.

This section will describe the geometry for the printing and display of one-step holographic stereograms in enough detail for the reader to understand the sources of and solutions for their geometric distortions.

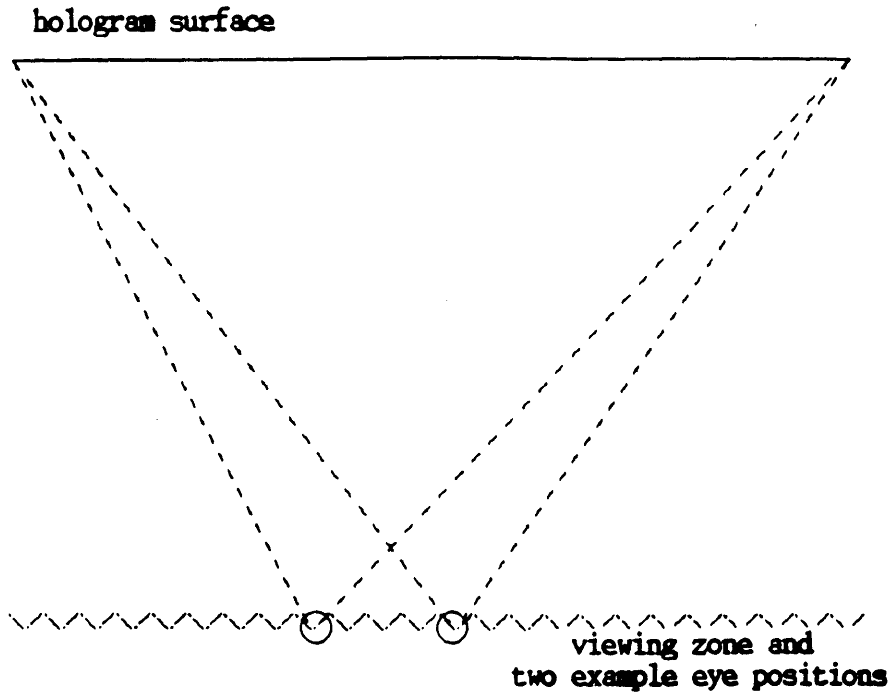


Figure 2.1: Generic holographic stereogram viewing geometry.

2.1.1 Flat-format One-step Holographic Stereograms

Figure 2.2 illustrates the printing geometry. 2D images projected onto a diffusing screen in coherent light are sequentially recorded holographically through a thin vertical strip mask side-by-side on holographic film. Although there will be as many exposures as there are 2D images, this method is called the one-step method because the systematic recording is considered as a whole.

The reference beam is not shown in Figure 2.2. For our work, we chose to make real-image laser-transmission playback style holograms most of which were made to reconstruct with a one-meter distant 45^o overhead diverging point light source (collimated light was used for our flat-format stereograms). The correct reference for this type of illumination is its conju-

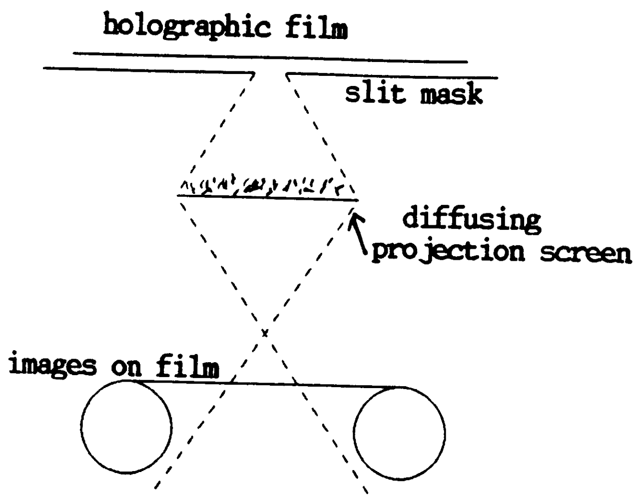


Figure 2.2: One-step holographic stereogram printing

gate (time-reverse) wavefront, which means we required a one meter distant converging reference beam incident on the holographic film from the same side as the diffuse projected image.

Each 2D image recorded this way becomes, upon playback, a vertical line projector of a flat diffusing screen with a projected image on it. Together, lined up next to each other, these vertical line projectors can reconstruct an extended image (see Figure 2.3). Each mini-hologram strip behaves very much like a lenticular lenslet in a lenticular parallax panoramagram[27]. The output angle for each vertical strip, θ, depends on the width for the diffuse projected image and its distance from the hologram surface by equation 2.1.

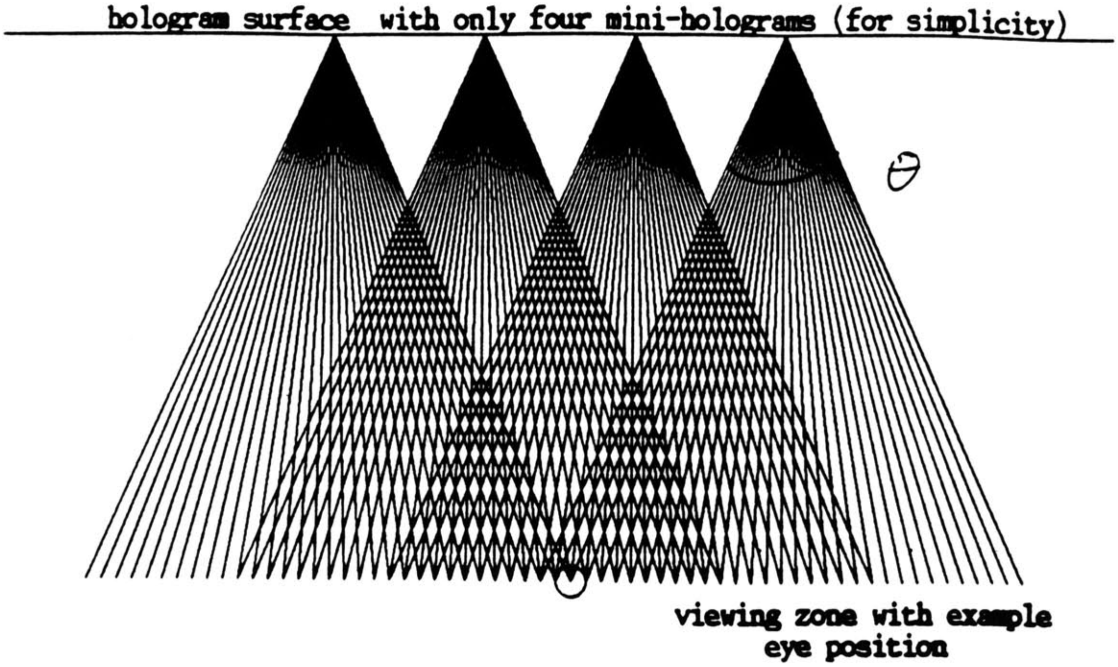


Figure 2.3: One-step holographic stereogram playback

$$\theta = \mathbf{2} * \mathbf{arctan}\left(\frac{\mathbf{image\ width}}{\mathbf{2} * \mathbf{viewing\ zone\ to\ hologram\ distance}}\right) \tag{2.1}$$

Our stereogram had a diffusion screen width of 27.9 cm , 30.5 cm away from the hologram surface, so that the output angle, θ, for each mini-hologram was about 49.2^o. The vertical mask width was 1 mm, and flat-format stereograms were all designed to be 30.0 cm wide, for 300 sequential exposures 1mm wide each. The alcove-format one-step holographic stereograms were printed with the same vertical slit mask, on a piece of holographic film that was shaped into a hemi-cylinder with 61 cm diameter. Therefore, the flat strip of film for the hemi-cylinder had to be 96 cm long, and was made from 950 sequential exposures 1mm wide each.

A viewing zone distance must be decided at some point early in the printer and display geometry design. It is very important for aesthetic as well as technical reasons. The parallax synthesis of a stereogram is only absolutely correct at the predetermined viewing-zone distance. Once the viewing zone distance is set, if a viewer deviates from this distance when observing a stereogram, anamorphic distortions will occur[6], but they are not very disturbing. The viewer will experience slight deviations in the horizontal-vertical magnification ratio and horizontal parallax away from the proper viewing zone, but human perception does not seem very sensitive to small deviations of this kind.

For our printer and display, we chose to have a viewing distance of 88.2 cm from the hologram surface. Figure 2.4 illustrates the flat-format display observed with one eye from the center of the viewing zone. This figure shows that one eye sees each mini-hologram as a 1 mm wide vertical-line sample at a distance of 88.2 cm, so each strip subtends only about 4 minutes of arc at that distance and the 300 side-by-side strips for a flat-format stereogram subtend about 19.3^o all together.

