Multiple-Viewer Autostereoscopic Display System

by

Paul Christie

B.S., Applied Physics
Columbia University, New York
May 1992

Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning,
in partial fulfillment of the requirements for the degree of

Master of Science in Media Technology
at the
Massachusetts Institute of Technology

June 1997

Signature of Author ______________________
Program in Media Arts and Sciences
May 9, 1997

Certified by ______________________
Stephen A. Benton
Allen Professor of Media Arts and Sciences
Program in Media Arts and Sciences
Thesis Supervisor

Accepted by ______________________
Stephen A. Benton
Chair
Departmental Committee on Graduate Students
Program in Media Arts and Sciences

Multiple-Viewer Autostereoscopic Display System

by

Paul Christie

Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning,
on May 9, 1997
in partial fulfillment of the requirements for the degree of
Master of Science on Media Technology
at the
Massachusetts Institute of Technology

Abstract

Three-dimensional displays are numerous. Some can be used as "computer monitor-type" displays where predominantly one user is involved, while others work well in "movie-like" settings with a captive. However, very few, if any, of these 3-D displays have what can be called a "television-like" feel.

For purposes of this thesis, a "television-like" feel is defined in this thesis as:

1) being autostereoscopic (no special glasses required),
2) having the capability to deliver a 3D image to a viewer at a variety of locations within the viewing area,
3) being able to accommodate multiple viewers,
4) being able to convey image realism,
5) utilizing only the minimum amount of data necessary to create a 3D image,
6) having a design that is scalable.

Seven new designs will be outlined and discussed in this thesis which will satisfy these criteria, or bring valuable insight as to how these criteria may be satisfied.

Thesis Supervisor:
Stephen A. Benton
Allen Professor of Media Arts and Sciences

This research was sponsored by the Korean Institute of Science and Technology and Samsung Electronics Company.

Multiple-Viewer Autostereoscopic Display System

by

Paul Christie

The following people served as readers for this thesis:

Reader ______________________________
Andrew B. Lippman
Associate Director of MIT Media Laboratory

Reader ______________________________
Joseph Jacobson
Assistant Professor of Media Arts and Sciences
MIT Program in Media Arts and Sciences

To my bride, Joanne

Acknowledgements

No thesis is ever truly the product of only a single person. Although the work presented within this text is my own, it would not have been possible without the assistance and support of the following people:

Steve Benton (my professor and thesis advisor) - for allowing me to have a honeymoon during my thesis crunch, for graciously spreading red ink all over the various drafts of this thesis, and for pointing out the shortcomings in certain ideas that were overlooked.

Joe Jacobson (thesis reader) - for excellent comments on my thesis drafts, and for continually showing interest in my work by asking "When do I get to see a demo?"

Andy Lippman (thesis reader) - for adding a unique twist to my thinking on how the displays described here could be used in a different way, and for continually expressing enthusiasm for my work by showing up for impromptu demos.

Rob Corbisier (Media Lab UROP) - for machining parts for the projection polarization tracking prototype, for conducting important experiments on the projection screen system, and for assisting with the preliminary work on the projection intensity tracking prototype.

Tom Slowe (Media Lab grad student) - for pulling together the viewer-locating system on such short notice, and for making my display prototype look very impressive as a result.

Adam Kropp (Media Lab UROP) - for last minute coding that gave my display great images to show off and a way to communicate with the viewer-locating system.

Gwelleh Hsu (Spatial Imaging grad student) - for locating and recruiting Tom, for acquiring components for the display and viewer-locating system, and for assisting with the fine-tuning of the viewer-locating system by patienty sitting in front of the camera.

Additionally, I would like to thank **Melissa Yoon** for her friendship and discussions that greatly enriched my time at the Media Lab, **Mike Klug** for the discussions of holography (my real passion) that were much needed distractions, **Ravi Pappu** for being the supportive office-mate, and the entire Spatial Imaging group of '95-'97 (**Melissa Yoon**, **Mike Klug**, **Carlton Sparrell**, **Wendy Plesniak**, **Ravi Pappu**, **Arno Klein**, **Don Kim**, **Gwelleh Hsu**, **Adam Kropp**, **Benjie Chen**, and **Rob Corbisier**) for keeping me sane by acting insane.

I must also say thank you to the woman I now call my wife, **Joanne Lee Christie**, for accepting my decision to move away from her to attend MIT, for deciding to marry me anyway, and for enduring my neglect of her during the final weeks of my thesis work.

Finally, I would like to thank **God** for so richly blessing me with the mind to grasp and implement the ideas described in this thesis, with the colleagues and friends to support me through the process, and with the opportunity to persue my dreams.

The sponsors of this research were the **Korean Institute of Science and Technology (KIST)** and the **Samsung Electronics Company**. Without their support and their investment in the future of 3-D displays, this research could not have been done.

Table of Contents

1 Introduction and Motivation

Creating three-dimensional moving images is a long sought after goal. After all, why should the ideas, stories, and communications of the world be displayed on two-dimensional devices when the world is actually a three-dimensional medium. By adding the third dimension of depth, more information can be conveyed with greater clarity of meaning. Stories and events can be told with the greater impact of true realism. Viewers can be drawn into an experience with a sense that they are truly there, or they can be connected to others across the world as if they were in the same room.

It is these visions that have enticed researchers to continually develop new and better three-dimensional display devices. Certain devices and techniques have had success in specific user environments. For instance, "movie-like" environments have had great success using three-dimensional techniques that require special glasses for viewing. In these situations, a captive audience and a special presentation atmosphere allows for the ability to distribute and utilize special viewing aids to a large number of viewers. In contrast, a "computer-like" user environment typically involves one viewer per display. These conditions work very well for three-dimensional displays that have only a limited view-zone capability or that require cumbersome head-mounted displays. Other 3-D devices have found specialized niche markets that can tolerate the restrictions of that specific device.

While these numerous techniques have had success in "movie-like," "computer-like," and specialty environments, few, if any, three-dimensional display devices work well as a "television-like" display. This is largely because television sets, while being the most pervasive and common display devices in modern technology, also carries with them a number of restrictions compared to other displays.

1.1 3-D "Television-Like" Qualities - Viewer Concerns

When viewing and using a computer monitor there are often peripherals involved that aid the person working at the monitor. For this reason, using special glasses or wearing a special tracking unit is not overly inconvenient in order to be able to visualize three-dimensional graphics or pictures on the screen. However, with a television set, the viewer requires much more flexibility and freedom than can be afforded with head gear or tracking devices. In the home, a viewer often wishes to relax in front of the television set without any encumbrances. The viewer may also periodically leave the room where the television set is located, causing problems for a display device requiring wearable peripherals. 3-D displays employing fixed viewing positions have similar difficulties in a home viewing environment, as viewers typically wish to sit in a place of their own choosing rather than a place of the display's choosing. And even once the viewer has chosen his viewing spot, he may still move around in the viewing zone from time to time.

Television sets used as marketing tools in public areas involve another dynamic, where a message must be communicated to passing or momentarily stopped viewers. If the viewer is required to put on a special piece of equipment in order to view the display, the effectiveness of the display and its message is significantly decreased. Likewise, if the viewers must sit or stand in pre-programmed positions in order to view the display, the appeal and usefulness of the display is once again less than optimal.

Television sets in the home are often enjoyed with a number of people watching simultaneously. In fact, for certain special televised events, people will often gather around a single television set to experience the event together. A "television-like" three-dimensional display should thus be viewable to more than one person at a time. In a marketing situation, the ability to communicate to more than one person at a time greatly enhances the television set's power as a tool for sales.

From the perspective of the viewer, there is one other desirable quality for a "television-like" three-dimensional display. This is the ability to convey realism. While often it seems implicit that a three-dimensional display would reproduce scenes with greater realism than a conventional 2-D display, this is not always the case. Certain types of 3-D displays, for instance, can only display one color. Others can only display images as ghostly three-dimensional replicas which are completely translucent. A "television-like" display requires that the images have the impact and realism of the solid, full-color world in which we live.

1.2 3-D "Television-Like" Qualities - Manufacturer Concerns

Taking a different perspective from that of the viewer, a "television-like" display must also overcome difficult restrictions from the point of view of a manufacturer. A three-dimensional display capable of meeting all of the above viewer requirements is useless unless the proper information needed to drive the display can be processed, transmitted, and received in a fast and easily manageable way. Therefore, it is important for a "television-like" display to be able to create the proper three-dimensional images using a minimum amount of information. Large amounts of information necessitate larger computing power to process and display the images, as well as more sophisticated methods for transmitting the high-bandwidth information from a broadcast point to the display. A minimum information display is simpler, faster, and, perhaps most importantly, cheaper.

Another important manufacturing quality for a "television-like" display is scaleability. Imagine if a television set only came in one, rather small size. While it may do the job of communicating a message, it certainly would not have the success that television has enjoyed in our society today. Or, conversely, imagine a television set that was excessively large. It may have uses in larger audience viewings or certain sales applications, but it certainly would not make it into the average household. Thus, the technology for a successful "television-like" three-dimensional display must be capable of scaling to many different sizes to meet the needs of different applications, different environments, and even different types of households.

1.3 Establishment of "Television-Like" Criteria

Considering both the viewer and manufacturer concerns described above, a set of criteria can be developed that defines a "television-like" 3-D display. This set of criteria will be used throughout the remainder of this thesis as both a means for evaluating current 3-D displays and as a guideline for designing new 3-D displays. In fact, seven new "television-like" 3-D displays will be presented in Chapter 5. The full set of criteria has been summarized in Table 1.

Table 1: "Television-like" 3-D Display Criteria

- Autostereoscopic
- Capability to deliver images to viewer's location
- Multiple viewers (4+)
- Image realism
- Minimum information requirements
- Scaleability

1.3.1 Autostereoscopic

Viewer flexibility, comfort, and convenience require that the display function without the need for special glasses or head-gear. Any type of wearable peripheral that is necessary for viewing the three-dimensional images will be detrimental to the long-term enjoyment of the display.

1.3.2 Capability to Deliver Images to Viewer's Location

Viewer's of a television set often "plop" down in a comfortable spot to watch television, and a "television-like" 3-D display should allow the same. Viewers should not be forced into special viewing locations in order to see the images. Similarly, the display should be able to continually provide the proper 3-D views as the viewer moves around or through the viewing area.

A special note must be made here as to how this criteria will be handled for the purposes of this thesis. Although total viewer freedom within the viewing area is the ultimate goal for a "television-like" 3-D display, this text will limit the viewer's range of movements to a single viewing plane located at a fixed distance from the display. While the viewer is not required to be positioned precisely at the viewing plane, he or she will be considered to be near to the plane at all times. Thus, viewer movement toward or away from the display will not be considered, and this criteria will be satisfied if the display is capable of delivering the 3-D views to all points along the viewing plane described. This restriction has been observed in an effort to narrow the field of research for this thesis to a more manageable size. However, the ability to track and accommodate different viewer-depths from the display is an important factor in complete viewer freedom, and it is hoped that future work will be able to apply the principles discovered here to the additional task of depth-tracking.

1.3.3 Multiple Viewers

As mentioned above, television is a shared experience and would have a very different impact if it were limited to only one viewer at a time. The utility of the display also depends on its ability to communicate with several viewers simultaneously. Although the term "multiple viewers" can technically be defined as two or more, its usage here will not be considered justified unless a display has the capability to accommodate up to four viewers. This will hopefully limit qualification for this criteria to displays that can truly handle parallel viewing, as opposed to displays that might add a few components or tricks to add one extra viewer.

1.3.4 Image Realism

The primary concerns here are that the display can deliver full-color 3-D images and can provide proper occlusion (the depth cue that allows objects positioned closer to the viewer to block the view of objects positioned farther away). Several displays claim to be "true" 3-D, and yet are unable to provide either of these qualities in their images.

