To appear in SPIE Proceeding #1461 "Practical Holography V" (SPIE, Bellingham, WA, February 1991) paper #21 (in press).

The Ultragram: A Generalized Holographic Stereogram

Michael W. Halle
Stephen A. Benton
Michael A. Klug
John S. Underkoffler

MIT Media Laboratory
20 Ames St.
Cambridge, MA 02139
USA

ABSTRACT

A method for producing holographic stereograms with reduced geometrical constraints is presented. The type of holographic stereogram produced, called the ULTRAGRAM, can offer a combination of large viewing zone, arbitrary viewing distance, minimal image distortion, and high spatial resolution, depending on alterable parameters in the image processing software. Computer-based image processing techniques are used to mimic the effect of optical devices while permitting simple re-configurability. The ULTRAGRAM holographic exposure apparatus can be built with reduced attention to the final viewing geometry. An astigmatic computer graphics camera design greatly simplifies image generation. The techniques described are applicable to both one and multi-step stereograms, optical predistortion methods, and both horizontal and full-parallax systems.

INTRODUCTION

The holographic stereogram is one of the highest quality three-dimensional display devices currently available, and the most practical holographic medium for displaying computer-generated synthetic images. Holographic stereograms present a series of discrete apertures to the viewer, each containing information from a single two-dimensional image of a scene. The majority of holographic stereograms can be classified into two groups: one-step stereograms, where these apertures are located at the plane of the final holographic display, and two-step stereograms, which use an intermediate holographic transfer step to position the apertures at some other plane. Because of the difficulty of recording a two-dimensional matrix of holographic apertures, the bulk of holographic stereograms are horizontal parallax only (HPO), using a series of slit apertures to present horizontal parallax while eliminating less-useful vertical parallax.

Conventional stereograms, of the type first described by DeBitetto[4], require a strict correspondence between the photographic capture geometry, the holographic mastering and transfering geometries, and the final viewing geometry. The capture camera's range of motion and optical field of view must correspond to the size and relative separation of the stereogram's holographic plate and the size of the projection screen onto which the two dimensional camera image is projected during holographic recording. In two-step stereograms, the distance between the master and the projection screen must correspond to the separation between the master and transfer plates during the holographic transfer step. Finally, the master-transfer separation in two-step stereograms dictates how far the viewer must be located from the transfer hologram in order to see an undistorted image, with the size of the master plate defining the size of the viewing zone.

These geometrical constraints severely restrict the hologram designer, the holographer, and the viewer. The designer can only work with holographic formats that can be made using straightforward holographic techniques. The holographer may have to use large, bulky, and expensive optics and holographic tables in order to make big holograms that will be viewed from several meters away. If the intended view distance changes, the holographer must make major changes in the holographic exposure geometry. If the constraints on the holographic process cannot be met, the quality of the image the viewer sees suffers. For example, the holographic image may appear distorted, or the image may have to be viewed from an inconvenient location, or the hologram may only be visible from a small range of viewer positions. In practice, the designer and the viewer are usually at the mercy of the optical and mechanical constraints to which the holographer must adhere.

Several researchers have examined the distortions that occur when the stages of the holo-stereographic production process do not precisely match[5]. Optical methods of eliminating the image distortion inherent in the Multiplex(TM) hologram were proposed by Benton[1]. Empirical study and correction of two-step flat stereograms were done by Molteni[14] in the *Star*

Wars stereogram. Analytic computer-based predistortion for curved format one-step Alcove holograms was presented by Holzbach[7] and Teitel[16]. These analyses, however, were restricted to specific holographic geometries and as a result have limited general applicability. In this paper, a more general study of distortions in holographic stereograms is discussed that is applicable to a wide variety of stereogram types and formats. The specific distortion addressed here is the non-linear perspective distortion that occurs when the viewer's position does not coincide with the location of the image of the holographic apertures. A set of efficient ways to compensate for these distortions is presented. The resulting distortion-compensated images, when inversely distorted by the holographic stereogram, are presented distortion-free to the viewer. For the work in this paper, computer-based image processing techniques are used exclusively to perform the image predistortion.

PERSPECTIVE DISTORTION IN HOLOGRAPHIC STEREOGRAMS

A DeBitetto type HPO stereogram, when made correctly, presents an undistorted view of the the scene captured by the stereogram input camera to a viewer whose eyes are positioned at the plane of the stereogram's slit apertures. If the viewer moves away from the HPO stereogram, the image begins to distort. This distortion is due to the fact that vertical and horizontal detail of the scene are displayed differently. In the horizontal direction, the depth of details in the image is approximated by the parallax-preserving properties of the stereogram. Horizontal viewer motion alters the relative position of horizontal detail located at different depths. Changes in the viewer's distance from the stereogram affect the geometrical relationship between the viewer and each slit, producing a natural change in perspective. In the horizontal direction, then, a distortion-free stereogram closely approximates the parallax properties of a continuous-parallax three-dimensional display.

Vertical detail, however, is recorded from a single vertical perspective: no vertical parallax is preserved from the original scene. Vertical details cannot change apparent position relative to each other because all vertical detail is fixed at the plane of the projection screen. No amount of viewer position can thus change the appearance of vertical details of the scene, and as a result the vertical perspective presented by the stereogram will be faithful to the appearance of the original scene only when the viewer depth coincides with the depth of the capturing camera. Only at that viewer location will the stereogram's fixed vertical perspective and its continuously-varying horizontal perspective match. In a DeBitetto type stereogram, this perspective agreement occurs only when the viewer is located at the plane of the stereogram's slit apertures. At this plane, each of the viewer's eyes is presented with a single image of the projection screen, which contains a single camera view.

Were the holographic stereogram a full-parallax display rather than HPO, the viewer would also be free to step away from the holographic plate, or "step through" the plane of holographic apertures (if the stereographic array is holographically transfered) and still enjoy an undistorted view. Instead of one and only one projection screen being visible with each eye, parts of many projection screens would now be visible. But the geometrical relationship between each aperture and the viewer changes in such a way that the perspective presented by the display as a whole will match that of the original scene when viewed from a comparable distance.

Unfortunately, the distortion exhibited by an HPO stereogram viewed from an incorrect view distance is not only present but highly visible. The scene shown in Figure 1 is the basis of a simple example. The objects in the scene are all squares of the same size lying at different distances from the capture camera. The holographic projection screen and camera's field of view are both wide enough to assure that all parts of each of the squares will be visible in each of the camera's frames as the camera travels along the view track. A sample of these views is shown in Figure 2. When the viewer looks into the center slit of a stereogram made from this input footage, the center view of the camera footage will be visible. The three squares will appear to be different sizes due to the effects of foreshortening, and the squares will be centered with respect to each other. The view is shown in Figure 3.