Example of One-step Distortion

Given this description of the printer and display, let us look at an example of what the stereogram might produce if we holographically print a standard perspective 2D image set of an extremely simple subject, namely, the image of a square on a plane. Suppose the images are recorded with a

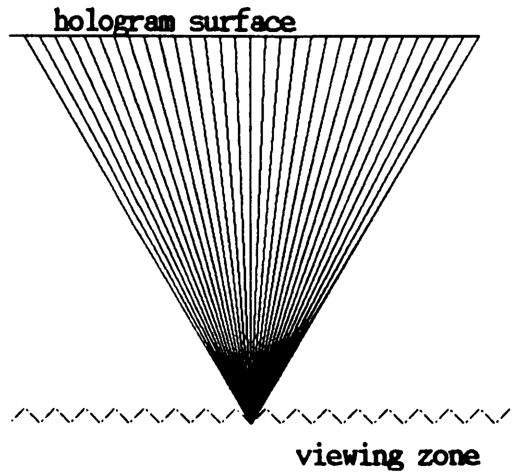


Figure 2.4: Reconstructing One 2D Output Image

keystone-free camera[27] on a sliding-track track. The camera could keep centered on a 10 cm edge square which is centered on a 30 cm edge square projection screen 88.2 cm away as it slides on a track parallel to the plane of the square. The images collected this way would be identical, all of a square centered in the center third of the image frame horizontally and vertically. Since the images are all identical, we can use one representative image to print this stereogram.

When printing the stereogram, it is desirable to fill the projection screen's full horizontal dimension because that will allow a wider output angle for each mini-hologram as was expressed by equation 2.1. Our projection screen is 27.9 cm wide, so if we project the image to fill the screen, the square on the projection screen will be $27.9/3 = 9.3$ cm on each side. When viewing this stereogram, because the projection screen image appears 57.7 cm away from the viewer, and the physical hologram plane is physically situated 30.5 cm behind it or $57.7 + 30.5 = 88.2$ cm away from the viewer, the vertical extent of the square the viewer will perceive is $88.2/57.7 = 1.53$ larger on the hologram surface than its extent on the projection screen, namely $9.3 * 1.53 = 14.2$ cm. Other one-step stereogram printers may have an even wider projection screen to allow an even wider output angle in the final display, and this problem would get proportionately worse. The proper solution is to project the image onto the projection screen with anamorphic projection optics: optics that magnify horizontal and vertical dimensions differently. The optics in this case should project the image to fill the projection screen horizontally, and minify the image vertically by a factor of $57.7/88.2 = .65$. The image will then appear to be the correct vertical size in the display.

The apparent horizontal extent of the square on the hologram surface is relatively easy to calculate in this example because each mini-hologram was printed with the same image, namely a square in the center of a square frame. The projection screen translates with the moving slit during the stereogram printing procedure, so every mini-hologram will project out an identical image of the projection screen, each image of the screen horizontally displaced 1 mm from its neighbor like the mini-holograms on the hologram surface. An eye at any location in the viewing zone will see a bundle of rays from each of the mini-holograms as Figure 2.4 illustrates. The mini-hologram that projects the view of the edge of the square into the eye will be perceived as the location of the edge of the square. This mini-hologram can be found geometrically as illustrated in Figure 2.5. By

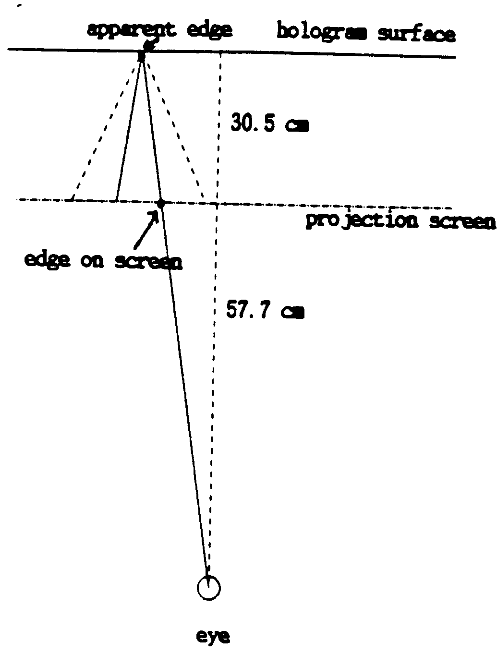


Figure 2.5: Horizontal distortion of standard recording of square

similar triangles, the horizontal extent of the square must be 27.0 cm wide (see equation 2.2), almost filling the whole hologram surface. If the projection of the square on the projection screen is not anamorphically distorted, but instead minified by a factor of .65 like the vertical dimension, the horizontal extent of the square from any one eyepoint will be 17.5 cm wide, and the output angle of the hologram will be 34.3° instead of 49.2° by equation 2.1.

$$27.0 = 9.3(width of square on projection screen) * \frac{88.2}{30.5} \qquad (2.2)$$

Because all the images are identical, this horizontally distorted reconstructed image will seem to be in a plane located at infinity because it will always seem to be directly in front of the eye independent of the eye's horizontal location in the viewing zone.

If the stereogram is to look undistorted, like the standard camera views, each standard camera view must be somehow distributed to all the mini-holograms so that they can reconstruct it correctly. This is the premise of the image processing technique which will be described in detail later in this chapter.

Alternatively, the images can be recorded in a non-standard way that also correctly pre-distorts the images, i.e. record the images through a cylindrical lens with the proper f-number. If the images of the square described above are filmed through a cylindrical lens located at the projection screen distance with focus on the plane that will become the hologram surface, the center image of the center of the square will fill the 2D image horizontally. As the images are recorded, and the lens is translated left or right, the images will be identical to the center image until the edge of the square is reached. At that point, the focus of the cylindrical lens will see and record entirely blank frames. When these 2D images are printed as a stereogram, the horizontal magnification and the apparent location of the square in space will seem correct. This is because the range of mini-holograms 5cm on either side of the center will project the image of the square over their whole output angle, and beyond that, they will only project out the solid blank background. If the images are to appear completely undistorted in the final stereogram, they must be vertically demagnified by the 1.53 factor, and recorded with a cylindrical lens with an f-number equal to $\frac{projection\ screen\ to\ hologram\ distance}{width\ of\ projection\ screen}$.

The position of the projection screen in space is always apparent from the vertical parallax of the display. Horizontal parallax, (if images are properly pre-distorted) will not reveal this aspect of the projection screen. There will be a marked discrepancy between vertical and horizontal parallax cues for the elements of the scene that cross through the hologram surface. The previously mentioned apparent vertical closeness of the projection screen relative to the hologram surface and viewing zone location can make everything in the scene appear vertically magnified if not corrected at either the image acquisition, image processing, or stereogram printing stages, by computational or optical means.

Upon viewing such stereograms with their projection screens out in front, it may be useful to present an empty frame around the projection screen image to further establish its location. Then, if the scene is arranged so that the center of interest also appears at that location, the viewer's attention is drawn to the plane where the horizontal and vertical motion parallax cues agree. Of course, if the viewer's vertical motion can be minimized, and the center of interest is arranged around the hologram surface plane, the display will look fine without the artifice of an empty frame out in front. Such control of the viewer's movement is usually difficult, however.

2.1.2 Alcove Format

The alcove-format stereogram bears close similarity to the flat-format one-step stereogram in some respects. Although there may be minor variations, the principle elements of the hologram printing set-up for both formats are identical. The major difference between the two formats is in the

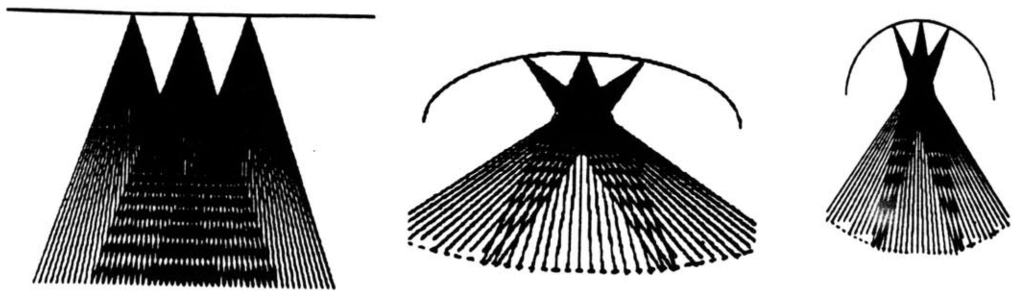


Figure 2.6: Transition between flat and alcove-format stereograms.

shape and location of the projection screen, and the image processing to make the 2D image set appear undistorted in the final display.

The alcove-format stereogram is printed through exactly the same projection screen as the flat-format. However, since the final display format is curved, the resulting image of the projection screen also curves. This is illustrated in Figure 2.6 which shows the transition between the flat format display and alcove display with an intermediate step. The rays from three mini-holograms on the surface are sketched along with their images of the projection screen. The resulting apparently curved projection screen image is formed from rays from different mini-holograms on the surface, each passing through different projection screen images at different rotation angles and horizontal displacements, all converging at a viewer eye location on the circular viewing zone.

It should be apparent from symmetry, that from any one viewing location, an eye sees a centered, concave projection screen. In order for 2D images to appear undistorted on such a projection screen, significant predistortion image processing must be performed as will be discussed later in this chapter. From the previous description of flat-format one-step stereograms, it should also be clear that there will be a constant anamorphic magnification distortion due to the projection screen location which must also be corrected. The empty frame to define the location where horizontal and vertical motion parallax cues best agree will no longer be useful, because the alcove format is found to draw the viewer's attention to its center where this situation occurs. However, if the viewer moves vertically, the curved projection screen manifests itself as the sides of the image move at a different rate relative to the image center. A straight horizontal line on the curved projection screen will appear straight only from the correct vertical perspective location; above that location, the line will "frown" with the center higher than the sides, and below it, the line will "smile".

The next sections will go into the details of the image processing for both flat and alcove-format one-step stereograms.

2.2 Description of Mapping Algorithms

2.2.1 Flat-Format One-Step Stereograms

This section will describe how, given a set of undistorted 2D images for a holographic stereogram, image processing for one-step flat-format stereograms should proceed.