1.3.5 Minimum Information Requirements

This criteria can be taken at face value. The less information required to communicate good quality three-dimensional images, the better.

1.3.6 Scaleability

There are two parts to this issue. One is whether or not it is technically possible to scale the size of the display to different sizes. This involves the physics, or inner workings, of the display at various sizes. The other part to consider is the ease with which a display can be scaled. This involves factors like size, bulk, and cost. Both parts must be met in order to satisfy this criteria.

2 Background and Categorization of 3-D Displays

Three-dimensional displays come in a wide variety of “flavors.” They vary in everything from their core technologies to their primary applications. Each different type of display also has its unique set of advantages and limitations. For the purposes of this thesis, the varied types of three-dimensional displays have been divided into five basic categories (see Table 2). These categories include 1) viewing aid or head-mounted displays, 2) lenticular screen displays, 3) volumetric displays, 4) electronic holography displays, and 5) macro-optic or specular displays.

Table 2: 3-D Display Categories

2.1	Viewing Aid / Head-Mounted
2.2	Lenticular Screen
2.3	Volumetric
2.4	Electronic Holography
2.5	Macro-Optic / Specular

2.1 Viewing Aid (Glasses) or Head-Mounted Displays

Displays that require some type of head-gear or glasses all follow a similar operational philosophy: control what enters the eyes, not what exits the display. By placing some type of wearable apparatus in front of the viewer's eyes, these systems can accept or reject information entering each eye separately. The idea behind this design goes back to the original stereoscope, first proposed by Sir Charles Wheatstone in 1838 (Wheatstone 1838). Wheatstone took two hand-drawn pictures, each drawn from a slightly different perspective, and placed them in a simple viewing device that allowed each eye to only see one of the pictures. Although each eye was seeing a different picture, Wheatstone realized that the viewer's brain could take the two slightly different images and fuse them into a single three-dimensional image. The exact same concept is still used today in head-mounted displays, augmented with today's advanced technology. Two tiny CRTs or LCDs, each bearing an image taken from a slightly different perspective, are placed in front of each of the viewer's eyes to create a final three-dimensional, or stereoscopic, scene.

Designs for other systems that utilize wearable accessories usually involve displaying both left- and right-eye information on the same screen, with the screen separated from the viewer. The left- and right-eye information is coded on the screen in a particular manner that can later be decoded by a pair of glasses worn by the viewer. An early technique of this type, called anaglyphic 3D, was invented and patented in 1891 by Louis Ducas Du Hauron (Potonniee 1930), and displays left- and right-eye images in separate colors, typically red and blue. The viewer is then able to separate out the left- and right-eye images by wearing special glasses with one lens tinted red and the other blue. More recent adaptations of this idea code the left- and right-eye images with orthogonal polarizations, and use glasses with orthogonally oriented polarizers. A slightly more sophisticated technique, called "Crystal Eyes," displays images on a screen which rapidly alternate between left- and right-eye images (Lipton 1985). A special pair of LCD-shutter goggles is then worn, which alternately blocks the left and right eye in synchronization with the alternating pictures. When the left-eye image is showing on the display, the left-eye lens of the goggles is clear while the right-eye lens is opaque, and when the right-eye image is showing on the display, the right-eye lens is clear and the left-eye lens is opaque. Thus, the goggles are controlling the images that are allowed to enter each of the viewer's eyes, allowing only left-eye images into the left eye and only right-eye images into the right eye.

Three-dimensional displays using glasses or head-mounted systems have been some of the most popular 3-D techniques. Anaglyphic movies and television specials are still being produced, long after the introduction of anaglyphs in the late 1800's. The technique of using polarized glasses is also very popular, being used in such venues as Disney World's 3-D show "Captain EO." Head-mounted displays have found a very strong foothold in the computer industry as a peripheral to 3-D computer software programs. The primary three-dimensional method being used in conjunction with computers is the Crystal Eyes shutter goggles system. Computer software synchronizes the alternately clear and opaque goggle lenses with an alternating left/right image on the computer screen. This system has become particularly successful because it can be used with standard monitors, televisions, and even VCR's. The shutter goggle technique is also the one used for Sony's big screen 3-D IMAX movies. Even Sega Corporation, the video gaming giant, has put out a low resolution 3-D head-mounted system called Virtual Boy to enhance some of its video games.

While viewing aid and head-mounted displays have enjoyed a fair amount of success, the obvious problem with these display systems is that they all require the viewer to wear some type of apparatus or accessory to see the three-dimensional image. In special presentations or movie environments wearing special glasses allows a large number of viewers to share the experience, but the situation is at best inconvenient. The glasses also often cause headaches or eye strain when the viewer looks away from the screen at the rest of the world, or when the glasses are used for long periods of time. More sophisticated head-mounted displays suffer the additional problem of being single-user devices, isolating viewers from one another and preventing them from sharing the 3-D experience. These factors add together to make the use of special glasses or head-mounted displays inconvenient and unsuitable for the long-term enjoyment of a three-dimensional display.

2.2 Lenticular Screen Displays

Another popular form of three-dimensional display depends upon lenticular optical technology, a linear array of narrow cylindrical lenses, to create separate viewing zones. Image information for the different view zones is spatially separated in the back focal plane of the cylindrical lenslets, allowing the lenslets to direct this information only to a narrow area of the viewing plane. This type of display has roots going back to 1903 and F.E. Ives (Ives 1903) development of the "parallax stereogram." More recently, lenticular displays have been given new life by utilizing Liquid Crystal Display (LCD) panels or LCD projected images to serve as an updatable means for creating the spatially separated information behind the cylindrical lenses. Alternating columns of pixels from the LCD display are used to display alternating left- and right-eye information. The lenticular screen placed over the LCD or LCD image then produces two separate view zones in the viewing plane, one for the left eye and one for the right eye, enabling a stereoscopic image to be seen by the viewer.

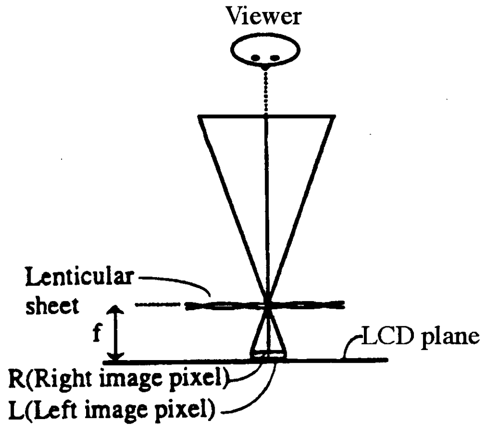

Figure 1 - Diagram of lenticular screen display with pixels spatially separated in back focal plane of lenslets (Tetsutani, et al. 1994).

With the advances in technology of not only the LCD industry, but also the lenticular lens industry, a number of large companies are pushing research and development in the 3-D lenticular display area. In fact, two companies, Dimension Technologies and Sanyo Electronics, have already come forward with commercial 3-D laptop computer displays based on a lenticular design. The display is autostereoscopic (no glasses are required to view the 3-D images), but the images can only be seen by one user at a time and the view zone is quite limited. One research effort of particular interest has emerged in only the last several months from the Sharp research laboratories in Europe (Woodgate, et al. 1997). This technique uses lenticulars and an LCD to create not two, but three separate viewing zones in the viewing plane. The LCD is then connected to a viewer tracking system which actively updates the images in the three different viewing zones to allow the viewer to move around in the viewing space without loosing the three-dimensional view, and to create the feeling of “looking around” the 3-D objects on the screen. The display is only for a single viewer, though.

Despite a relatively simple design for creating these autostereoscopic (no glasses or head-gear) displays, the lenticular 3-D systems have a number of shortcomings. Image resolution tends to suffer because the overall resolution of the LCD display must now be divided among the individual view zones. So a lenticular display with two view zones will only have half the resolution of the LCD used in the system, and a display with three view zones will only have one-third the resolution. Even if the LCD resolution itself is increased to accommodate handling twice the image information, the ultimate resolution of the display is still limited by the diffraction of light through the narrow apertures of the lenticular lenslets that cover the LCD. As a result, display resolution finds itself in a "Catch-22," where increasing LCD resolution means narrower lenticular lenslets and worse diffraction problems, while wider lenticular lenslets means less diffraction but lower LCD resolution.

Beyond the image quality concerns, lenticular displays have further difficulties when it comes to viewer tracking and handling multiple viewers. Viewer tracking can be implemented by either shifting the image information behind the cylindrical lenslets, similar to the method implemented in the Sharp design, or by shifting the lenticular lenslets themselves. In either case, the view zones created by the display can be shifted laterally to follow a single viewer. However, use of this method of viewer tracking precludes the possibility of multiple viewers, unless all of the viewers are to move in exactly the same way at exactly the same time. Additional techniques have been developed by Tetsutani, Omura, and Kishino (Tetsutani, et al. 1994) to track viewer distance from the display, but again can only handle a single viewer. An alternate lenticular display design which allows the possibility for multiple viewers abandons the dynamic tracking technique, and instead opts to increase the number of view zones in the viewing plane. While this does allow more than one person to view the display, the viewers must locate themselves in specific, predetermined positions in order to see the correct three-dimensional view. If the viewers move around in the viewing area, or position themselves at an incorrect location, the three-dimensional image breaks apart, often appearing to be pseudoscopic (flipped inside-out). This is not only an annoyance, but also has a tendency to create headaches. Thus, lenticular displays can either accommodate only one viewer who is free to move about in the viewing area, or multiple viewers in rigidly fixed locations.

2.3 Volumetric Displays

Volumetric three-dimensional displays involve using some type of medium to fill or scan through an entire 3-D volume. Different schemes are then devised to address and illuminate small volumes, often called "voxels," within this medium. Ideas for such displays have been proposed over the past 60 years or so (Blundell, et al. 1993), and have included spinning panels of LED's, spinning helixes addressed by lasers, translating membranes, and even highly pressurized, heated gases excited by infra-red lasers. Designers of such systems often tout the displays as being "true 3-D" because they actually address individual points within a volume space rather than relying on psychological depth cues to create the illusion of depth. The systems also do not require any glasses to see the images, can handle multiple viewers, and often have a view zone that spans a full 360 degrees laterally around the display.

Several recent works of interest must be noted in this category. One idea being developed through the collaboration of RGB Technologies, NEOS Technologies, and NRAD utilizes a 36 inch diameter spinning helix that rotates at speeds of approximately 600 rpm. The helix is then addressed from above by a scanning laser system that illuminates specific points on the helix as it sweeps through the full cylindrical volume of the display. Another spinning display technique is being studied at the University of Canterbury in New Zealand. This system utilizes the same technology used in the Cathode Ray Tube, the technology incorporated in almost all televisions and monitors today. The new system, called the Cathode Ray Sphere, has a panel of phosphors that spins within a spherical chamber and is addressed from different directions by two or three electron guns. A solid state version of a volumetric display has been developed by Stanford University, IBM, and SDL Corporation. The display volume, currently only the size of a sugar cube, is filled with thin layers of rare-earth doped glass that are addressed by invisible laser light. By addressing different points within the layered volume with intersecting beams from the lasers, small portions of the doped glass can be forced to fluoresce. 3-D images can then be constructed out of these fluorescing points within the volume.

An immediate disadvantage to volumetric displays is the difficulty involved in scaling up the designs. Because their basic concept dictates that the active medium fill or scan the entire image volume, larger images require even larger displays, becoming too bulky to be practical. For some designs, larger volumes of the necessary medium may not even be possible. Volumetric displays also have an inability to represent occlusion, which means that the resulting 3-D images are always transparent, with a ghostly quality. The realism of the images is thereby degraded for almost all three-dimensional scenes. One final consideration is the amount of information required to properly address each image point within the full volume of the display. Creating a volumetric display with even low resolution would require at least an order of magnitude more information than standard two-dimensional displays.