If the viewer moves to a position very far from the stereogram, however, the appearance of the squares is no longer what the viewer would expect. This view is shown in Figure 4. The vertical details of scene (the horizontal lines of the squares) appear the same as they did when seen from the correct view distance. Horizontally, though, the squares all appear to be the same size, their vertical edges overlapping just as all the edges of the original squares would if viewed from far away. The middle square, located on the projection plane, is the same size vertically and horizontally as before; the front square is compressed horizontally compared to the undistorted case, while the rear square is stretched horizontally. A viewer located between the stereogram and infinity would see a distortion of a severity relative to the distance from the correct view depth.

If a DeBitetto stereogram is transfered to a second hologram without introducing any distortions, the viewer becomes able to "step through" the plane of the slit apertures to locations closer to the projection screen. The view seen from such a position is distorted in the opposite way from that seen from an infinite view distance, as shown in Figure 5. From here, the front square

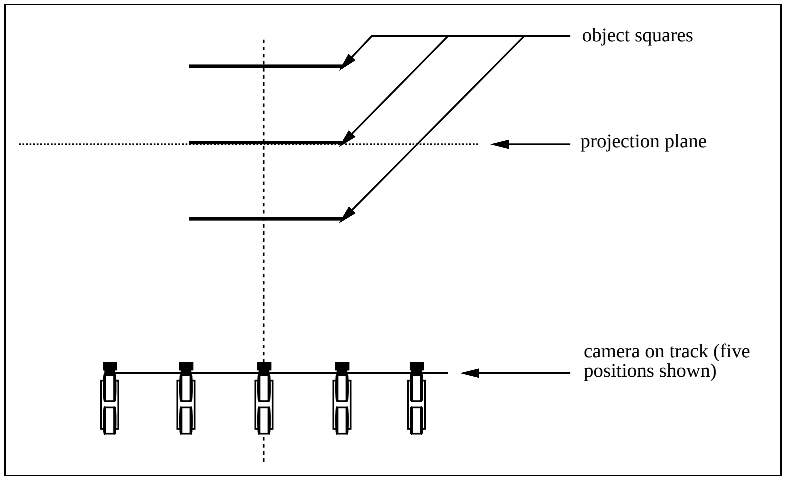

Figure 1: Camera geometry for a simple stereogram.

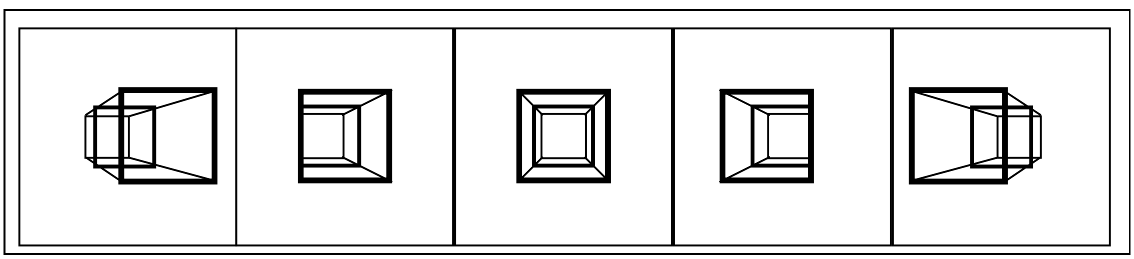

Figure 2: A sample of the frames produced by the simple stereogram camera.

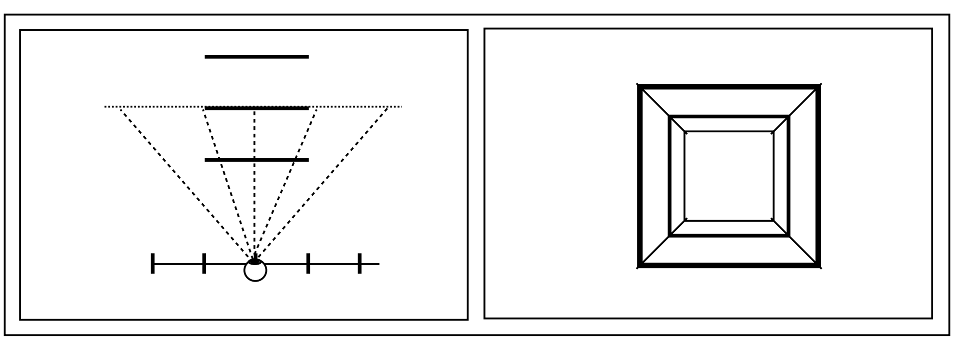

Figure 3: View of the stereogram as seen by a viewer located at the slit plane.

is stretched horizontally, while the back square experiences compression. Once again, vertical perspective remains unchanged. Moving closer to the projection screen exaggerates the distortion, as shown in Figure 6.

Clearly, then, a conventional HPO stereogram requires that the viewer be positioned very close to the plane of the slit aperture in order for the display to appear undistorted. From other viewer positions, objects in the scene compress or expand horizontally by an amount relative to the object's distance from the projection plane. This requirement is a serious limitation in conventional stereographic displays, especially large-scale stereograms designed to be viewed from a distance of several meters. These stereograms must be made in a large laboratory to accommodate the distance between the projection screen and the stereogram plane. Conventional two-step stereograms are further limited because they depend upon phase conjugate illumination of the final display hologram to project an image of the holographic apertures out to the view zone. In phase conjugate illumination, the reference beam used to expose the hologram provides a wavefront of the same shape as that of the intended illumination source, but which travels in the opposite direction. Perfect phase conjugate illumination is difficult to achieve in holograms designed to be illuminated by white light point sources; these holograms require a converging reference source from a large lens or mirror to form to reference the transfer plate with a phase conjugate of the illumination source during holographic transfer. When perfect phase conjugation cannot be achieved, significant image distortion is usually the result. So, while the conventional stereogram design allows the views from a simple camera to be used directly, it complicates holographic production and limits the full utility of the holographic display.

COMPENSATING FOR PERSPECTIVE DISTORTION

The perspective distortion that can occur in HPO holographic stereograms is due to a violation of the following requirements for stereogram production:

- the relative location of the horizontal focus of the capture camera's lens with respect to the camera's projection plane must correspond to the relative location of the horizontal focus of the slit apertures with respect to the horizontal focus of the holographic projection screen,
- the relative location of the vertical focus of the capture camera with respect to the projection plane must correspond to the relative location of the viewer with respect to the image of the vertical focus of the projection screen as presented by the final display.