The anamorphic magnification difference problem described in the example in section 2.1.1 should be an early consideration in preparing the image set. The option exists to perform an anamorphic vertical demagnification with special projection optics in the stereogram printer. Because the images we are discussing here are film images taken of a cathode ray tube, the horizontal-scanline density limits the vertical resolution. If the demagnification is performed at the printing stage, the optics effectively compress the lines together and increase the normal vertical resolution. Of course, the same demagnification can easily be performed during the image processing phase or even at the image acquisition phase with normal resolution.

The rays in Figure 2.4 can be interpreted as the sampling position markers for the remapping procedure. If we assume that the image the eye sees in Figure 2.4 is the undistorted center view, the center-most ray of that image belongs to the center-most mini-hologram, the left-most and right-most rays belong to the left and right-most mini-holograms respectively, and so on for all intermediate rays and mini-holograms. Each undistorted 2D view is decomposed into n-vertical strips, where n equals the number of mini-holograms that share part of the projection of that view. The exact location and width of each vertical strip is determined by the projections of the mini-hologram boundary lines (instead of the mini-hologram centers as Figure 2.4 suggests) onto the projection screen plane.

Each undistorted 2D view should be systematically sliced vertically and distributed among the mini-holograms in the same manner as illustrated

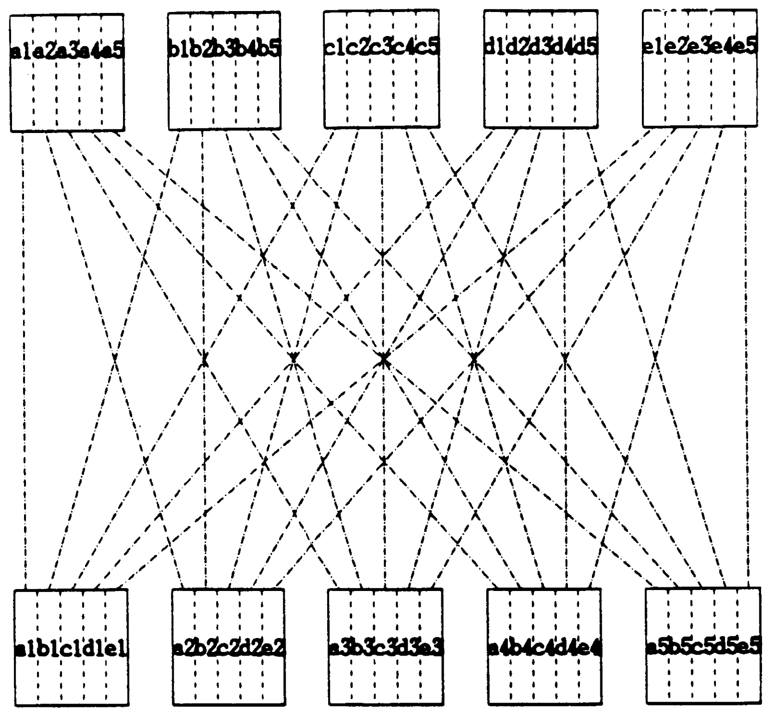


Figure 2.7: Simplified Remapping Distribution for Flat-format

in Figure 2.7 for a 5 image set. The correct 2D predistorted image for printing any single mini-hologram contains vertical slices from many of the original undistorted 2D images. For images that fill the whole flat hologram, the systematic method for compositing the mini-hologram views is very simple indeed. Each 2D view is segmented into n equal-width vertical strips, where n equals the number of mini-holograms on the hologram plane. The left-most strips of all the images ordered left to right from left-most to right-most perspective view, compose the 2D image to be printed onto the left-most mini-hologram. The right-most strips compose the right-most mini-hologram analogously, and all intermediate mini-holograms are likewise analogous interpolations.

Figure 2.8 shows the image processing input and output images for the previous example of a flat square on the hologram surface plane. The 2D

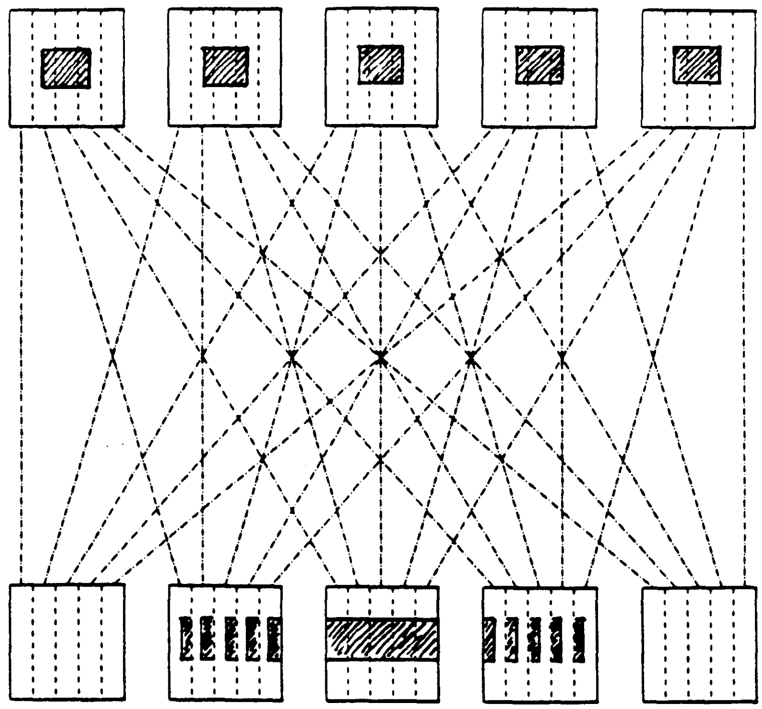


Figure 2.8: Flat-Format Image Processing Example: Square on Hologram Plane

recorded image set is shown above, and the processed results below. If we record the same square at a distance other than the hologram surface distance, the square will no longer appear centered in all the views, it will translate across. The images of the square at the distance of the projection screen are a special case as is demonstrated in Figure 2.9. The translation rate of the square in the image set is the same as the sampling shift rate, so the processed image set looks identical to the source image set. This rate matches exactly only for objects exactly in the projection screen plane like the square. 3D objects that are centered at the projection screen depth will be minimally distorted if printed into a stereogram without image processing. The degree of their distortion depends on their extent in the dimension away from the projection screen plane in that case.

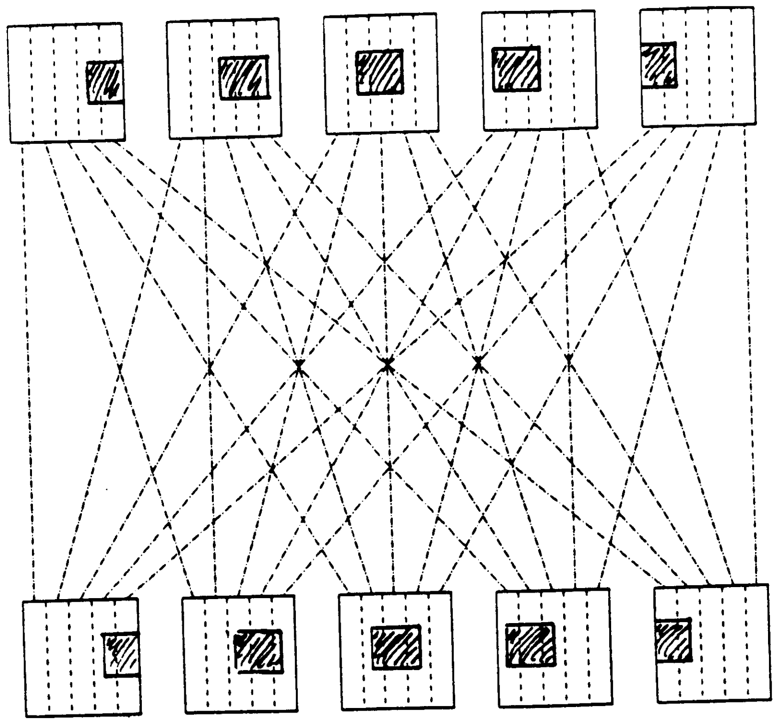


Figure 2.9: Flat-Format Image Processing Example: Square on Projection Screen Plane

2.2.2 Alcove-Format One-Step Stereograms

This section will describe the mapping procedure for the alcove-format one-step stereogram. It closely resembles the flat-format procedure, but is a bit more complicated.

The anamorphic magnification problem mentioned in the previous section is also evident here. This is because the same printing set-up is used for both the flat and alcove stereograms. As discussed before, the vertical demagnification remedy for this problem can be performed either at image acquisition, processing, or printing time. Note that this anamorphic distortion is separate from the curved projection screen distortion which will now be discussed.