2.4 Electronic Holography Displays

One of the most recent developments in three-dimensional displays is electronic holography. This field was pioneered by Stephen Benton and Joel Kollin in 1989 (Benton 1990) (Kollin 1988), and has since drawn a small gathering of researchers working along the same lines. The basic idea is to calculate the fringe pattern, or small grating structure, that makes up a real hologram, and then dynamically place this information on a beam of light. The computed information should affect the beam of light in a similar way that an actual hologram would, creating a holographic three-dimensional image. The advantage of this system over using standard holograms is that the 3-D images can now be updated by simply computing a new set of fringe patterns for the new scene.

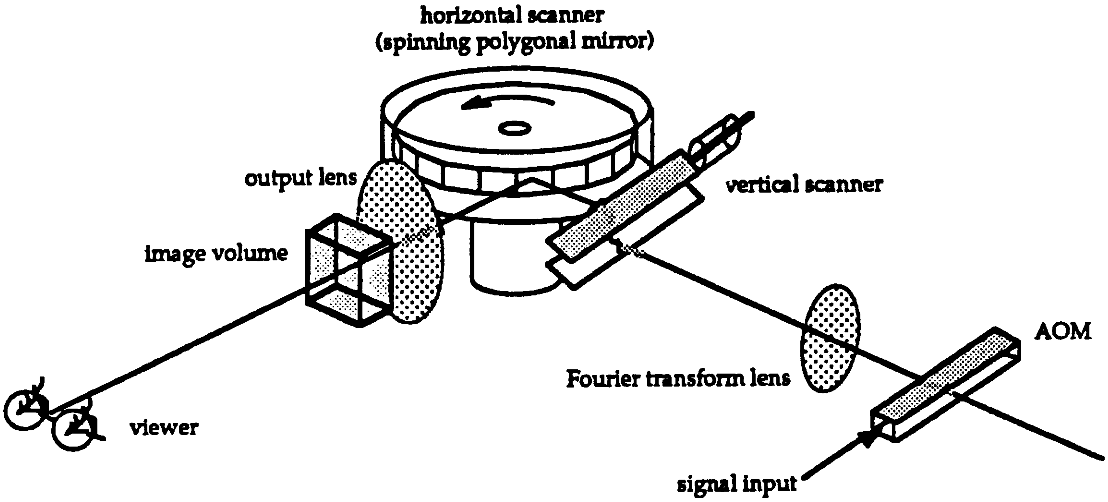

Figure 2 - Diagram of early model electronic holography display, called Holovideo, at the MIT Media Lab.

The original electronic holography design, invented by Benton and Kollin, utilizes an acousto-optic modulator (AOM) to place the computed fringe patterns on a beam of laser light. The holographic fringes for a particular image are first calculated by computer and then sent to several AOM's where they are dynamically turned into shear sound waves that travel within the acousto-optic crystals. Finally, an optical scanning system takes these tiny pieces of "simulated hologram" on the AOM's and pieces them together to form the final holographic image. A new design following this same concept has been implemented by a Japanese research consortium called the Technology Advancement Organization (TAO). Rather than using one laser beam with several AOM's, they have used 45 separate diode lasers to create and control the 3-D information. Another version of electronic holography uses LCD technology in combination with static, preformed fringe patterns to generate 3-D images. Each individual pixel on the LCD is overlaid with a tiny grating; different pixels having different grating frequencies. These gratings direct light exiting the pixels into different view zones in the viewer plane, thereby creating three-dimensional perspective information.

Electronic holography techniques have one main drawback, which is the huge quantity of information required to create just one image. The AOM version at the MIT Media Lab, for example, requires 36 megabytes of information for just a single holographic image. Broadcasting and receiving this amount of information in a timely fashion remains a substantial challenge. While the LCD version is not as computationally expensive, it suffers from image resolution problems similar to those of the lenticular displays.

2.5 Macro-Optic/Specular Displays

In recent decades, three-dimensional displays utilizing large scale optics and mirrors, as opposed to the micro-optics of the lenticular displays, have gained a new following. These display systems take light emanating from or passing through one or more two-dimensional display devices and carefully deliver the images to selected view zones. If two images which form a stereo-pair are delivered to adjacent viewing zones such that a viewer can only see one of the images with each eye, a three-dimensional image will be seen. Systems following this concept have a history dating back to H. Swan's "Crystal Cube" in 1862 (Swan 1862), and a display designed by J. Clerk Maxwell in 1868 (Maxwell 1868). The focus of such designs is to deliver the three-dimensional images to the viewer without the aid of special glasses, head-gear, or other equipment; an autostereoscopic display.

It is the recent research in this area that has brought renewed emphasis to the future of macro-optic/specular displays (hereafter referred to only as macro-optic displays). The work of Hattori, et al. and Ezra, et al. have created novel optical systems that allow easier delivery of a stereoscopic image to a viewer at different locations in the viewing space, and allow the possibility for multiple viewers in the viewing space (Hattori, et al. 1993) (Ezra, et al. 1995). Both of these systems will be discussed in detail in the following chapter. Another technology under development by Richmond Holographics (Trayner, Orr 1996) utilizes a similar technique to the lenticular displays, but adds a slight twist by using narrow holographic optical elements (HOE) over alternating pixel rows of an LCD to create the separate view zones instead of lenticulars. This HOE design allows the display to overcome the diffraction problems of lenticular designs by arranging the HOE strips horizontally rather than vertically, as well as the ability to shift the position of the view zones in the viewing area by shifting a light source behind the display. These two factors make the HOE design much more of a macro-optic display than a lenticular-type display. One other macro-optic display of note is a system being developed at Cambridge University (Travis 1995). This system uses an extremely high scan-rate CRT in conjunction with a fast switching

LCD shutter and some optics to deliver multiple two-dimensional images to multiple separate view zones in the viewing area. While a single 2-D image is being displayed on the CRT, a narrow strip of the LCD shutter is opened which corresponds to a narrow viewing zone in one part of the viewing area. As the image of the CRT changes to the next 2-D picture, a different strip of the shutter is opened which corresponds to a new viewing zone. In this manner, the current system at Cambridge can scan out 16 different view zones over a narrow viewing area. As long as a reasonably large number of view zones are scanned, the position and number of viewers is only limited by the angle of the viewing area.

Macro-optic displays have previously been limited by their ability to deliver the proper perspective information to the viewer. Many designs have been nothing more than a hands-free version of a hand-held stereo-pair viewer, requiring the user or users to remain in a fixed location to see the images. Early systems also often violated the maximum comfortable depth range for the stereoscopic image in order to get "more 3-D," causing a rivalry between the convergence and accommodation of the eyes, often resulting in head-aches. Systems that did direct the images to a non-stationary viewer were often sluggish and inaccurate, causing disappearance or "depth-reversal" of the image. Almost none of the systems were capable of following more than one viewer at a time. In addition, systems which try to deliver many view zones to the viewing area require large amounts of input information and often display very noticeable flicker due to inadequate display rates. However, as mentioned above, new developments in macro-optic display techniques have ameliorated many of the earlier problems, making these types of displays a strong candidate for future use.

3 Macro-Optic Display State of the Art

In order to meet the challenges of designing a 3-D display with a "television-like" feel, as described in Chapter 1, it is first necessary to choose a display category that best suits the design goals and then investigate the existing technology. The displays using head-mounted equipment or the lenticular displays seem to be adequate for a "computer monitor" approach, which most often involves only a single user. Displays working in combination with special glasses lend themselves reasonably well to "movie-like" conditions or special presentations where the audience is a captive one. Volumetric displays may find a niche application in areas like air traffic control, where the transparent images are less important than the 360 degree viewing zone. And electronic holography currently appears to be best suited for scientific visualization, where computing power is more accessible and the accuracy of the display is more important than its speed. It is the area of macro-optic displays that seems to best fit the idea of a "television" type system, with recent advances allowing viewer tracking and use by multiple viewers without the aid of special glasses. If these advances could be improved and refined to meet the other design goals, the desired "television-like" feel might well be achieved.

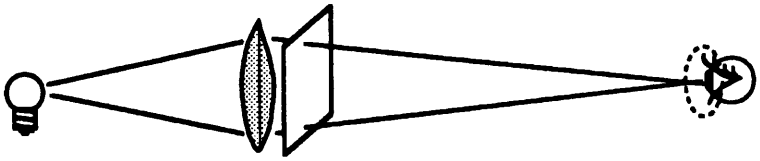

Figure 3 - Basic concept for macro-optic displays; showing source, lens, image-bearing device, and viewer

The basic idea behind a macro-optic display is to start with a light source, pass it through an image bearing device, and then focus the light to the viewer's eyes (see Fig. 3). Two such optical systems may be combined with the aid of a beamsplitter, creating a stereoscopic display if the light from each separate optical path is directed to separate eyes of the viewer (see Fig. 4). This allows each eye to see a different image from the system, forming a three-dimensional view if the two images make up a stereo-pair. This design dates back to the 1930's, when Joseph Mahler developed a stereoscopic slide-viewing system called the "Photo-Plastikon" (Mahler 1935). The early displays of this type simply used static stereo-pair images on transparencies as the image bearing device in each leg of the display, while more modern versions utilize transmissive LCDs as dynamically updatable image bearing devices. The interesting and challenging part of the display design arises in trying to properly deliver the light to a viewer's eyes at different locations in the viewing space, or delivering the light simultaneously to several viewers in the viewing space.

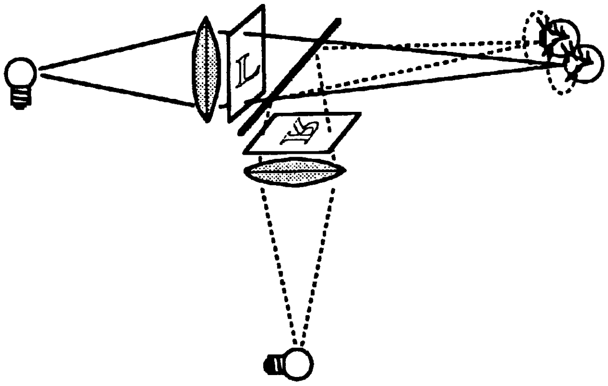

Figure 4 - Two beam paths combined to create stereoscopic display.

3.1 Hattori, Omori, Katayama, and Sakuma

One approach to this challenge was developed by Hattori, Omori, Katayama, and Sakuma in 1993 at a Japanese laboratory (Hattori, et al. 1993) (Omori, et al. 1993). Their approach started with a very similar set-up to that described above for a basic macro-optic stereoscopic display. Two LCDs, one for left-eye information and the other for right-eye information, are combined by a beamsplitter, with the light passing through each LCD being focused to a separate viewing zone. However, Hattori, et al. added a unique twist to the standard design by using a monochrome CRT monitor behind each LCD as the illuminating light source. Each monochrome monitor is driven by a camera that is watching the viewing area in front of the display, capturing a picture of the viewer. This picture of the viewer on the monitor is then imaged by a lens near the LCD out to the viewing area such that the picture of the viewer overlays the viewer himself. An ingenious use of the cameras with an infra-red viewer illumination system and infra-red filters allows each monochrome monitor behind each LCD to direct light to only the left or the right side of the viewer's face.