Conventional cameras have horizontal and vertical lens foci that lie at the same location, so the viewer's position must be the same as the slit position. A modification to the capture camera, however, allows the camera's vertical and horizontal foci to be separated, permitting arbitrary slit and viewer locations. This camera modification is at the heart of image predistortion.

The effects of image predistortion can be thought of in the following way. For a fixed separation between the viewer and the holographic display, an HPO stereogram produces some amount of optical distortion. This distortion affects the image of the projection screen seen through each slit. The image predistortion process calculates the extent of this image distortion and alters the capture camera's images in a way such that they exhibit precisely the opposite distortion. To a viewer, these predistorted images appear unusual and distorted. But once the stereogram is made using these images, the distortion of image and hologram nullify each other, and a viewer located at the pre-calculated view distance will see an undistorted three-dimensional image. An example of the images produced by the image predistortion process is shown in Figure 7.

Optical methods can be used to separate the horizontal and vertical foci of physical cameras. The spherical lens of the camera can be replaced by two crossed cylindrical lenses, or the normal lens can be supplemented by a single cylindrical optic. Such an optical compensation method was used by Benton to correct the cylindrical abberations of the Multiplex hologram. Optical predistortion methods, while simple, are limited in practicality and applicability. The optical properties of simple lenses are fixed and cannot be changed to meet the requirements of different stereogram formats. Because the image fidelity of the stereogram depends on the optical quality of the capture camera's lens, the required optics are usually expensive, large, and difficult to obtain. Finally, optical predistortion methods are of little use for computer-generated synthetic holographic stereograms, where an animation camera captures images displayed on a two-dimensional display. Computer-based image predistortion techniques are more flexible and general than optical methods in the situations where they can be applied.

The goal of synthetic predistortion methods is the same as for their optical counterparts: to position the horizontal focus of the camera at the plane of the slit apertures, and to match the position of the vertical focus of the camera to the intended viewer

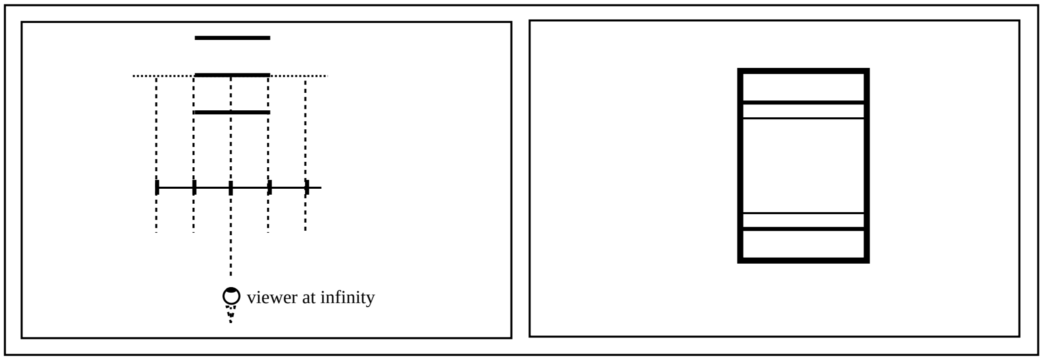

Figure 4: View of the stereogram as seen by a viewer far away.

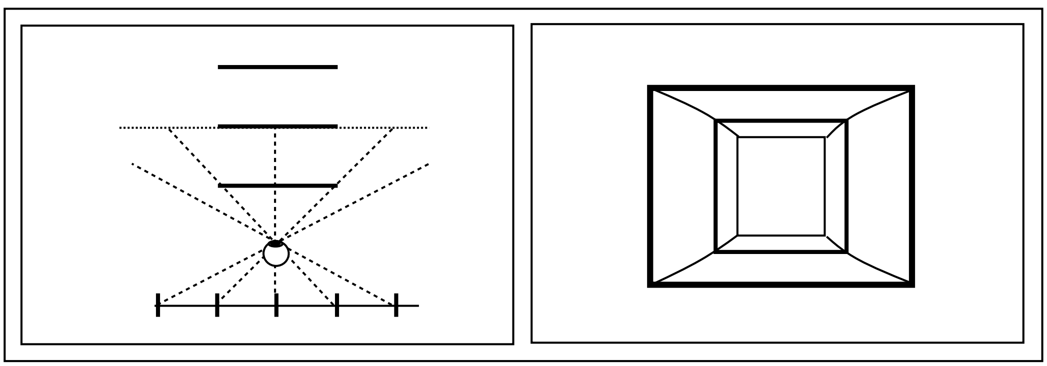

Figure 5: View of the stereogram as seen by a viewer in front of the slit plane.

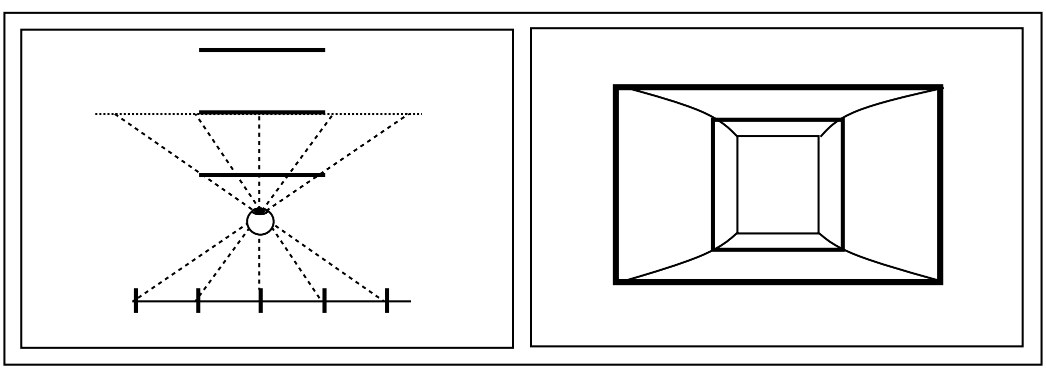

Figure 6: View of the stereogram as seen by a viewer even closer to the projection plane.