Figure 2.10 is analogous to Figure 2.4 in the previous section; it illus-

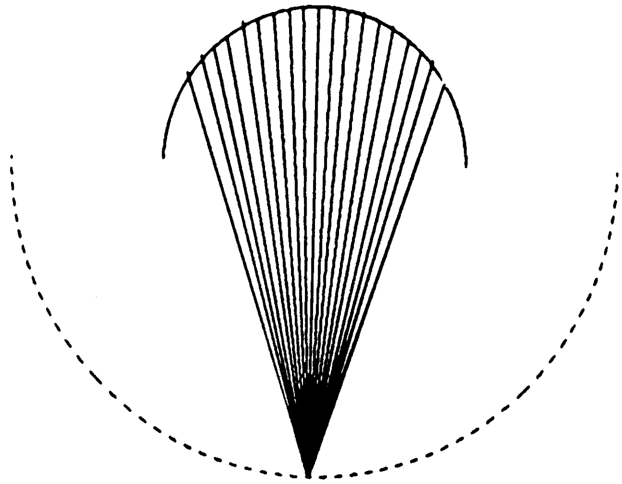


Figure 2.10: A single 2D view from the center of the alcove stereogram viewing zone

trates the 2D view at the center of the viewing zone with one ray from each mini-hologram. Whereas the projection screen image formed a plane parallel to the hologram surface plane in the previous section, in this case the image of the projection screen reconstructed by each ray is at a slightly different distance from the viewer. Together all the rays reconstruct an image of the projection screen that is a curved concave surface, similar to the alcove itself. Unlike the alcove, however, this curved screen image is not a simple hemi-cylinder, but has a more complex shape. Because of the symmetry of the alcove display, the shape of the screen will appear the same from every viewing position along the viewing zone semi-circle. In order to map the undistorted 2D views onto this curved screen, we need to understand its shape in detail.

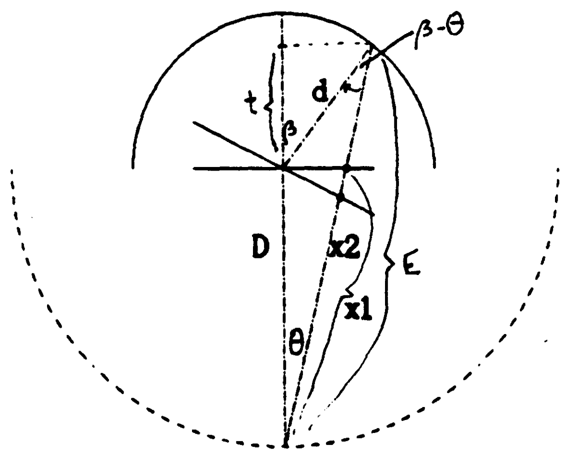


Figure 2.11: Alcove Mapping Position Marking Rays

Figure 2.11 is a view of the alcove hologram with only two rays converging at the center viewing zone position. One ray emanates from the center-most mini-hologram, and passes through the center point shared by the alcove hologram surface and the viewing zone circle. The other ray is from an off-axis mini-hologram. The projection screen's image for each ray is also illustrated.

The known values are as follows:

- β, the angle at the alcove center between the center axis and any mini-hologram on the alcove hologram surface.
- d, the alcove hologram radius.
- D, the viewing zone radius.

The unknown values are as follows:

- θ, the angle at the viewing zone between the center axis and the mini-hologram on the alcove hologram surface.
- x1, the distance to an ideal flat projection screen normal to the viewers line of sight for this particular mini-hologram ray.
- x2, the distance to the projection screen segment intersected by this mini-hologram ray.

We would like to see an image as if it were on an ideal flat projection screen that is always normal to the viewer's line of sight for any 2D view. Since the images really appear on the curved surface, we must demagnify the vertical strip projected by each mini-hologram by the ratio of the real screen distance to the ideal screen distance, $\frac{x2}{x1}$. The mini-holograms are most conveniently indexed by the angle, θ, they make relative to the view point.

Geometrically, the knowns are related to the unknowns by the following equations:

$$\mathbf{tan}\theta = \frac{\mathbf{sin}\beta}{\frac{\mathbf{D}}{\mathbf{d}} + \mathbf{cos}\beta} \tag{2.3}$$

$$\mathbf{x1} = \frac{\mathbf{D}}{\mathbf{cos}\theta} \tag{2.4}$$

$$\mathbf{x2} = \frac{\mathbf{D}}{\mathbf{cos}\theta} + \mathbf{d}*\frac{\mathbf{cos}\beta}{\mathbf{cos}\theta} - \frac{\mathbf{d}}{\mathbf{cos}(\beta - \theta)} \tag{2.5}$$

Derivation of the Geometry Equations

To find θ, use the $\theta - \beta$ angle and the shared-edge equality of two right triangles:

$$\mathbf{d} * \sin(\beta - \theta) = \mathbf{D} * \sin\theta \tag{2.6}$$

or

$$\frac{\mathbf{D}}{\mathbf{d}} * \sin\theta = \sin\beta\cos\theta - \cos\beta\sin\theta \tag{2.7}$$

or

$$\sin\theta(\frac{\mathbf{D}}{\mathbf{d}} + \cos\beta) = \sin\beta\cos\theta \tag{2.8}$$

which when both sides are divided by $cos\theta * (\frac{D}{d} + cos\beta)$ becomes equation 2.3.

Equation 2.4 can be shown by the right triangle formed by the hypotenuse x1, opposite angle θ, and adjacent side D.

Equation 2.5 can be shown by first constructing a length t on the center line so that t + D forms the adjacent side of a right triangle with opposite angle θ and the eye-to-mini-hologram distance, E, as the hypotenuse. The distance E - x2 is the side of a right triangle, which allows solution for x2. The relationships are as follows:

$$\mathbf{t} = \mathbf{d} * \cos\beta \tag{2.9}$$

$$\mathbf{E} = \frac{\mathbf{t} + \mathbf{D}}{\cos\theta} = \frac{\mathbf{d} * \cos\beta + \mathbf{D}}{\cos\theta} \tag{2.10}$$

$$\mathbf{E} - \mathbf{x2} = \frac{\mathbf{d}}{\cos(\beta - \theta)} \tag{2.11}$$

$$\mathbf{x2} = \frac{\mathbf{d} * \cos\beta + \mathbf{D}}{\cos\theta} - \frac{\mathbf{d}}{\cos(\beta - \theta)} \tag{2.12}$$

Equation 2.12 simplifies to yield Equation 2.5.

Alcove Mapping Procedure

The procedure for mapping an undistorted flat 2D view onto the curved projection screen is then the following. For a given view point on the viewing zone, the range of mini-holograms that can project vertical line image segments to that viewing location is limited by the output angle for each mini-hologram (see equation 2.1). Once the range of mini-holograms that contribute to project one full 2D image is determined, the angle β for each mini-hologram in that range can be determined, and from the βs, the θs can be calculated for each one with the above equation. The θs for each mini-hologram determine the directions for the rays through the view point that can be interpreted as the sampling position markers for the mapping procedure. The demagnification factor, $\frac{x2}{x1}$, must then be calculated with the above equations and applied for each vertical line image sample. The demagnified vertical strips are then sorted into the mini-hologram assigned to them by the sampling position marking rays.

Starting with the right-most view on the viewing zone circle, the range of mini-holograms that include this image must first be determined as mentioned above. Obviously, if the alcove is a perfect hemi-cylinder, the right-most view does not intersect any mini-holograms and therefore does not contribute to this display. The next view to the left will start to intersect some mini-holograms, so left-most vertical edge of the corresponding undistorted 2D image for this view should be mapped to the intersected

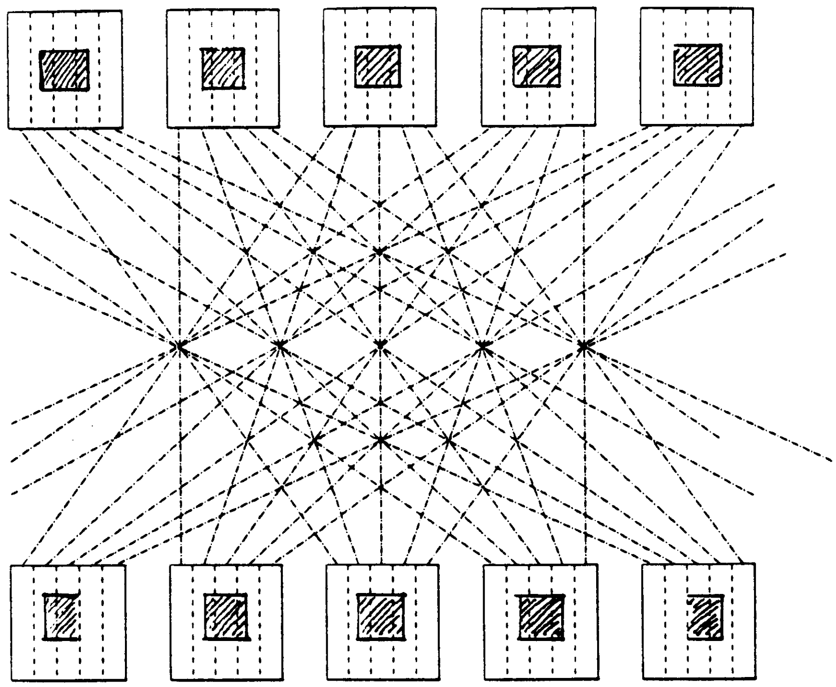


Figure 2.12: Simplified Remapping Distribution for Alcove

mini-holograms according the previous paragraph's explanation. The next view to the left will intersect even more mini-holograms than the previous one, and so on until at some view point, all of that view is intersected by some (or maybe all) of the mini-holograms. The alcove display is symmetrical, so the process ends the same way it begins: the next to left-most view contributes its right-most vertical edge, and the left-most view on the viewing zone semi-circle does not contribute to this display.