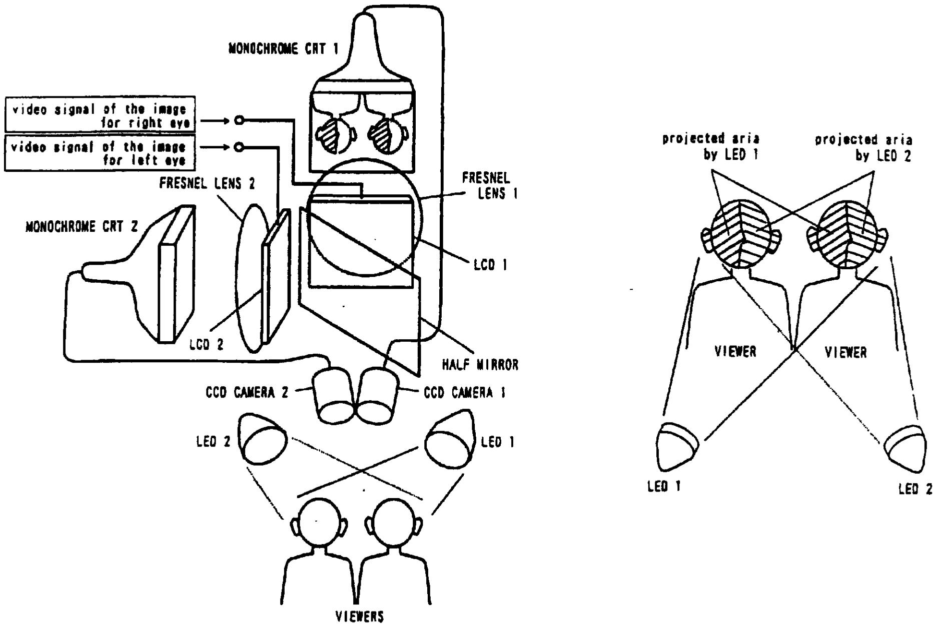

Figure 5 - Diagram of Hattori, et al. display (left), and viewer illumination system (right) (Omori, et al. 1993).

The system starts with an infra-red illuminator positioned off to the left side of the viewer watching the display, illuminating the left side of his or her face. One of the cameras watching the viewing area in front of the display has a filter corresponding to this illuminator, and therefore captures a picture of only the illuminated left side of the viewer's face. This camera is connected to the monochrome monitor behind the left-eye image LCD, so that the monitor now displays the picture of the left side of the viewer's face behind the left-eye image LCD. The lens near the LCD then images this picture of the left side of the viewer's face onto the left side of the actual viewer. Because light passing through the left-eye image LCD only goes to the left side of the viewer's face, the viewer's left eye only sees left-eye information. An identical process takes place for the right-eye information, directing it to only the right side of the viewer's face. As the viewer moves in the viewing space, the image on the monitors moves with him, and thus the view zones for the left- and right-eye images are always properly positioned over the viewer's left and right eyes. Additional viewers can easily be added, as a picture of each added viewer shows up on the monochrome monitors next to the picture of the first viewer.

Analyzing the Hattori, et al. display in terms of the criteria for a "television-like" display (Chapter 1), one can see that almost all of the standards are met with a fair degree of success. The display is autostereoscopic, can deliver the 3-D images to a viewer anywhere in the viewing area, and can handle several viewers at once. In addition, the system uses LCDs as the primary image source for displaying stereo-pairs, allowing full color images that can exhibit natural, realistic 3-D scenes. Since only two LCDs are used, the total amount of information needed to drive this three-dimensional display is only twice that of a standard television or monitor, and the system could be used to display regular 2-D television information.

It is the final criteria of scaleability that gives the Hattori, et al. display some of its greatest difficulties. Because the viewer-tracking is implemented with CRTs, larger displays will require larger CRTs or more powerful lenses to increase the viewing zone proportionally. As a result, the display size and complexity dramatically increases as the 3-D image size increases. Additionally, the three final components in the system, the two image LCDs and the beamsplitter, must be scaled up in direct proportion to the 3-D image size. Since these three components form a large voluminous space at the front of the display, the overall foot print of the display quickly reaches unmanageable sizes for even modestly sized 3-D images.

Other problems for this display technique include problems which are inherent to the CRTs themselves. CRTs are notorious for having an image intensity that varies with the content of the images they display, with small images appearing very bright, and larger, more complex images appearing dimmer. In the case of this display, the implications are that the 3-D images would be brighter with only a single viewer, since the CRTs illuminate the LCDs with only a small picture of this one viewer, while the 3-D images would get dimmer as more viewers were added. Another problem with this system is that the two CRTs perform rather redundant tasks. Each one provides the illumination for an LCD by displaying almost identical pictures of the viewer in front of the display. It would be preferable if some of this redundancy could be eliminated by using a single component to illuminate both the left- and right-eye image LCDs at once, creating a simpler overall design.

One final point about the display is to notice that because the left- and right-eye LCDs must be viewed through a beamsplitter, the 3-D images that are created have the psychological feeling of being inaccessible to the viewer. This is due to the fact that stereoscopic images display the least distortion when the 3-D content is localized at or near the surface of the display medium. In this system, the 3-D images will look best when they appear to be near the image LCDs, and thus separated from the viewer by the output beamsplitter. The result is that the viewer can see the three-dimensional imagery, but is inhibited from the often inevitable desire to "reach out and touch." While this situation has no real effect on the capability of the display to convey 3-D images, it does limit the freedom of interaction between the viewer and the display.

3.2 Ezra, Woodgate, Omar, Holliman, Harrold, and Shapiro

In 1995, the team of Ezra, Woodgate, Omar, Holliman, Harrold, and Shapiro (Ezra, et al. 1995), working in England, developed a slightly different technique for meeting the challenges of a "television-like" display. Starting once again with the two image LCDs combined by a beamsplitter, an additional system of fold mirrors and another beamsplitter were added to allow both LCDs to be backlit by a single light source. A lens was placed near each LCD, in a similar fashion to the Japanese design, such that the single light source was imaged out to the eyes of the viewer. However, these lenses were offset a slight amount laterally from the optical axis of the LCDs so that not one, but two images of the light source were created in the viewing area (see Fig. 6). Light passing through the left-eye LCD would form an image of the light source near the viewer's left eye, while light passing through the right-eye LCD would form an image of the light source near the viewer's right eye. Now, by moving the single light source, or "dynamic light source," behind the two LCDs, the left- and right-eye view zones could be made to follow a viewer in the viewing area. For additional viewers, additional "dynamic light sources" could be added to the system to create additional view zones.

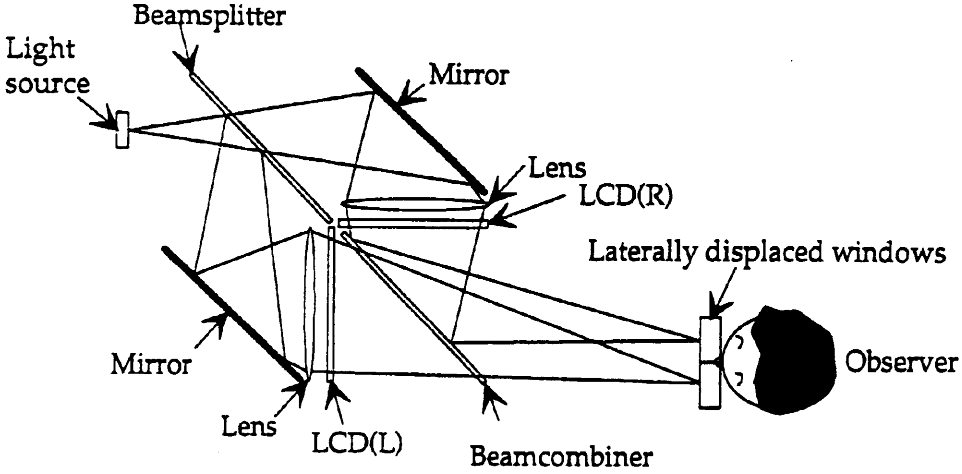

Figure 6 - Diagram of Ezra, et al. macro-optic display, with dynamic lightsource (Ezra, et al. 1995).

A subsequent publication from this same group in 1997 (Woodgate, et al. 1997) expands on the basic design by utilizing a single specialized illumination component rather than the individual "dynamic light sources" for each viewer. This specialized illumination consists of a number of thin, vertical cold-cathode sources arranged in a one-dimensional array. When one of these cold-cathode sources is turned on, it creates a vertical bar of light which is passed through the optical system of the display and is then focused to two vertical view zones in the viewing area. The system uses an undisclosed method of locating the viewer within the viewing area to assure that these view zones are imaged in front of the viewer's eyes, with only one view zone over each eye. As the viewer moves across the viewing area, the tracking system activates different cold-cathode sources in the illumination array such that the view zones follow the viewer. When a new viewer enters the viewing area, the tracking system activates another cold-cathode source in the array which corresponds to the new viewer's position. In this manner, one or more viewers may be tracked throughout the viewing area of the display with only a single illumination device.

The Ezra, et al. system, like the Hattori, et al. system, successfully meets many of the "television-like" criteria. The display is autostereoscopic, keeping the viewers free from using any special glasses or head-gear. The system also accommodates multiple viewers at any position in the viewing area, and is capable of conveying strong image realism through the use of stereo-pairs. The use of conventional LCD technology as the display medium allows the display to be reverse compatible with standard 2-D signals, while the use of only two LCDs allows lower bandwidth requirements. This design also overcomes a few of the difficulties described in the Hattori, et al. system by using only a single illuminating source for both the left- and right-eye LCDs. Not only is the redundancy of two monitors reduced to one element, creating a simpler, more unified design, but the array of cold-cathode sources is also much more compact than the monitors.

The problems with this display again start with scaleability. The CRT monitors have been eliminated, but the two LCDs and the beamsplitter still occupy a very large space for a display of only modest 3-D image size. In addition, the array of cold-cathode sources have a limited on/off switching speed, creating possible lags in tracking speed. They also may not be bright enough for displays over a certain size. Finally, the 3-D image is again trapped behind the output beamsplitter, making the images feel inaccessible. A system that brought the three-dimensional images into more intimate proximity to the viewer would lend greater impact and realism to the display.

4 Viewer-Locating Systems

The term viewer-locating system has been used here instead of the term viewer-tracking system in order to differentiate two different parts of the 3-D displays being discussed. In order to be autostereoscopic, the displays discussed above in Chapter 3, as well as the new display designs detailed below, require a mechanism for finding the viewer within the viewing area and determining the location of the viewer's eyes. With this information, the display can then deliver different image information to each of the viewer's eyes, resulting in a three-dimensional image. For purposes of clarity within this thesis, the viewer-locating system has been designated as the mechanism which locates the viewer and gathers the information about the viewer's eye locations, while the viewer-tracking system has been designated as the integral part within the display which takes the eye information and delivers the left- and right-eye images appropriately. Thus the viewer-locating system finds the locations of the viewer's eyes, and the viewer-tracking system directs the proper images to these locations.

The information required from the viewer-locating system by the viewer-tracking system, and the display system as a whole, is often only one or two data points per viewer, detailing the location of the viewer's two eyes or the mid-point between the viewer's two eyes. The viewer-tracking components of the display system then use these data points to differentiate between the viewer's eyes, sending different image information to each eye. As an example, a viewer-locating system might pass the x,y coordinates of each of the viewer's eyes to the Ezra, et al. display described in Section 3.2. The Ezra display would then position the dynamic lightsource, which is part of the viewer-tracking system, halfway between the coordinates for the eyes, allowing the display system to project two view zone windows to the exact position of the viewer's eyes. On the other hand, a similar viewer-locating system might pass the x coordinate, or horizontal position, of the mid-point between the viewer's eyes to a system like the Hattori, et al. display. In this case, one of the viewer-tracking CRTs would display a picture which was white at every point to the left of this eye mid-point coordinate, and black to the right, while the other CRT would display a picture which was black to the left of the mid-point and white to the right. The display system would then use these pictures to send the left-eye image to only to the left side of the viewer's face, the left side of the mid-point between the viewer's eyes, while the right-eye image was sent to only the right side of the viewer's face.