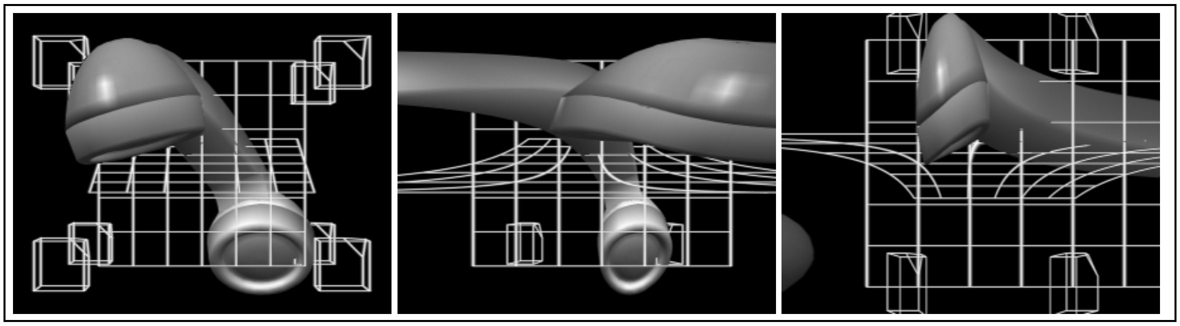

Figure 7: On the left is a single frame from a computer-generated three-dimensional test pattern. The center frame shows the effect of image predistortion where the holographic stereogram is to be illuminated in phase conjugate illumination. On the right is an image designed to expose a non-phase conjugate (direct) illuminated stereogram.

location. This predistortion can be done in two general ways. In the first method, the computer graphics camera is adapted to include an anamorphic camera lens model. Raytracing algorithms are well suited to this type of predistortion. The second method performs predistortion as a post-processing step, using as input a sequence of camera views from a simple computer graphics camera, and outputting another sequence of views that have the desired distortion properties.

Both methods have advantages and disadvantages. The anamorphic rendering technique requires that a special purpose renderer be created to produce the unusual optical model required. It can, however, produce the exactly the optical distortions required for a particular stereogram in a single computational step. The post-processing method allows the output of existing rendering programs to be used, eliminating the need to re-program all of the computer graphics techniques commonly used to produce high quality synthetic images. The range of image sources is greatly widened by using post-processing techniques. On the other hand, post-processing requires that many images of the input sequence be available in order to produce a single output image, placing increased demands on primary and secondary computer memory store. For flat format stereograms, post-processing image predistortion is computationally simple, with most operations consisting of moving data in memory. The amount of data to be moved may be several hundred megabytes, however, an amount that may be prohibitive depending on the storage capacity and architecture of the computer used. For the work done for this paper, post-processing predistortion is used exclusively.

POST-PROCESSING PREDISTORTION

A major difficulty of producing images using a special purpose renderer occurs when the slit plane of the stereogram falls within an object of the scene. In this case, the camera must capture the image of parts of the object both in front and behind the camera. Post-processing methods avoid this problem by capturing a range of input views with a simple camera on a track located at or behind the intended viewer depth. Nothing behind the camera need ever be captured by the camera. Further processing of the image data is required because while the input sequence may have all the perspective views of all parts of the image required, the image data needed to expose each slit is distributed over many input views. Post-processing fragments the original input views and reassembles the pieces into the individual slit images. The specific implementation of the image generation process requires that parameters of the input camera and the predistortion processing match each other; in addition, the method of post-processing can be chosen to best suit the format of stereogram being made. We present two image generation methods here: the infinite camera technique and the perspective slice technique.

The infinite camera technique is actually a hybrid of predistorted rendering and post-processing predistortion methods. The input camera is not quite conventional: while the vertical focus of the camera is positioned at the intended view distance, the horizontal focus of the camera is moved back to infinity. As the camera moves along the track, its lens is translated horizontally so that the images of objects that in the plane of the slit apertures remain stationary on the camera's film plane. Figure 8 shows how the infinite camera moves. The horizontal resolution of the input views is chosen to match the number of slits of the stereogram, one pixel for one slit. (The vertical resolution of the input views can be arbitrarily high.) The pixels for each view can be thought of as representing the intensities of a set of parallel rays, each ray passing through one slit. Each camera view captures a set of rays traveling in only one direction; the camera's motion on the track sweeps out a set of ray cones, with the

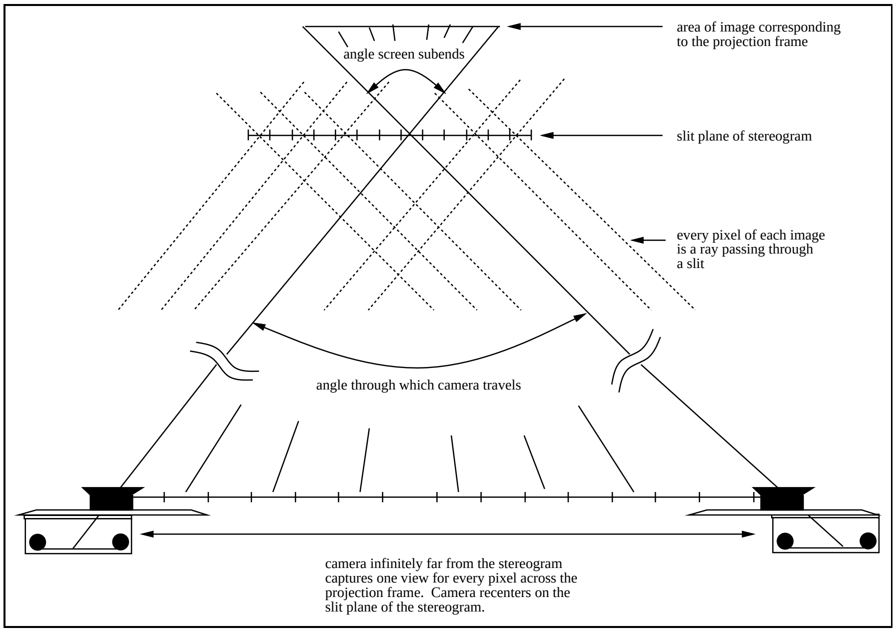

Figure 8: The input camera used to capture perspective views in the infinite camera technique.

apex of each cone located at a slit. In effect, the rays passing through each slit form a synthetic horizontal focus at the plane of the slit. The post-processing step produces a new set of views, with the rays passing through each slit assembled into a single view. These images have a vertical focus at infinity and a horizontal focus at the slit plane, precisely the optical geometry required to expose each slit. The angle of rays that the input camera sweeps out corresponds to the horizontal extent of the projection screen located directly in front of each slit as that slit is exposed.

The simplicity of the infinite camera's post-processing step is one of this method's major advantages. To predistort the input views, the roles of the input views and the columns of those views are exchanged. For example, the first pixel column is taken from each image in the sequence of input views and is used to form the first view of the output view sequence. This column-to-image exchange can be performed as an efficient memory movement operation, with no filtering or other noise-introducing operations required.

Because the input views for the infinite camera technique have only one pixel per slit, the horizontal resolution of the objects in the final scene is limited to the hologram's slit width. For medium- or large-scale images, this limitation is generally acceptable. Also, because the input camera always recenters the slit plane, the infinite camera method is preferred for one-step stereograms, where the slit plane is generally the central plane of interest. Finally, because of the complication of creating an input camera with a horizontal focus at infinity, this method can be adapted to use a conventional camera through modifications in the holographic exposure geometry.