Figure 2.11 is analogous to Figure 2.8, it illustrates the shift that takes place in the remapping for the alcove, however it does not attempt to show the 2D distortion correction for the curved projection screen. The source images in this example are once more of the 10 cm-edge square on the projection plane 57.7 cm away from the camera. However, instead of a keystone-free linear-track camera, we keep the camera stationary and rotate the plane of the square about it's center vertical axis to record the perspective views. It is evident from this Figure 2.11, as in Figure 2.8, that objects in the projection screen plane will appear minimally distorted in the stereogram without image processing. The added distortion of the curved projection screen will always be apparent, however, if 2D image processing is not also applied.

The next chapter will give an account of the actual procedures and results of our research.

Chapter 3

Procedures and Results

3.1 Flat-format Stereograms

3.1.1 "Shark Sushi"

Out first attempt at producing a flat-format one-step stereogram successfully produced an image of a small object in the projection screen plane. The subject was a computer-graphic rendering of a stylized shark emerging from a sushi rice roll, and was therefore dubbed "shark sushi".

The 3D computer model of the scene was positioned relative to a computer simulated camera that was designed to match our flat-format display geometry. The simulated camera had a perspective angle based on the width of the final hologram surface and the viewing zone distance from that surface. The 3D model of the shark and sushi were positioned at the location of the projection screen and the synthetic camera rendered 300 different views along the horizontal dimension of the viewing zone, spaced 3 mm apart.

The source image set and processed image set for this stereogram looked very similar for the reasons illustrated in Figure 2.9 in the last chapter, namely because the 3D model of the shark sushi was relatively shallow and centered in the projection screen plane.

The resulting hologram was displayed with a physical frame around the projection plane as described in the previous chapter. The reconstructed image correctly appeared centered in the projection plane, and the disparity appeared correct at the calculated viewing distance. The vertical dimension appeared magnified, however, because the vertical magnification distortion described in the previous chapter had not yet been anticipated.

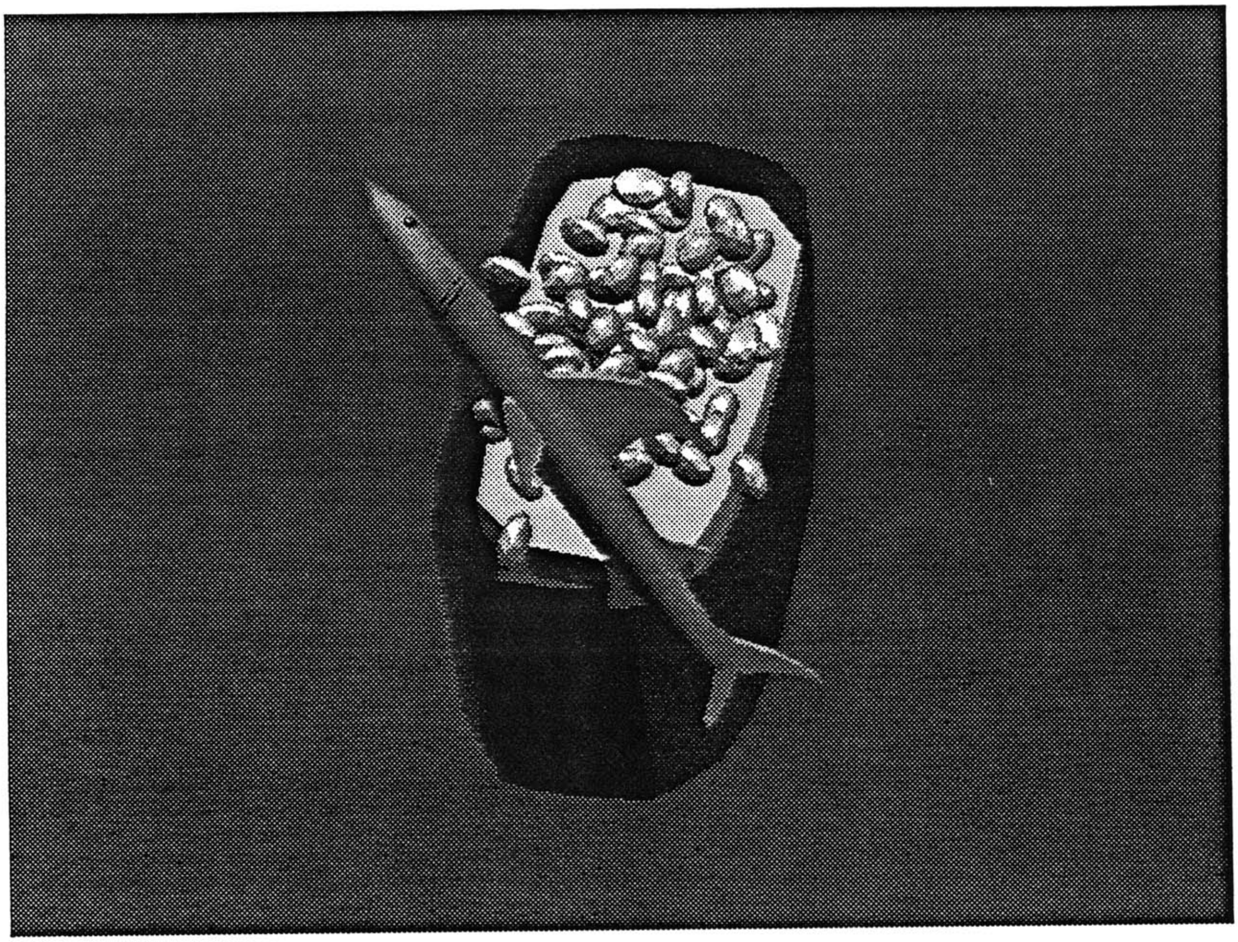


Figure 3.1: "Shark Sushi"

3.1.2 "Sanjigen"

The 3D computer-graphic scene for this stereogram included objects in the space behind the hologram plane, in the hologram plane, in the projection screen plane, and also well in front of the projection screen plane. Straddling the hologram plane was a large cubic array of tiny cubes. In back of the hologram plane were the Japanese Kanji characters for "3D" (Sanjigen). In and in front of the projection screen plane were placed a few simple 3D shapes: a pyramid, a ring, and a ball with spikes.

By its very noticeable and easily measured distortion, the cubic array confirmed the vertical magnification factor of 1.53 mentioned in the last chapter. Some of the simple shapes in front were too close (6 inches) to the viewing zone for comfortable viewing. In order to view these at a comfortable distance, one had to move beyond the ideal viewing zone and anamorphic distortions[6] became very apparent.

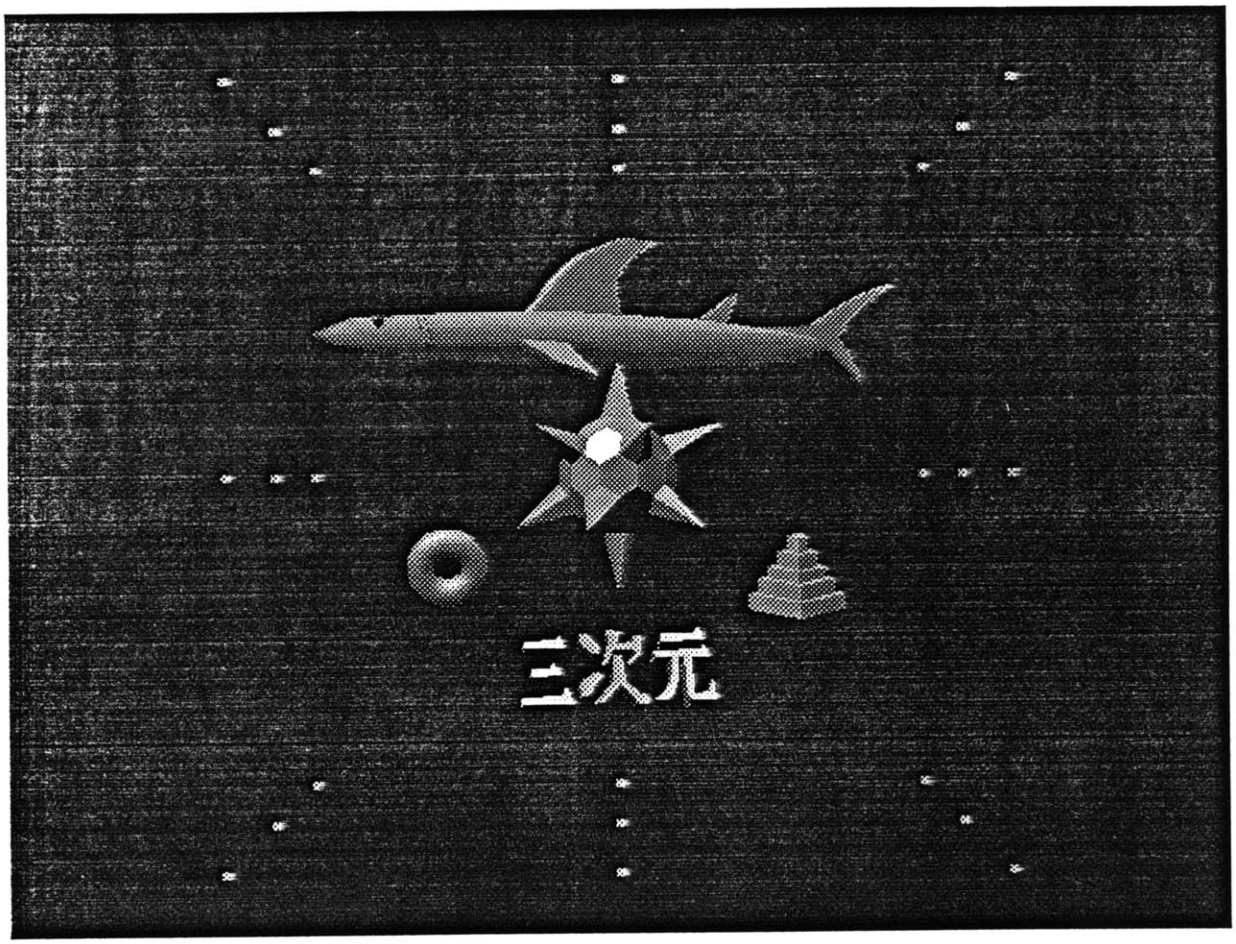


Figure 3.2: "Sanjigen"

3.2 Alcove Stereograms

3.2.1 "Banana Camaro"

The vertical magnification distortion was corrected for the first time by scaling the vertical dimension of the computer-graphic car model by a factor of .65 before rendering. The car was rendered as if it were at the center of the alcove in the projection screen plane, and the images were not remapped or processed in any other way. As expected, the resulting holographic image of the car looked recognizable but somewhat distorted. The middle of the car appeared bowed toward the viewer while the ends curved away.