The viewer-locating system in many cases can be thought of as an almost completely separate sub-system of the autostereoscopic display, and will therefore be discussed independently here in Chapter 4, separate from the actual display system to be discussed next in Chapter 5. While the primary thrust of this thesis is the optical design and engineering of the display system and not the viewer-locating system, it is recognized that the display system cannot function properly without the information provided by the somewhat separate viewer-locating system. This chapter will outline a few different methods for viewer-locating, providing a small range of possibilities that could be used to complete the display designs to follow in Chapter 5. However, it is important to note that the display designs to be detailed in Chapter 5 do not require any one specific viewer-locating system described here, but can be completed using any viewer-locating system that provides the proper viewer information.

4.1 Hattori, et al. Face Illuminating System

Described in Section 3.1 as part of the full Hattori, et al. autostereoscopic display, this viewer-locating system uses lightsources, or infra-red sources, to illuminate the left and right side of the viewer's face with different lighting. In the case of the Hattori display, two infra-red sources of slightly different wavelengths were used, with each source illuminating only one side of the viewer's face. Two cameras were then used to capture pictures of the viewer's face, each camera with a different filter corresponding to one of the infra-red sources. The result was that the cameras capture a picture with one half of the viewer's face illuminated, and the other half of the viewer's face dark. In this way, the viewer-locating system has encoded one of the viewer's eyes as a white section of the picture along with the illuminated side of the viewer's face, while the viewer's other eye is encoded as a black section of the picture along with the dark side of the viewer's face. When these images are displayed on the viewer-tracking CRTs of the Hattori display, the left- and right-eye images can be properly directed to only the viewer's left and right eyes, respectively.

The face illuminating viewer-locating technique is rather ingenious, despite its simplicity. The system never actually performs any kind of search for the viewer or the viewer's eyes, but rather is able to differentiate between the viewer's two eyes through the geometry of the infra-red sources and the cameras. The viewer-locating system thus requires almost no processing power and is extremely fast. Within certain constraints, this system works quite effectively. However, because the success of this system is based entirely on the simple illumination geometry, several simple conditions can cause the system to act improperly. For instance, a number of tests indicated that the size of the viewer's nose had a large impact on how well the system could differentiate between the viewer's left and right eyes. For viewers with larger noses, or a tall bridge of the nose, the infra-red side illumination clearly illuminated the half of the viewer's face closest to the infra-red source, while the viewer's nose helped to shadow the other half of the viewer's face, keeping it dark. For viewers with smaller noses, though, or a small bridge of the nose, the side of the viewer's face that was away from the infra-red illumination source was not always adequately shadowed by the viewer's nose, and therefore would not be completely dark but would have bright patches in certain areas. In an effort to reduce the system's reliance on viewer nose size, the illumination could be moved farther to the side of the viewer, providing a steeper angle of illumination of the face and better shadowing of the dark side of the face even for smaller noses. A problem now arises when two viewers are attempting to view the display simultaneously, as the steeper infra-red illumination angle creates a better chance of one viewer completely shadowing the other. The viewer being shadowed is thus unable to see the 3-D images because his or her entire face is dark as seen by the cameras.

4.2 Skin Tone Searching System

A slightly more sophisticated viewer-locating system might use a camera to capture a picture of the viewing area in front of the display and then perform computerized search algorithms to search the picture for viewers. One possible way to perform this search would be to look for areas of skin tone within the picture, assuming that large areas of skin tone are the faces of viewers. The viewers are thereby separated out from the background and surrounding objects.

4.2.1 Centroid Technique

Once the large areas of skin tone have been found, and assuming that they are faces, the next step for the viewer-locating system is to determine the mid-point between the viewer's eyes. This mid-point can be approximated by assuming that the viewer's face will be roughly symmetrical, and therefore the mid-point between the viewer's eyes will be in the middle of the viewer's face. The centroid of the large area of skin tone is calculated as an x,y coordinate, and then the x coordinate is sent to the viewer-tracking system of the display as the mid-point between the viewer's eyes.

Several assumptions are made in the above process, leading to several points of possible breakdown for this viewer-locating system. The first assumption is the general color used for the skin tone search. Skin tones obviously vary over a wide range of colors, therefore making it extremely difficult to search and find an arbitrary face of arbitrary skin tone. Next, the areas of skin tone visible to the viewer-locating camera not only include faces, but also arms, hands, and even legs. The system will compute and pass along the centroids of each of these skin tone areas, in addition to face areas. This may not cause viewing problems, as it will simply result in more viewing windows than viewers, but it will slow processing speed, slowing the ability of the viewing windows to rapidly follow a moving viewer. And finally, the assumption that the facial skin tone areas will be symmetric is often incorrect. While facial features are roughly symmetric, different hair styles can cover one side of the face more than another, throwing the centroid of the skin tone area away from the mid-point between the eyes.

Thus, although a highly constrained set of viewer conditions and parameters would allow this type of viewer-locating system to work with a 3-D display, it is certainly not optimal for most generalized circumstances.

4.2.2 Feature Finding Technique

Perhaps a more favorable approach to using skin tone searching might be to use it in combination with another search parameter. In this case, skin tone searching is used in combination with a search looking for facial features arranged in a particular configuration. So the first level of searching finds large areas of skin tone within the picture that is captured by the camera. Within these areas of skin tone, a second search is performed looking for the arrangement of shadows caused by two eyes (no skin tone color in eyeballs) just above the nose (shadows on the side and below the nose have darker color) which is just above the mouth (lips have a darker color). If this arrangement of shadows is not found in a skin tone area, the area is discarded from consideration and is assumed to not be a face. If, on the other hand, the arrangement of facial features is found, this skin tone area is most likely the face of a viewer. The appropriate coordinates can now be calculated by either calculating the position of the two dark "eye" areas within the skin tone area, or by using the dark "nose" area as the center point between the eyes. These coordinates for the viewer's eyes or the viewer's nose are finally passed to the viewer-tracking components of the display.

This system still suffers from the fact that skin tones fall into a variety of colors and therefore cause difficulty in finding all types of skin tone. However, if the skin tone areas can be located, this technique seems able to eliminate spurious skin tone areas caused by arms or legs and focus on the facial regions. In addition, the method for finding the location of the viewer's eyes or the viewer's nose is much more reliable than the previous centroid method. Provided that the system can be properly calibrated to find a particular viewer's skin tone, this viewer-locating method seems relatively reliable for finding the proper location information needed for a display to deliver a three-dimensional image.

4.3 Retinal Retro-Reflection System

This final system holds a great deal of promise for a robust viewer-locating system. A single camera is located at the front of the 3-D display and is directed toward the viewing area. A beamsplitter is then used to combine the light from an infra-red source along the same optical axis as the camera. The light from the infra-red source enters the eyes of the viewer and is retro-reflected back toward the source and into the camera. The camera thus picks up a picture of the viewer with bright intensity peaks at the viewer's eye locations. A search algorithm can now be used to analyze the picture of the viewing area, searching for pairs of bright intensity peaks which will correspond to the viewer's eyes. The locations of these intensity peaks is finally reported to the viewer-tracking components within the display.

The potential for this viewer-locating system lies in the fact that it does not rely on any viewer-specific quantities. Neither the size of the viewer's nose or other facial features, nor the color of the viewer's skin are relevant details for this system, only the natural retro-reflection of the viewer's eyes. The system also has the capability of working under a variety of lighting conditions, from a well-lit room to total darkness, as the retro-reflection of the infra-red source will be almost identical under most conditions. Additionally, the use of two search requirements, searching for bright intensity peaks in the picture and then requiring these peaks to be in pairs, will help eliminate spurious intensity peaks caused by random reflections of the source in the picture.

The only real concern for this method is the ability to get intensity peaks for the eyes which are sufficiently brighter than reflections from other parts of the viewer's face or other objects in the viewing area. If the retro-reflections from the eyes are substantially brighter, the intensity values of the picture can be high-pass filtered leaving only the eye reflections and spurious high intensity reflections. These extra reflections can then be filtered out by the pair-searching algorithm. However, if the retro-reflections from the eyes are not substantially brighter than reflections from the viewer's face, the bright peaks of the eyes may be difficult to pick out from the surrounding noise, even with the pair-searching algorithm.

5 New Macro-Optic Display Designs

In an effort to further advance the "television-like" qualities of macro-optic displays, a number of new designs have been created in the course of this thesis research. Each evolves a step farther from the Hattori, et al. and Ezra, et al. displays which served as their starting points. The initial two designs are only slight modifications of these displays, one mirroring the Hattori design (Section 5.1.1) and another mirroring the Ezra design (Section 5.1.2). However, these proved to be important steps as they led to a third design (Section 5.1.3), creating a new and novel method for a simplified, unified viewer tracking mechanism behind the two image LCDs. This design combines the unified viewer tracking element of the Ezra display with the simplified tracking technique of the Hattori display. It also provided the spark for two other new designs (Section 5.2) involving projection of the stereo-pair onto a viewing screen, rather than viewing the images directly through the beamsplitter. These projection designs provide some truly exciting prospects for future "television-like" displays, allowing large 3-D images and the ability to bring the 3-D images out from behind the beamsplitter into more direct contact with the viewers. Finally, two additional designs (Section 5.3) are detailed which utilize only a single image LCD, as compared to the two image LCDs for all of the other designs.

5.1 "Through-the-Beamsplitter" Designs

The following three display designs all start with two LCDs, one to display the left-eye image and the other to display the right-eye image, and a beamsplitter to combine the two separate images. Thus the viewer looks directly at the image-bearing LCDs through the beamsplitter. The differences between the three designs arises in their methods for delivering each of the images to the appropriate eye of the viewer.

5.1.1 Modified Hattori, et al. Design

A straightforward approach to modifying the Hattori, et al. macro-optic display is to replace the monochrome CRTs, used for viewer tracking, with monochrome LCDs. In this manner, a large part of the size and bulk of the display can be reduced. The overall function of the LCDs remains exactly the same as that of the original CRTs, but in a smaller, tighter package. Also, because LCDs act as light valves, switching the viewer tracking mechanism from CRTs to LCDs would allow the display to be illuminated with a light source of arbitrarily high power. LCDs would further eliminate the brightness fluctuations caused by additional viewers entering the viewing area, since LCDs exhibit constant brightness of their displayed images regardless of the content of the images.

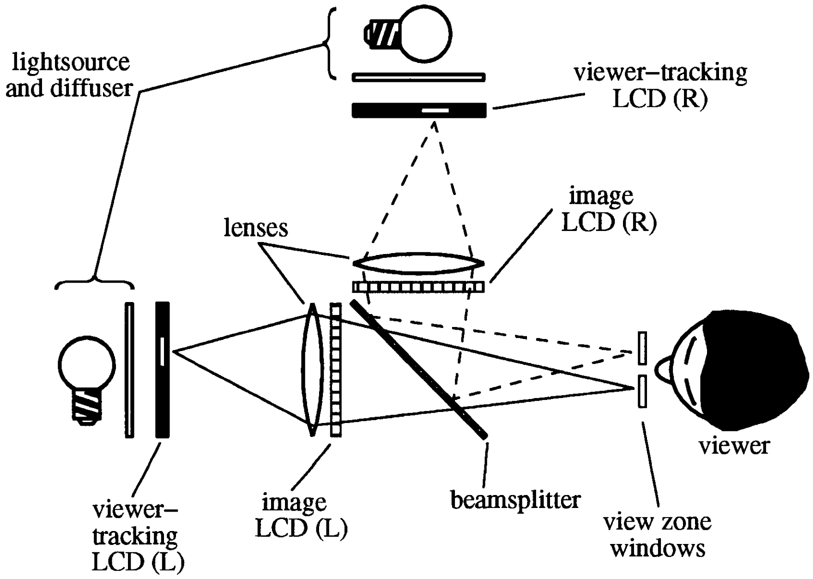

Figure 7 - Optical layout for modified Hattori, et al. display design, using LCDs rather than CRTs for viewer-tracking.