For stereograms with larger slits and projected images with higher resolution, a second technique, called perspective slicing, is preferred. In this method, a conventional camera moves along a view track located at the intended view distance, but recenters the projection plane of the object in the captured images. When the slit structure of the stereogram is superimposed on the input images, parts of each image will be seen through different slits. The slices of different input views seen through a single slit are assembled into a single output view. This assembly is shown in Figure 9. This image, a piecewise approximation to an anamorphic camera view, is used to expose the slit. If the slits of the stereogram are very wide, each image slice may consist of several pixel columns and the interface between two slices may be noticeable in the final display. On the other hand, the spatial resolution of the scene presented in the stereogram is not limited to the size of the stereogram's slits as in the infinite camera technique. Also, because the input camera recenters the projection screen, the perspective slicing method is superior to the infinite camera technique for two-step stereograms, where the projection plane is usually the plane of primary interest in the final display.

is no longer located in front of the transfer plane. Such a direct-illuminated display is much less prone to the distortions introduced by improper illumination. The advantages of direct illumination can also be applied to one-step stereograms: the projection screen for each slit can appear to be behind the hologram plane instead of in front of it. Once again, direct illumination greatly simplifies exposure and display, especially for large scale displays.

THE ULTRAGRAM

Distortion compensation is such a powerful and widely applicable tool in stereography that the name ULTRAGRAM was coined to describe the class of stereograms that use it. This section describes some of the ULTRAGRAMS produced to date. The first ULTRAGRAM, *Cadillac Hubcap and Wheel*, is a synthetic image produced from a CAD database provided by the Design Staff of the General Motors Corporation. A scene from the movie *Diner* was reflection-mapped onto the surface of the wheel. The hologram itself was a two-step reflection type, with the transfer designed for direct illumination. The master consisted of 300 1mm-wide slits, each 300mm high, while the transfer measures 250mm wide by 200mm high. To maximize the view zone of the final display, the master and transfer were separated by only 100mm, producing a view zone of over 90 degrees when viewed from 1 meter. The slit images were predistorted using a variation of the infinite camera technique, with each slit image having a resolution of 600 by 480 pixels. Figure 11 shows the holographic exposure apparatus used to produce the master for *Cadillac Hubcap*, while Figure 12 shows the transfer setup. Figure 13 illustrates how the hologram is to be viewed, with an image of the stereogram shown in Figure 14.

ULTRAGRAPHIC techniques were also used to make a large-format one-step transmission stereogram, *Large Chevrolet Wheel*, created from another General Motors database. This stereogram was designed to show that a large scale display (1 meter by 1 meter square) could be made in a relatively small laboratory. The holographic exposure apparatus, diagrammed in Figure 15, consisted of a large (980mm square) projection screen positioned 500mm front of a holographic film transport mechanism. The film was exposed slit-by-slit through a long 1mm slit aperture. A vacuum mechanism held the film stationary during exposure, while a motor advanced the film from a supply to a takeup spool after each exposure. The entire exposure process took approximately twelve hours to complete. One of the most unusual features of this exposure mechanism is the tower on which the reference source was located. This tower was used to provide a piecewise-diverging reference source which closely matched the intended illumination. The tower's optical stage must translate after every slit exposure. Because the projection screen's vertical focus is located off of the plane of the stereogram, monochromatic illumination, provided by a mercury arc lamp, is required to avoid chromatic blur. Predistortion of the image was done using the infinite camera technique, requiring more than 600 megabytes of data to be transformed. In the final stereogram, each slit is visible through an angle of 90 degrees. Figure 16 shows a two pictures of the stereogram. The first picture shows the display viewed from the correct view distance of 2 meters. The second shows the perspective distortion that occurs when the viewer moves to a distance 8 meters from the hologram.

Finally, a high-resolution two-step direct-illuminated reflection ULTRAGRAM has been produced. The *Breakfast Attempt, Ultragram Version* is a photo-realistic computer graphics image of a fanciful breakfast scene designed by two of the authors. Although the image is small (100mm x 100mm), the resolution of the rendered images is much higher than the other ULTRAGRAMS produced (880 x 880 pixels). The master was positioned 250mm behind the transfer plate. The master plate consisted of 300 1mm-wide slits. A re-centering stereogram geometry was used to maximize image visibility, with the perspective slicing technique used to predistort the images. Figure 17 shows a picture of the stereogram. When the final stereogram was viewed at the intended view distance of 500mm, part of the image was visible over a region 900mm wide.

CONCLUSIONS

The ULTRAGRAMS presented in this paper are proof of the potential of distortion compensation techniques. The predistortion methods presented here are practical and efficient, and can be tuned to specific display formats. Distortion compensation requires an accurate modeling of all steps of the stereographic production process. If this modeling is done correctly, a viewer at an arbitrary fixed distance can be presented with an undistorted three-dimensional image. A wide range of otherwise impractical stereogram formats becomes realizable, and more commonplace formats can be manufactured more simply and with greater precision. Distortion compensation is applicable to many different types of stereogram displays, and to those who can use it, it offers an versatile, adaptable way to loosen the constraints of the stereographic production process.

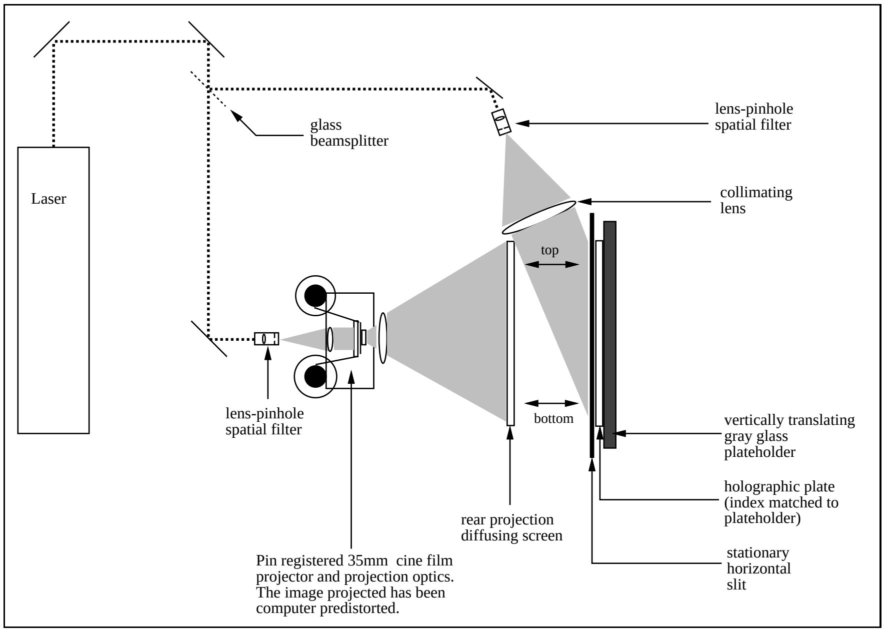

Figure 11: ULTRAGRAM two-step mastering setup.