This distortion is somewhat counter-intuitive; the curve of the projection screen alone would magnify the ends of the car more than the middle and one might expect the opposite kind of distortion. The reason for this type of distortion is because the vertical strips composing the right end of the car image are from views of the car from viewpoints to the left of the current viewpoint, and vice versa. The car effectively is turning away from the viewer at either end.

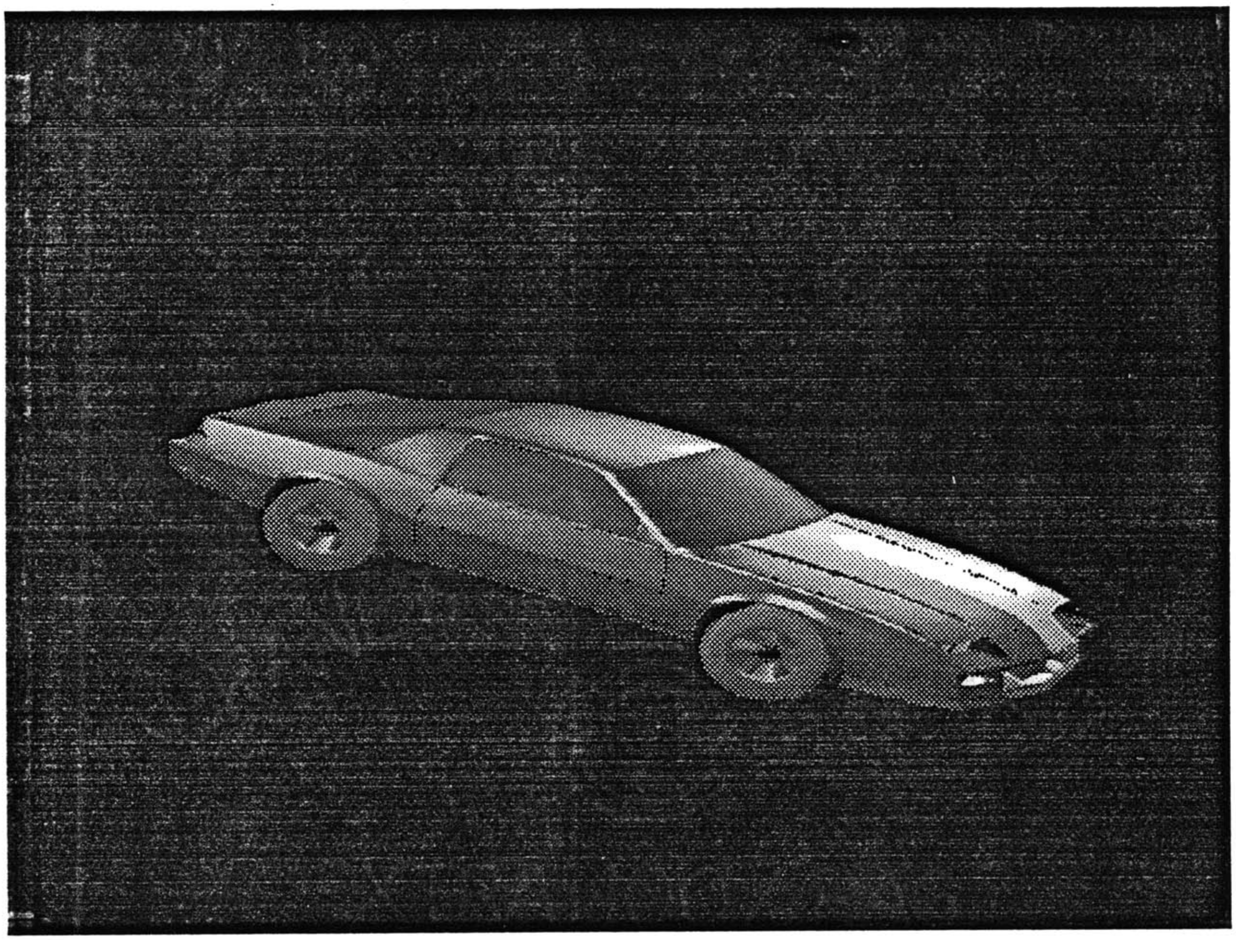


Figure 3.3: "Banana Camaro"

3.2.2 "Corrected Camaro"

The image of the camaro from the previous hologram was processed to correct for both the remapping and the curved-screen distortion. The result was the first undistorted alcove hologram in our laboratory. The image appeared quite solid, suspended in the center of the alcove. Lighting highlights from the phong-shaded[15] computer-graphics moving realistically as the viewer changed position contributed subtlety to the illusion.

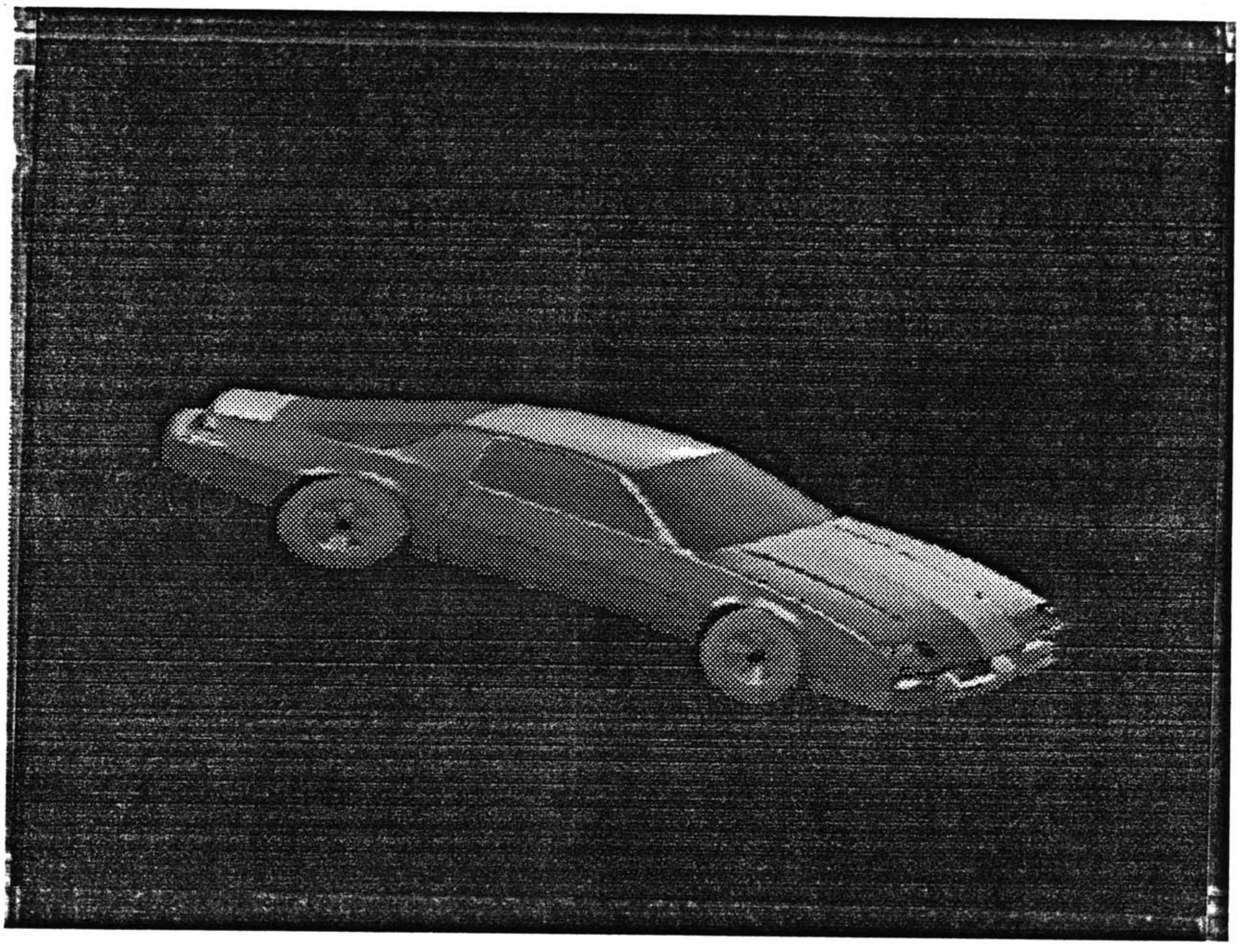
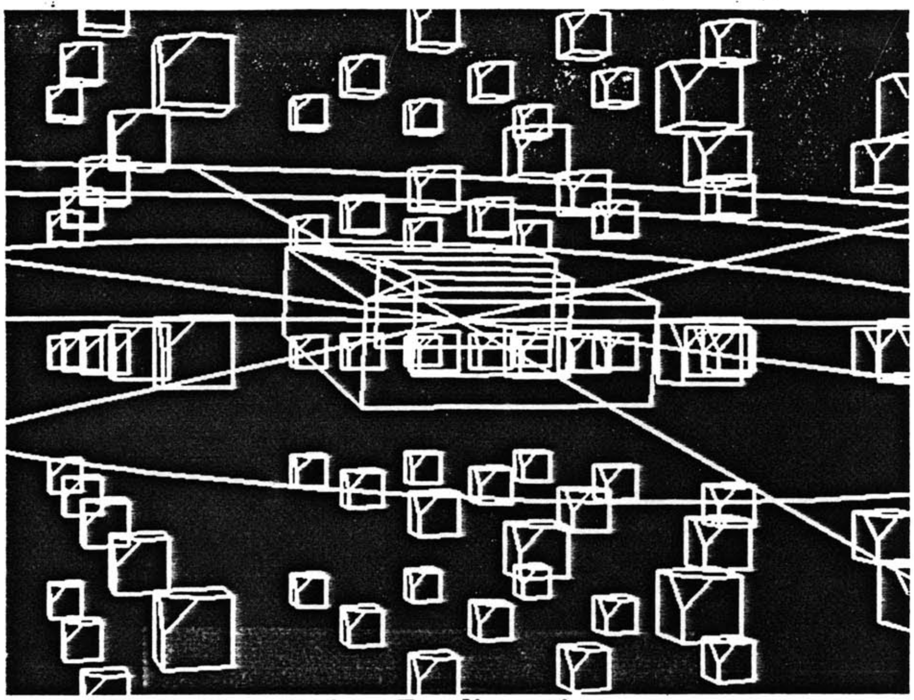