The altered Hattori design is comprised of two identical optical paths, which are joined by a beamsplitter. Starting at the beamsplitter and working backwards (see Fig. 7), each leg of the system has an image LCD that displays the left- or right-eye information for creating the stereo-pair view. Behind the image LCD is a lens and a viewer tracking LCD. The lens is positioned very near to the image LCD, and has the function of focusing the picture on the tracking LCD out to the viewing area. Thus, the lens behind the left-eye image LCD will take the picture of the left side of the viewer's face that is displayed on the viewer tracking LCD and focus it out onto the left side of the viewer's actual face. The final elements in each leg of the system are a light source and a diffuser behind each viewer tracking LCD to provide the illumination for the system.

Through the simple change of the viewer tracking mechanism from CRTs to LCDs, this new design addresses many of the problems outlined in Section 3.1 while maintaining the advantages of the original design. However, a few of the previously discussed problems still remain. For example, the two image LCDs and the beamsplitter still take up a very large volume of space at the front of the display. Thus the display design has not rid itself of all of its scaleability limitations. The beamsplitter design also leaves the three-dimensional images locked up inside the display and away from the viewer. And finally, this design still uses two viewer tracking elements that have a very high degree of redundancy. Condensing these two elements into a single viewer tracking element would be a much more efficient use of system hardware.

5.1.2 Modified Ezra, et al. Design

Once again minor modifications were made, this time to the Ezra, et al. macro-optic design described in Section 3.2. And once again, an LCD has been implemented to take the place of a less convenient device. In this case, the "dynamic light source" of the Ezra system is replaced with a monochrome LCD that passes a small rectangle of light corresponding to the proper position for what would have been the dynamic light source. This small area of light on the viewer tracking LCD is imaged through the display and focused to two separate, adjacent rectangles of light that serve as view zones, one for the left eye of the viewer and one for the right eye. As the viewer moves in the viewing area, the viewer tracking LCD moves the rectangle of light to follow the viewer, eliminating any moving parts of a dynamic light source. As another viewer enters the viewing area, another rectangle of light is created on the viewer tracking LCD to follow this viewer, allowing several viewers to be tracked with the single LCD rather than several dynamic light sources.

The LCD also has several advantages over the cold-cathode illuminator system used in later versions of the Ezra design. Similar to the Hattori design, the cold-cathode illuminator may not be bright enough for larger display sizes. The light-valve properties of the LCD allow it to provide the same viewer tracking function as the cold-cathode sources, but with an independent illumination source which can be as bright as required for the display size. Faster switching speeds further allow LCDs to providing faster, more accurate tracking of the viewer as he or she moves through the viewing area. LCDs also have much higher resolution, both horizontally and vertically, than is available from an array of cold-cathode sources. This allows a finer control over viewer tracking and provides the capability to track viewers vertically through the viewing area as well as laterally.

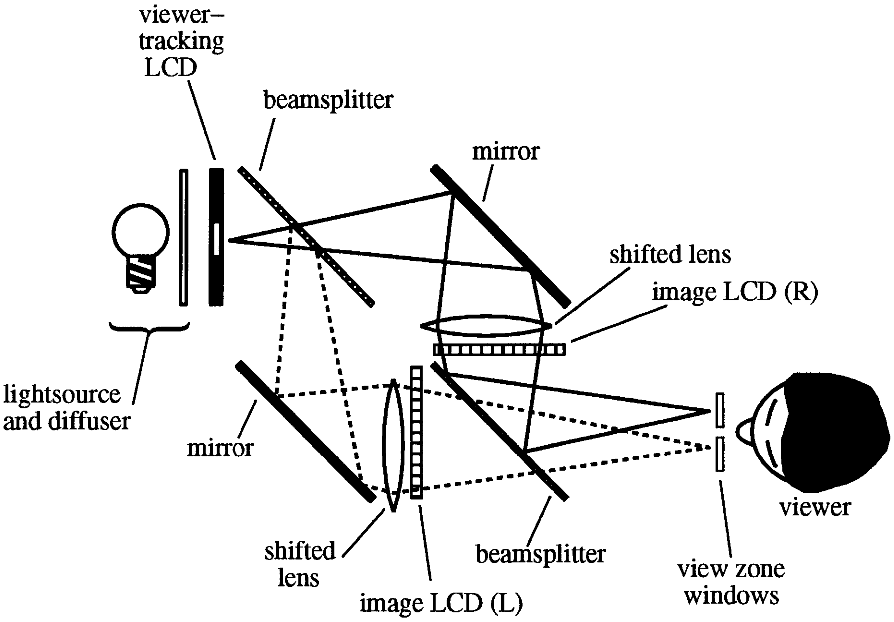

Figure 8 - Optical layout for modified Ezra, et al. display design, using LCD rather than dynamic lightsource for viewer tracking.

The optical layout for this design begins with the light source and a diffuser at the rear of the display. The viewer tracking LCD is located just in front of the diffuser, and passes a small rectangular patch of the light from the diffuser for each viewer. The light passing through this rectangle on the LCD is split into two parts by a beamsplitter and fed to the back of each image LCD by fold mirrors. Just before each image LCD is a lens that takes the light from the viewer tracking LCD and focuses it out to the viewing area. These lenses behind the image LCDs are offset laterally such that the one rectangle of light from the viewer tracking LCD is focused to two laterally separated rectangular viewing zones in the viewing area. The final beamsplitter combines the images from the two image LCDs along a common optical axis, so that the stereo-pair information can be properly fused by the viewer.

The Ezra design, with the simple modification of using an LCD as a single, solid-state viewer tracking element, holds excellent potential for a television-like 3-D display. However, it would be greatly advantageous to combine the single tracking element layout of this design with the elegant, infra-red tracking system of the Hattori design. The modified Ezra display requires some type of separate tracking mechanism to find the viewer in the viewing area, tell the display to produce a rectangle on the tracking LCD to correspond to the viewer's position, and then update this position as the viewer moves. The Hattori method of cameras and infra-red illumination creates a closed loop system that requires little or no computation power and would greatly simplify the processing requirements of a system like the Ezra design. Additionally, this design still suffers from the large space taken up by the image LCDs and beamsplitter at the front of the display, and still places the 3-D images behind the beamsplitter away from the viewers.

5.1.3 New Polarization Tracking Design

The goal for this design was to create a system that combined the best parts of the Hattori display and the Ezra display; namely, a design capable of implementing a simple, closed-loop tracking method while utilizing only a single viewer tracking hardware component. The layout for this design thus started with the same configuration as the modified Ezra display (Section 5.1.2), with two image LCDs being rear illuminated by a single viewer tracking LCD and a system of fold mirrors. However, in order to implement the same viewer tracking method used in the Hattori display, each image LCD must look back at the viewer tracking LCD and see a different picture; the left-eye image LCD seeing a picture of the left side of the viewer's face and the right-eye image LCD seeing a picture of the right side of the viewer's face. The modified Hattori design (Section 5.1.1) accomplishes this by simply using two viewer tracking LCDs, each driven by a separate camera that captures the appropriate side of the viewer's face. The issue becomes more challenging with the Ezra layout, though, as each image LCD is looking back through the system to the same viewer tracking LCD. It was necessary to create a method that allowed the two image LCDs to look back at the same viewer tracking LCD, but to have each one see a different picture coming from that one viewer tracking LCD.

A solution to this problem was found by taking a more in-depth look at how an LCD works at its basic level, and how this might be exploited for use in the new display design. A liquid crystal display (LCD) starts with a thin layer of liquid crystal material that is sandwiched between two pieces of glass, each with an electrical conducting layer deposited on it (Collings 1990). When the inside surfaces of this glass sandwich have been properly treated, the liquid crystal material is forced to align its molecules such that they rotate in a helical fashion from one glass plate to the other. Light passing through this sandwich is similarly forced to rotate its polarization in correspondence to the rotation of the liquid crystal molecules. However, when an electrical voltage of sufficient amplitude is applied between the two glass plates, the molecules of liquid crystal no longer form a rotational path from one plate to the other, and therefore light passing through the material no longer experiences the polarization rotation effects. Thus this sandwich of liquid crystal material that is at the heart of most LCDs is actually a device for switching light between different polarization states.

LCD manufacturers take advantage of this controllable polarization rotation by placing the above-described sandwich between two crossed polarizers. The first polarizer pre-conditions the light so that only one polarization is passing through the liquid crystal sandwich. The liquid crystal sandwich is divided into a multiplicity of pixels, each of which can be turned on or off independently, creating the resolution for the display. When the polarized light passes through a pixel where no electric voltage is applied, the light rotates its polarization by 90 degrees and exits through the final polarizer. However, the light passing through a pixel that has an electric voltage applied to it does not have its polarization rotated and is absorbed by the final polarizer. In this manner the polarization properties of a liquid crystal sandwich can be manipulated to control the intensity of the light passing through it, forming a display that acts as a "light valve."

A simple light valve action is not sufficient, however, for the viewer tracking element of the new display design, because only a single picture can be displayed on the LCD with this technique. It is by taking a step backwards, utilizing the LCD as a means for controlling polarization rather than intensity, that a solution for the new design can be found. By removing the final polarizer on the output face of the viewer tracking LCD, this device loses its intensity modulation capabilities and can instead be analyzed in terms of two separate polarization states. One polarization state is that of pixels on the LCD that are turned off, and thus transmit light that has had its polarization rotated 90 degrees from the orientation of the input polarizer. The other polarization state is that of the pixels that are turned on, and transmit light with the same polarization orientation as the input polarizer.

This altered LCD is now capable of displaying two complementary images, one corresponding to each polarization state. A simple experiment can demonstrate this fact by placing a beamsplitter after the viewer tracking LCD to split the light into two paths (see Fig. 9). In one of the paths following the beamsplitter (path 1), a polarizer is placed with its orientation aligned with the on pixels on the viewer tracking LCD. In the other path (path 2), a polarizer is placed with its orientation aligned with the off pixels. If a test pattern consisting of a small square of on pixels surrounded by off pixels is displayed on the viewer tracking LCD, viewer 1 looking through path 1 will see a bright square surrounded by a dark area. However, viewer 2 looking through path 2 will see a dark square surrounded by a bright area. While these two images are not completely independent, one being the inverse of the other, they are perfectly suited for producing the two different viewer tracking images required for the new display design.