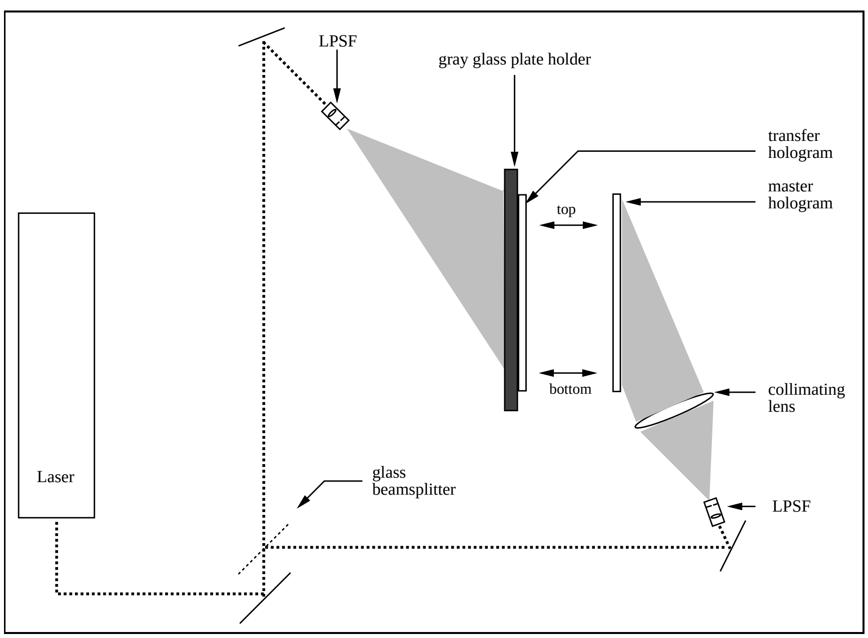

Figure 12: ULTRAGRAM two-step transfering setup, where the transfer is designed for direct illumination.

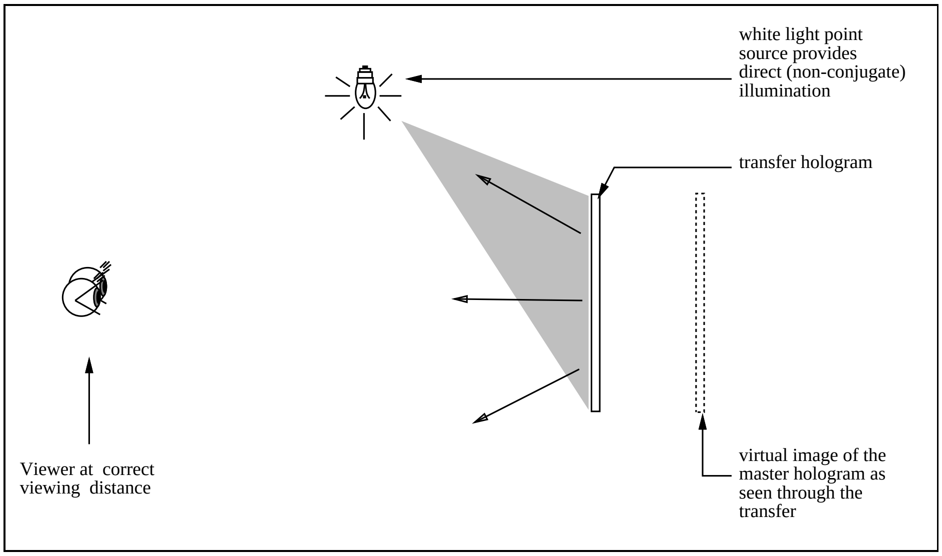

Figure 13: Viewing a direct-illuminated ULTRAGRAM.

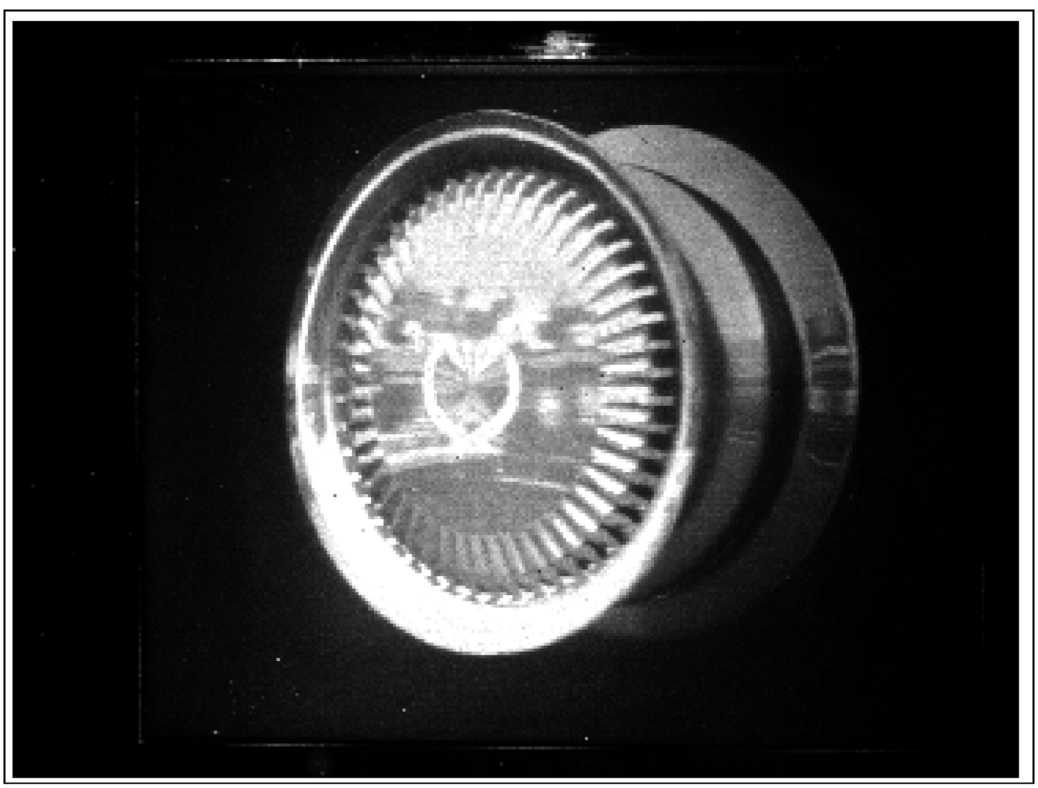

Figure 14: Photograph of the *Cadillac Hubcap and Wheel* ULTRAGRAM.