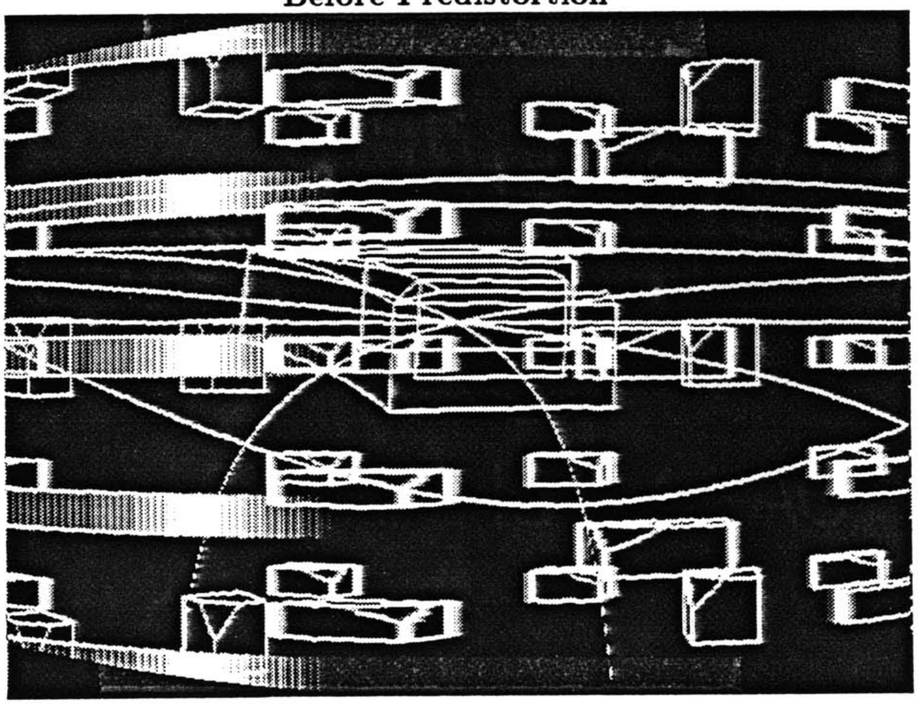
Figure 3.4: "Corrected Camaro"

3.2.3 "Test Target"

A wireframe computer-graphic image of barbecue-grill-like spokes and concentric rings was made. An array of cubes and the letter E at the center showed no noticeable distortion. The cubes and the far part of the barbecue grill demonstrated that the image can successfully penetrate the hologram surface.



Before Predistortion

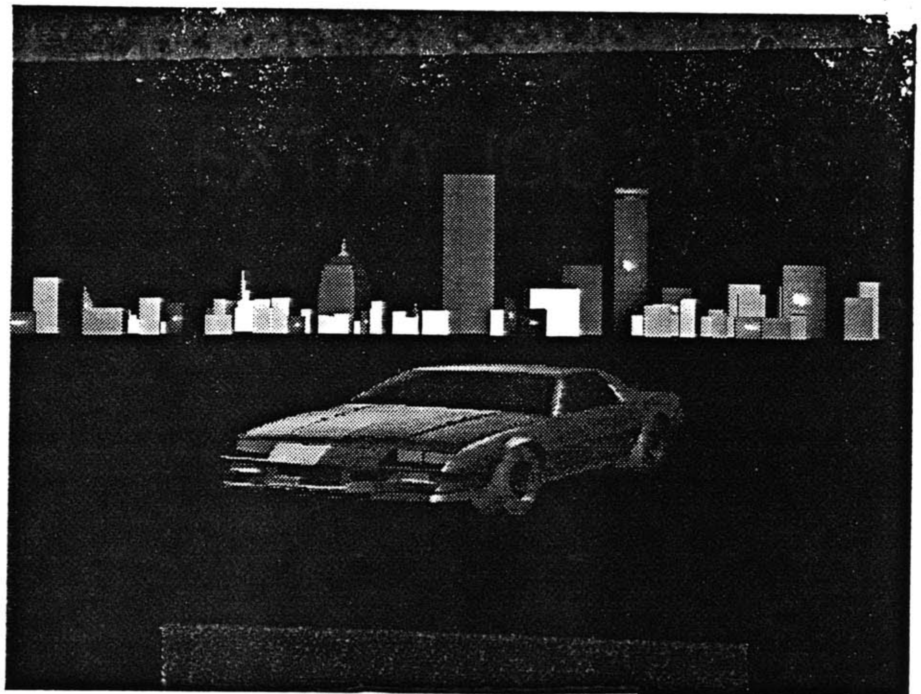


After Predistortion

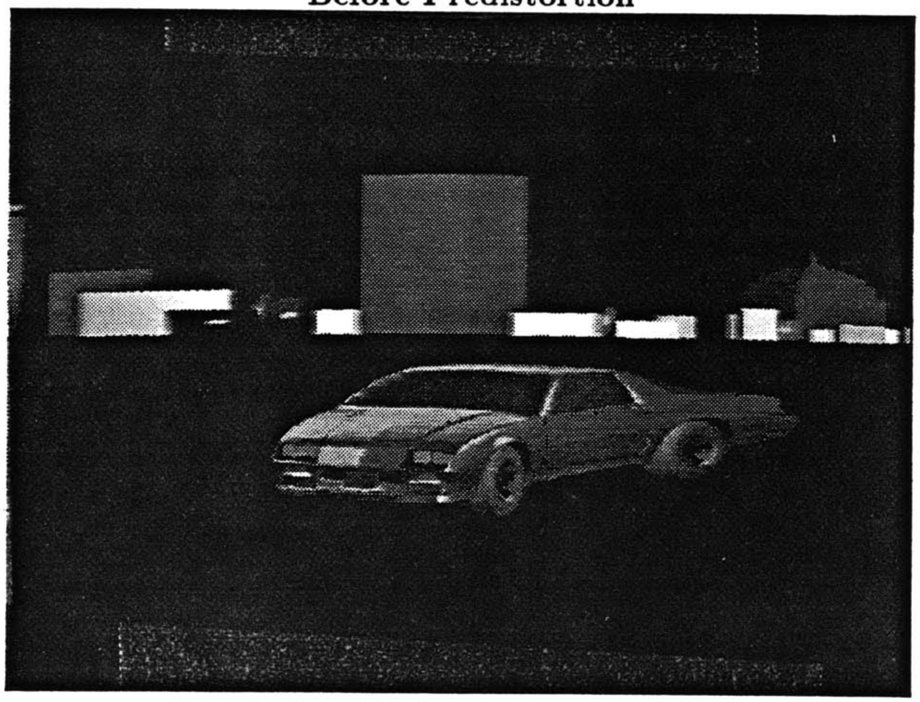
Figure 3.5: "Test Target"

3.2.4 "Bos-Cam"

This stereogram placed the camaro in the center with a different orientation from the previous camaro hologram. A stylized computer-graphic model of Boston was placed in the background behind the hologram surface. The 950 images took about 7 CPU minutes each to render and process. The stereogram printing process had become routine at this point. It took about 1.5 hours to shoot the 950 mini-holograms and process the film.