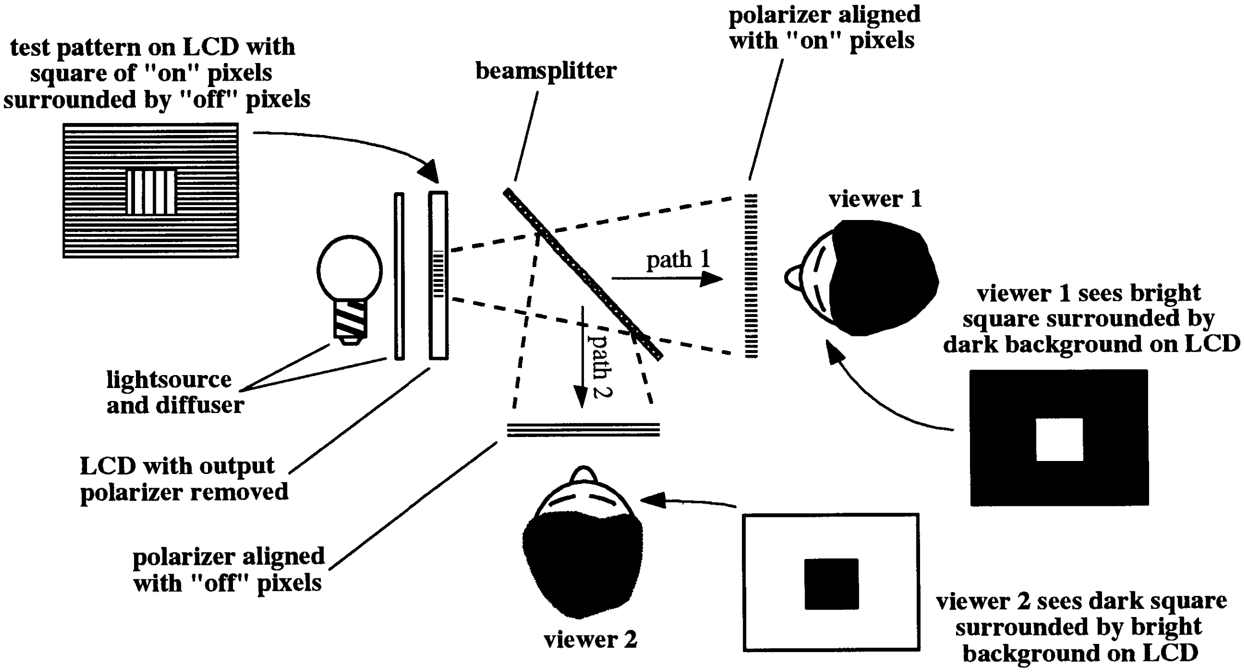

Figure 9 - Experiment to demonstrate function of altered LCD.

The new design starts with an optical layout almost identical to that of the modified Ezra layout (Section 5.1.2), but with a few subtle changes that make a substantial difference. The viewer tracking LCD is now operated without the use of its output polarizer, allowing it to function as the polarization controlling device outlined above. In order to take advantage of this new feature, the left- and right-eye image LCDs are oriented such that their input polarizers are aligned in orthogonal directions, one aligned with the on pixels of the viewer tracking LCD and the other with the off pixels. Due to this special orientational arrangement, each of the left- and right-eye image LCDs will now see a different picture coming from the viewer tracking LCD. The Hattori-style tracking method is implemented with the use of a single camera near the front of the display, and a single infra-red illuminator positioned so as to illuminate one side of the viewer's face.

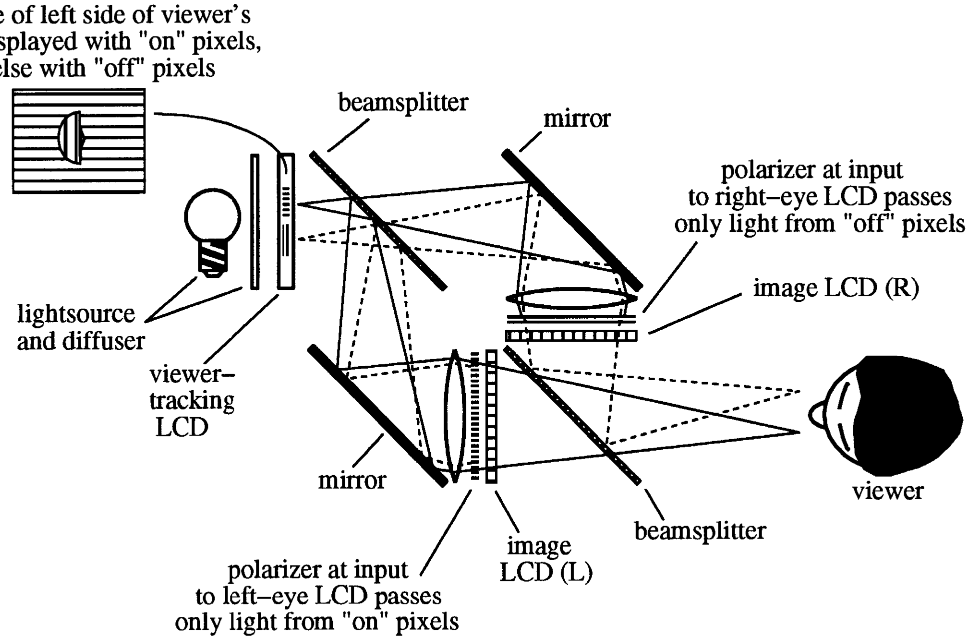

Figure 10 - Optical layout for the new polarization tracking design.

When a viewer is positioned within the viewing area, the camera at the front of the display captures the picture of the viewer with one side of his face illuminated. (For the sake of easier explanation, the illuminated side of the viewer's face will be designated here as the left side.) This picture is displayed on the viewer tracking LCD with the illuminated, left portion of the viewer's face represented by on pixels and the unilluminated, right portion of the viewer's face represented by off pixels. At the left-eye image LCD, the input polarizer is aligned with the on pixels of the viewer tracking LCD, and therefore passes only this light. The left-eye image LCD thus looks back at the viewer tracking LCD and sees a bright image of the left side of the viewer's face against a dark background. The lens just before the left-eye image LCD then focuses this picture of the left side of the viewer's face out to the viewing area such that the picture of the left side of the viewer's face on the viewer tracking LCD is superimposed onto the left side of the actual viewer's face. At the right-eye image LCD, the input polarizer is aligned with the off pixels of the viewer tracking LCD, allowing the right-eye image LCD to see only a bright image of the right side of the viewer's face against a dark background. This light is focused out to the viewing area such that it is superimposed upon the right side of the actual viewer's face. As the viewer moves within the viewing area, the picture on the viewer tracking LCD automatically moves to compensate, keeping the left- and right-eye information properly positioned in front of the viewer's left and right eye respectively. When a new viewer enters the viewing area they are likewise illuminated by the infra-red system, and the viewer tracking LCD displays a picture of their face to deliver the left- and right-eye images appropriately.

The combination of the Hattori and Ezra designs has finally been achieved in this new macro-optic display design. The system is capable of implementing a very simple viewer tracking method that delivers stereo-pair information to the viewer, while utilizing a single viewer-tracking component and a minimum of hardware to do so. This new design also meets all of the criteria outlined in Chapter 1 for a "television-like" display except for the final point of scaleability, and a number of factors have been addressed on this issue as well. The only remaining concerns are the large space occupied by the image LCDs and beamsplitter, and the inaccessibility of the image trapped behind the beamsplitter.

5.2 Projection Designs

Attempting to bring the three-dimensional images of the above designs out from behind the beamsplitter required a new approach to the problem. New designs were created for projecting the stereo-pair information onto a screen in front of the viewer. The images would no longer be separated from the viewer, allowing a more natural "reach-out-and-touch" response to the images. In addition, projection systems might allow large 3-D images to be produced from smaller image bearing devices, addressing the scaleability issue that had been elusive in earlier designs.

5.2.1 Projection Polarization Tracking Design

The idea for this projection design was drawn from the polarization tracking system introduced in Section 5.1.3. The basic form was conceived by trying to place a projection lens after the final beamsplitter to project the left- and right-eye image LCDs onto a rear-projection screen. In this manner, the three-dimensional image would likewise be projected out from behind the beamsplitter and onto the screen. Two obstacles were encountered in trying to implement this design in concert with a viewer tracking system. The first was the realization that the screen material could not be diffusing, as this would mix the left- and right-eye images into one, instead of delivering them to separate view zones. The screen needed to be transparent with some optical focal power in order to properly focus the view zones to each of the viewer's eyes. The second obstacle was the positioning of the viewer tracking LCD. If this device remained behind the image LCDs, as in Section 5.1.3, it was not possible to focus the picture of the viewer displayed on the viewer tracking LCD out to the proper place in the viewing area. The viewer tracking LCD would need to be moved out in front of the image LCDs to properly perform its function.

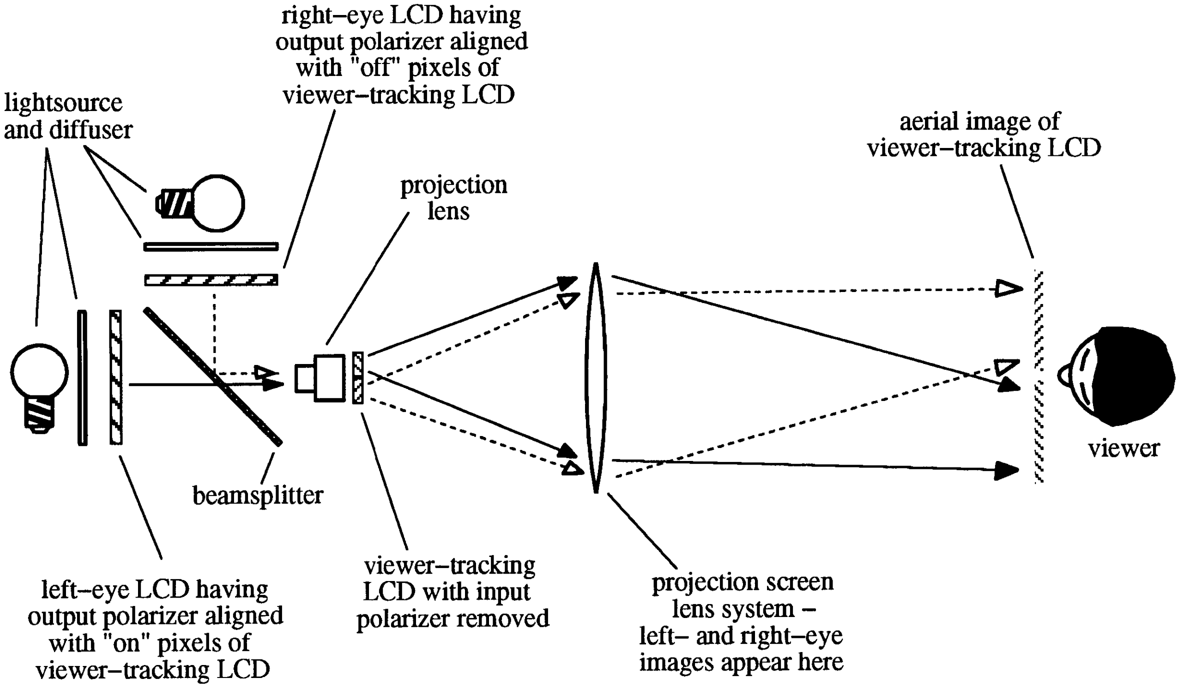

Figure 11 - Optical layout for the new projection polarization tracking display design.

A design was finally found that preserved the concept and functionality of the new polarization tracking design, but in a projection mode. The heart of the display is still the two image LCDs, which provide the left- and right-eye images, and a beamsplitter to combine the images along a common optical path. However, behind each image LCD there is now only a simple diffuser and light source to provide adequate illumination. Light from the two image LCDs is then directed into a projection lens which projects the two images together onto the rear of the projection screen. The viewer tracking LCD is placed near the projection lens and again acts as a polarization controlling device, but now in a reversed fashion from that described in Section 5.1.3. Now, the input polarizer is removed from the viewer tracking LCD instead of the output polarizer. To work properly in conjunction with this mode of the viewer tracking LCD, the left-eye image LCD is oriented such that its output polarizer is aligned parallel to the output polarizer on the viewer tracking LCD, while the right-eye image LCD is oriented such that its output polarizer is perpendicular to the output polarizer of the viewer tracking LCD. In this configuration the image on the left-eye LCD can only pass through on pixels of the viewer tracking LCD and the image on the right-eye LCD can only pass through off pixels. Separate view zones can thus be formed on the viewer tracking LCD corresponding to separate left- or right-eye images. By using a lens or lens system as the projection screen in this design, these separate view zones on the viewer tracking LCD can then be focused to the appropriate position in the viewing area.