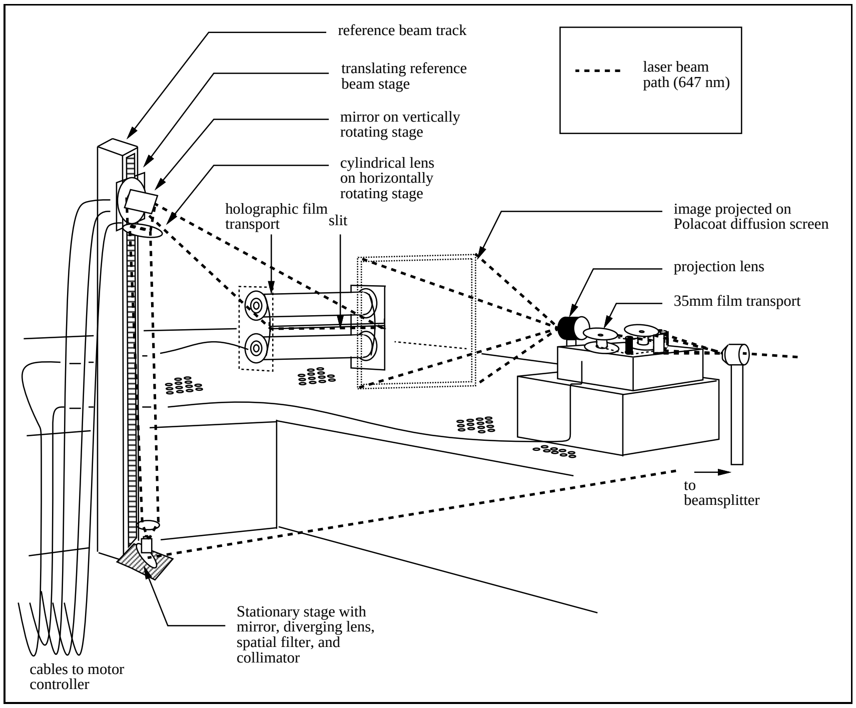

Figure 15: Holographic apparatus used to expose *Large Chevrolet Wheel.*

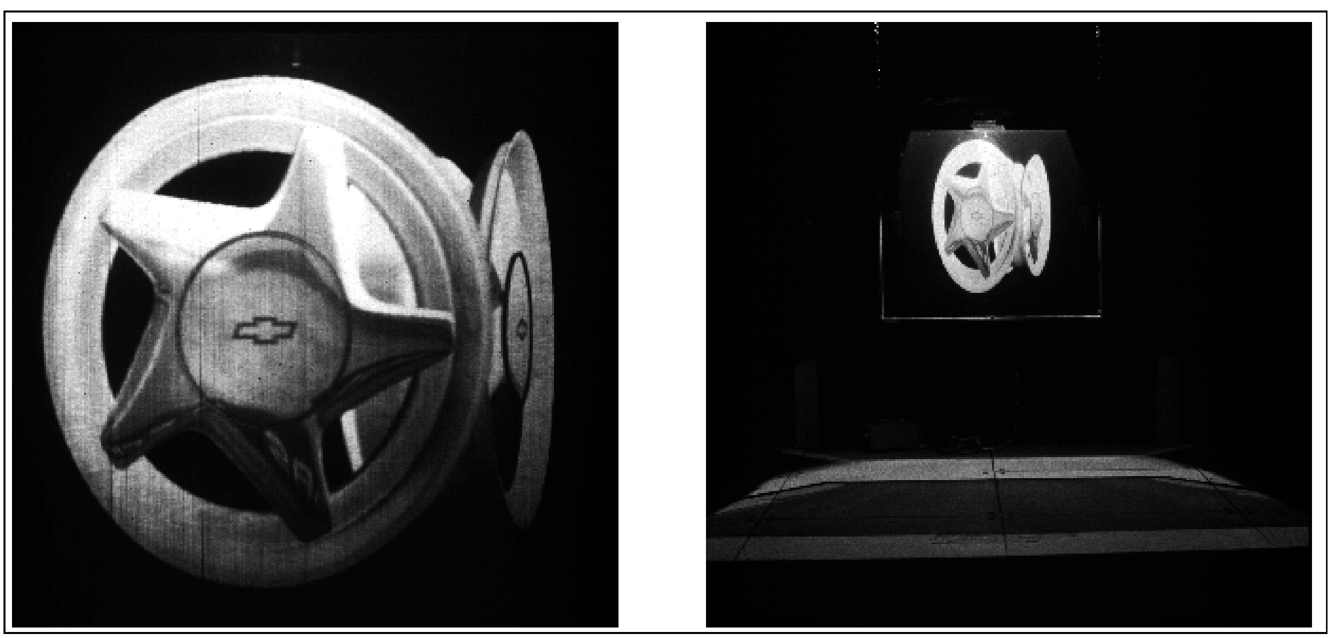

Figure 16: Photographs of the *Large Chevrolet Wheel* one-step transmission ULTRAGRAM, the left one taken from the correct view distance of 2 meters, the right taken from about 8 meters.