Before Predistortion

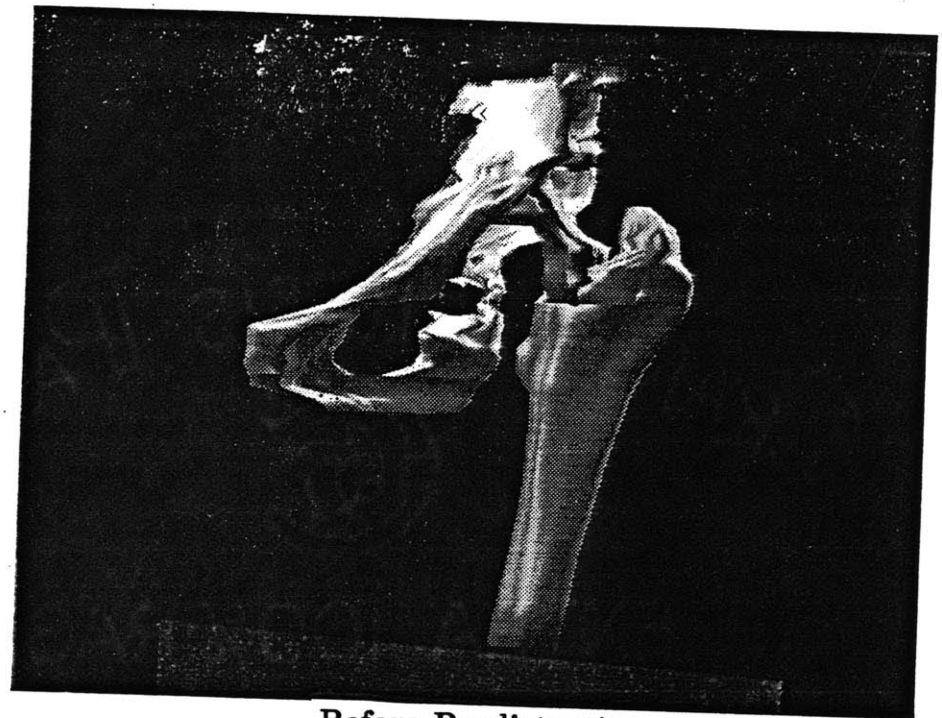


After Predistortion

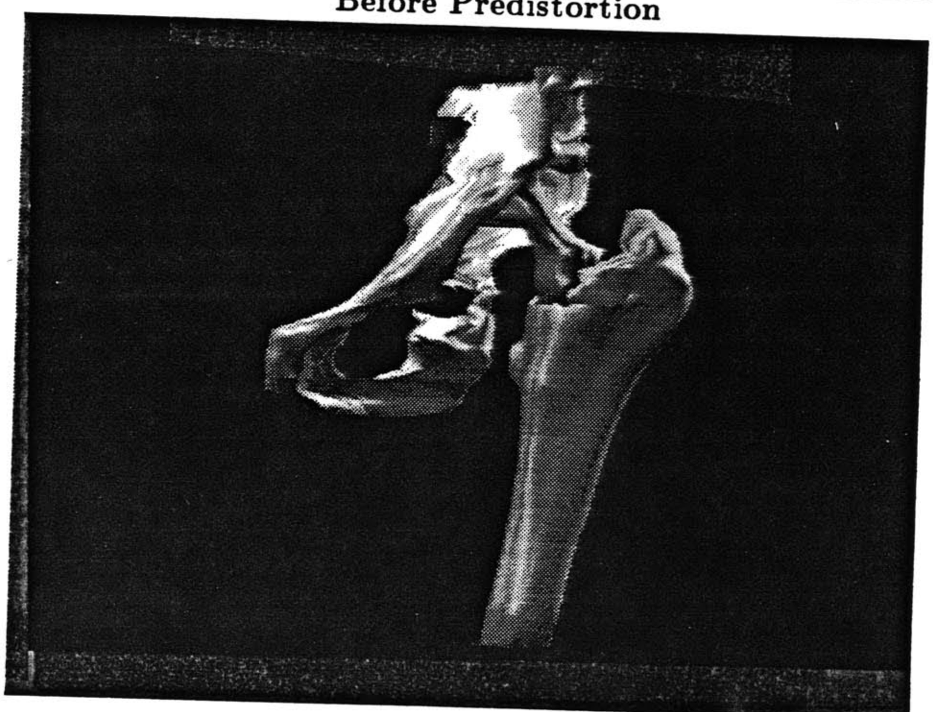
Figure 3.6: "Bos-Cam"

3.2.5 "Pelvis"

A computer-graphic polygon model from from CAT scan data was used to render this image of a pelvis and hip with an artificial joint. This image was made to demonstrate the potential of this display format for 3D visualization of 3D problems in medicine. It seems that the addition of vertical parallax would be very desirable for this application, because the structures are complex and the information may be necessary for an accurate evaluation of the subject.



Before Predistortion



After Predistortion

Figure 3.7: "Pelvis"

Chapter 4

Evaluation

The image predistortion techniques described in this thesis succeeded in producing undistorted one-step stereograms of scenes that could cross through the hologram surface. However, our implementation of the techniques could have been improved in some ways.

In our alcove geometry, the full projection screen was sampled by 382 mini-holograms. Because the images were processed at NTSC resolution (640 x 480 pixels), it was conceptually simple to first shrink the 640 pixel wide images to 382 pixels, slice them into 382 one-pixel columns, and compose the remapped images from these columns. The remapped images then were interpolated back up to NTSC resolution before they were recorded on 35mm and finally printed into the stereogram. Although this technique is straightforward, it wastes horizontal image resolution. The procedures for sampling the 640 pixel wide images into 382 columns for remapping to the final 640 pixel wide images without losing as much resolution are not difficult, but they involve more computational bookkeeping. The images could be supersampled by a common factor of 640 and 382, i.e. 122240, before they are sliced and remapped. The resulting supersampled images would be interpolated back down to 640 pixels in the end.

This problem would be even less noticeable if the projection screen was larger. If the projection screen was subtended by exactly 640 mini-holograms, the computation involved in slicing and remapping the columns would be at a minimum, and the image would fill more of the alcove display. If all 950 mini-holograms in the alcove display were to subtend the projection screen, there would be no downward interpolation, and thus no resolution loss. The display would also allow use of all potential volume for the display in this case.

The biggest practical disadvantage of the remapping technique for one-step holograms is that it requires all the images to be resident in computer disk memory at once. For 10^3 images at NTSC resolution (640x480 pixels) and 24-bit color per pixel, the memory required is about 10^3 megabytes. If each color is done separately, the memory requirements would be reduced by a factor of three, but the processing time would be three times as long. Current time requirements on a VAX11/785 running 4.3bsdUNIX are about 2 minutes CPU time per image, or about 30 CPU hours to process the 10^3 images for an average alcove hologram. These times are very machine dependent, they can be dramatically different for other machines and operating systems.

Chapter 5

Discussion and Conclusion

5.1 Relation of This Work to Past Efforts

This work is refinement of the solution first proposed by Huff and Fusek[8]. Huff's implementation of the technique was quite crude and difficult to perform because an optical printer was used instead of a computer. Instead of the hundred or so vertical strip samples required for smooth image resolution, only eleven samples were taken from each image to composite optically into the predistorted result[9]. It is very clear that the computer is by far the better tool for this technique.

The use of computers to employ this technique has been discussed by both Okada and Jaffey[13,10]. Compensation for the curved projection screen has not been included in the remapping procedure until this thesis work.

5.2 Present Implications

The techniques presented in this thesis show how computer assistance in preparing images for holographic stereograms can be a tremendous asset in overcoming some of the practical problems. This is because computers have unsurpassed flexibility in generating and manipulating images with the degree of control necessary for holographic stereogram techniques. This opens up the variety of scenes to include virtually anything that can be brought to the computer.

Conventionally produced film and video, CAD system designs, computer paint and text overlays, are examples of some sources for images that are easily accessible for the computer. The computer also can synthesize images from several sources to create images that would be impractical or impossible to create any other way: a computer model for a bridge or a building overlayed on the photographic image of its intended site[12], simulated previews of the results of plastic surgery[3], and text labels on Landsat satellite images, are but a few of the current applications of computers in graphics. The potential for what can be represented on a computer is greater than most other media because computers can accept images from other media as well as generate their own.

Obviously though, computers haven't rendered other media obsolete because computers need hardcopy output. In order to store and convey the images to places where no convenient computer networks exist, hardcopy is necessary: photographs, plotted drafts, film and video computer-graphic animation. The computer-graphic holographic stereogram is a 3D hardcopy format that promises to be a valuable hybrid of technologies. Together, computer-graphics and holographic stereograms greatly extend both of their previous capabilities.

When it comes to computer aided design (CAD) work, holographic 3D hardcopy of computer-based architectural and industrial designs (eg. homes and automobiles) are possible. Computer generated 3D hardcopy is just an additional benefit of using a computer to manage a database. The same database might also be used to run structural analyses, project building costs, and attempt "what if" simulations (eg. What if this car design were in a head-on collision at 60 mph?).

5.3 Directions for Future Work

The remapping solution is general and powerful enough that it may warrant parallel hardware implementation. This would be a necessary component in a very fast holographic stereogram machine. If the 35mm film is replaced with an 8-bit greyscale, high-resolution liquid crystal light gate, the one-step printer really has the potential to become a practical 3D hardcopy peripheral to a computer.

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