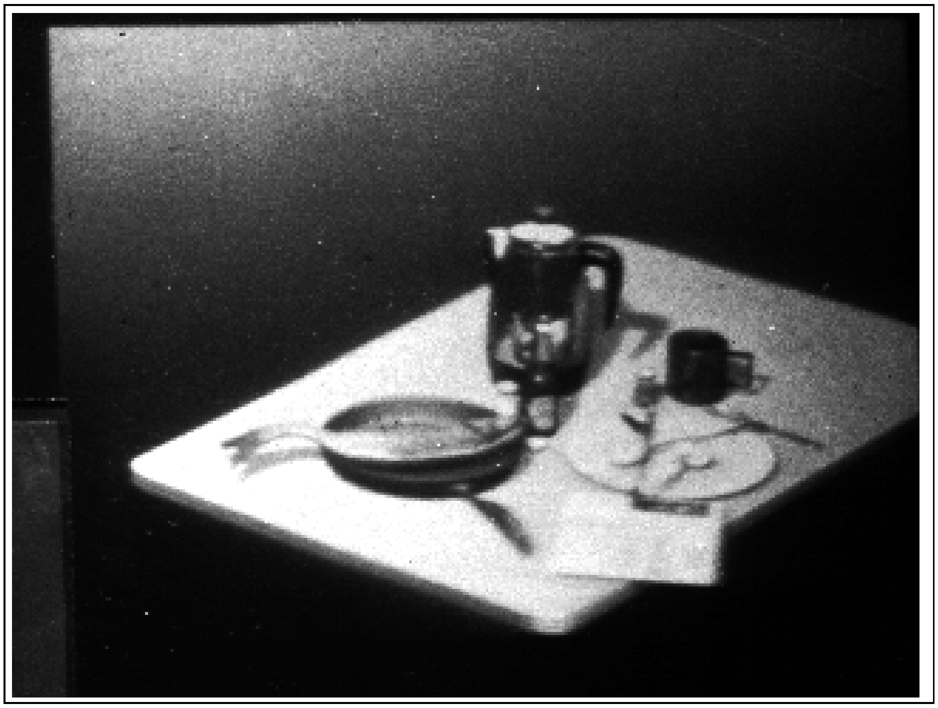

Figure 17: Photograph of *Breakfast Attempt, Ultragram Version.*

ACKNOWLEDGMENTS

The authors would like to recognize the contribution of the Computer Graphics and Animation Group of the Media Laboratory, whose rendering library *RenderMatic* was used to produce the high quality synthetic images used for the holograms described here. Furthermore, we would like to credit the work of machinist Terry Maxedon, whose engineering skill and craftsmanship brought to reality the custom holographic hardware used to produce the ULTRAGRAM.

The authors are supported under a variety of grants and sponsorship. These include the Defense Advanced Research Projects Agency under Rome Air Development Center (RADC) Contract F30602-89-C-0022, NYNEX, and the Design Staff of the General Motors Corporation.

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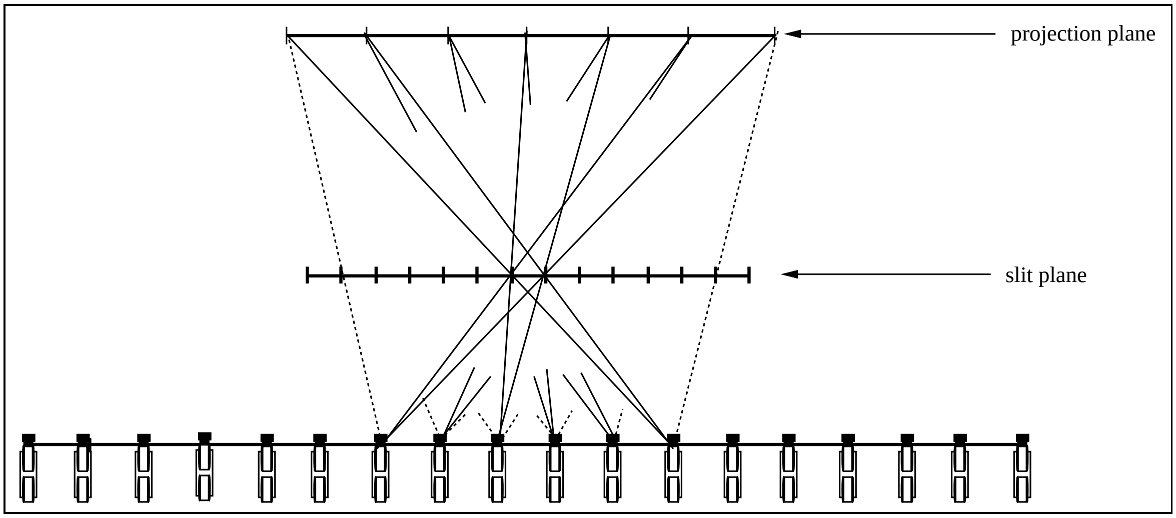

Figure 9: In perspective slicing, the projection screen image for each slit is formed by collecting the pieces of each camera view that pass through that slit.

ADVANTAGES OF DISTORTION-COMPENSATED STEREOGRAMS

Distortion-compensated stereograms place no limitation on the location of the slit plane with respect to the viewer or the projection plane. As previously mentioned, this freedom allows a stereogram with an arbitrary view distance to be designed. But predistortion offers several more important advantages. For instance, the view zone of distortion-compensated two-step stereograms can be made significantly wider than that of conventional stereograms by placing the master and transfer plates close together. In this case, the image of the master hologram appears to move slowly with respect to the transfer plate as the viewer moved in front of the display, increasing the range of viewer positions from which the image can be seen. This widening of the view zone is shown in Figure 10. A close proximity between the master and transfer plates is also important when the hologram is exposed; the holographic table layout can be very compact when distortion compensation is used.

One of the most important applications of predistortion is in the production of direct-illuminated two-step stereograms. In contrast to phase conjugate illumination, direct illumination uses a reference source with a wavefront of both the same shape and direction as that of the eventual illumination source. The transfer hologram can be lit with an illumination source that closely mimics the original reference beam, producing an image of the slit master behind the plane of the transfer. Computer predistortion allows the final three-dimensional scene to appear correct even though the image of the slit apertures of the master

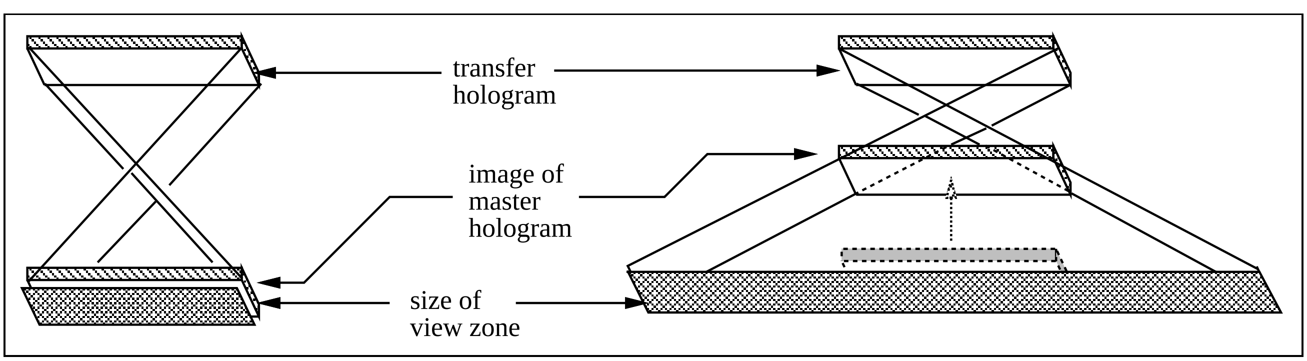

Figure 10: When the plane of the master stereogram is moved away from the viewer and closer to the transfer plane, the size of the view zone widens. Not shown in this picture is the similar widening of the vertical view zone.

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