As in the previous design, this system uses an infra-red illuminator and a camera to capture a picture of the viewer with one side of his or her face illuminated. (Again, for convenience the illuminated side of the viewer's face will be designated here as the left side.) This picture is displayed on the viewer tracking LCD, with the illuminated, left side of the viewer's face represented by on pixels and the unilluminated, right side of the viewer's face represented by off pixels. Light from the left-eye image LCD travels through the beamsplitter to the projection lens, and can only pass through the area of the viewer tracking LCD where the left side of the viewer's face is displayed (on pixels). The left-eye image is then projected onto the projection screen lens system, which takes the light passing through the picture of the left side of the viewer's face from the viewer tracking LCD and focuses it out onto the left side of the viewer's actual face. A similar path is followed for the right-eye image, passing only through the area of the viewer tracking LCD displaying the right side of the viewer's face (off pixels), and being focused to only the right side of the viewer's actual face.

In simpler terms, this new projection design can be thought of as a polarization-dependent stereoscopic display that required polarized glasses to view the 3-D images. If the head tracking LCD were removed from the system, the display would be projecting a left- and right-eye image onto a screen, each with an orthogonal polarization orientation. The proper 3-D images could then be seen by a viewer wearing polarized glasses with the left eye lens oriented to accept only the left-eye image and the right eye lens oriented to accept only the right-eye image. The effect of placing the viewer-tracking LCD back into the system is similar to taking the polarized glasses off of the viewer and placing them inside the display. Now, rather than having the viewer place the polarized glasses over his eyes, it is the display that finds the viewer and places a pair of virtual polarized glasses over his eyes.

It is the author's belief that this 3-D display design is the first of its kind, meeting all of the criteria for a "television-like" 3-D display. The system is autostereoscopic, requiring no special glasses, head-gear, or accessories. Essentially, a viewer should be able to walk into the viewing area and see the three-dimensional images right away. The system can also track the viewer as he moves, providing the proper stereo view at any location within the viewing area. The system is not limited to only one person, but can be viewed simultaneously by several viewers. And the system can display full-color, solid-looking three-dimensional images with strong image realism. On the manufacturing and broadcast side of the analysis, this display requires only two images to create its three-dimensional scenes. The result is a lower cost system that only needs twice as much information as a standard television to deliver vivid 3-D images. This amount of information could be easily transmitted by a number of methods: by linking together two television channels, by compressing the information for the two images into a single television channel, or by using digital HDTV channels to deliver the two images together on a single channel. The display is also backwards compatible with standard 2-D television, allowing users to not only view 3-D images and programs, but to also continue to watch traditional television images and programs. If the viewer were interested in watching today's episode of "Seinfeld" or some "I Love Lucy" reruns, he or she would only have to press a single button telling the system to completely turn off the head tracking LCD and to display the 2-D signal on only one of the image LCDs. The display would then act like any normal television set that is in millions of homes and businesses today. And finally, the elusive criteria of scaleability is easily achieved with this display. Because this design is based on optical projection, the actual components for the system can be substantially smaller than the projected 3-D images. Only the projection screen needs to be as large as the final images, with the rest of the system capable of being packaged compactly behind the screen.

The impressive qualities of this display system do not stop at only the "television-like" criteria. It should not be forgotten that the original purpose for turning to a projection-style design was to bring the 3-D images out from behind the beamsplitter of the previous designs. Now the images are no longer out of the reach of the viewers, tempting them to believe that the images might actually be touched. On more practical terms, this design consists of a minimum of hardware, following the Ezra philosophy of a single viewer tracking element and pairing down the Hattori infra-red illumination and capture system to only one infra-red source and one camera. The display also requires only minimal processing power for viewer tracking, since only the one viewer tracking element is needed, being driven by a very simple closed loop technique. Thus the system has a number of advantageous aspects, beyond just the "television-like" features.

5.2.1.a Projection Screen System

While working on the projection polarization tracking design, it became apparent that the view zone size was strongly connected to the projection lens aperture size and the viewer-tracking LCD size. If the projection screen is chosen to be just a simple lens, probably a large Fresnel lens, then the angular size of the view zone as seen from the projection screen will be the same as the angular size of the viewer-tracking LCD entering the projection screen. Attempting to increase the angular size of the view zone means increasing the size of the projection lens and the viewer-tracking LCD. At a certain point, this option becomes limited due to the complexity and cost of large size projection optics and large LCDs. In an effort to increase the viewing angle without increasing the size of the projection lens or viewer-tracking LCD, I designed a special projection screen system that would serve as an angle multiplier for the light projected onto the screen. The resulting projection screen would take a small angular size entering the screen system from the viewer-tracking LCD, and widen it to a larger angular size for the view zone.

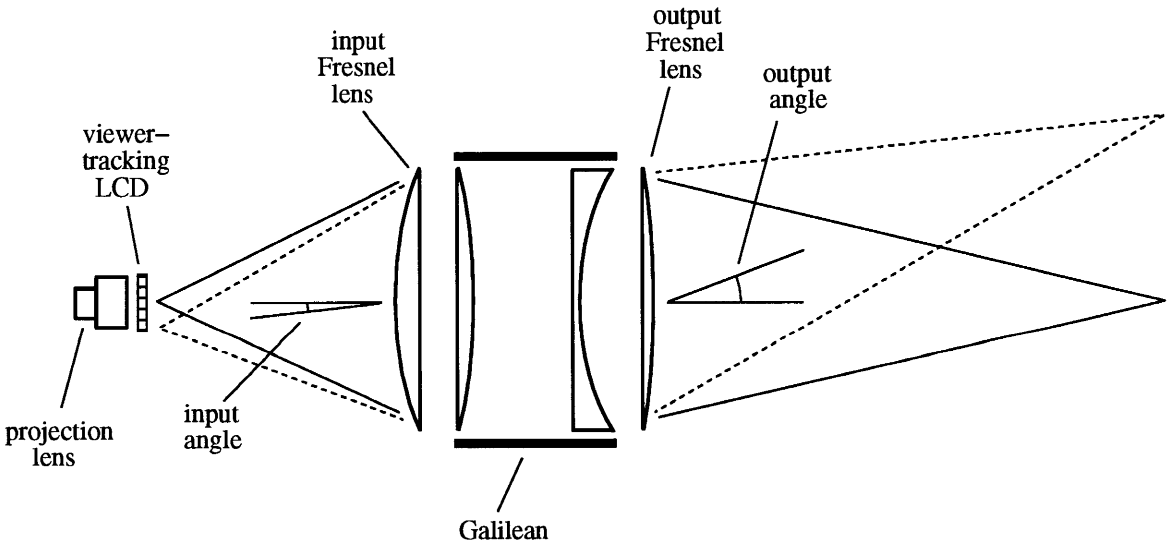

Figure 12 - Conceptual diagram of the new projection screen system.

The basic concept for the new screen system consists of placing a Galilean telescope arrangement between two lenses. The Galilean telescope has one positive focal length lens and one negative focal length lens, with the two spaced apart such that they share a common focal point. In this manner, the telescope arrangement serves as an angle multiplier for the light passing between the two outside lenses. The input lens to the system collimates the light coming from the viewer-tracking LCD and the projection lens, the Galilean telescope magnifies the angles of this collimated light, and the output lens focuses the light to a magnified image of the viewer-tracking LCD at the proper viewing distance, which is at its front focal point. The screen system now has a simple magnification of the outside lenses combined with the angular magnification of the Galilean telescope arrangement. The result is an increase in the size and the angle of the view zone. However, a screen system of this nature is hopelessly bulky if implemented with standard optical elements, as depicted in Fig. 12. A screen design is needed that can accomplish the same goal, but in a collapsed size.

A compact screen system was created by using two cylindrical lenslet arrays, one with a positive focal length and one with a negative focal length, to form a multiplicity of tiny Galilean telescopes rather than a single larger Galilean telescope. This micro-lens version of the telescope arrangement is sandwiched between the two outside lenses, which can be Fresnel lenses in order to further condense the system. The resulting compact design is shown in Fig. 13. The first Fresnel lens serves to collimate the light emanating from the viewer-tracking LCD, and thus the viewer-tracking LCD is placed at the focal point of this lens. Following this input Fresnel lens, the light encounters the two lenticular arrays that act as a multiplicity of Galilean telescopes. The light passing through a positive lenticule of this telescope arrangement forms an image of the viewer-tracking LCD a short distance beyond the negative lenticule. The negative lenticule then re-collimates this light before it becomes an actual image. Finally, the output Fresnel lens takes the collimated light leaving all of the negative lenticules and forms a single image of the viewer-tracking LCD at its focal point. The proper viewing distance is at the plane of this image of the viewer-tracking LCD, which is one focal length away from the output Fresnel lens.

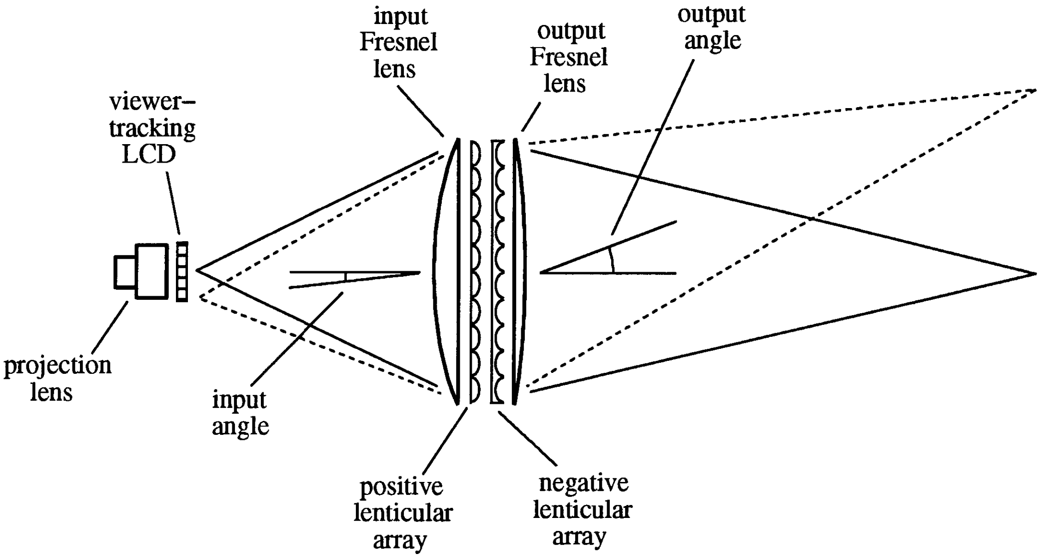

Figure 13 - Optical layout for the new projection screen system using lenticular arrays and Fresnel lenses.

The magnification of the screen system can be broken into two sections, the Fresnel lens magnification and the lenticular magnification. The distinction is somewhat important, as the angular magnification of the light passing through the screen system is determined solely by the lenticular magnification, while the size magnification of the view zone with respect to the size of the viewer-tracking LCD is determined by a combination of the lenticular and Fresnel lens magnifications. The magnification arising from the lenticulars, $m_{lenticular}$, if found simply by a ratio of the focal lengths of the positive and negative lenslets

$$m_{lenticular} = \frac{f_{positive}}{f_{negative}} \qquad \text{Eqn. 5-1}$$

The magnification due to the input and output Fresnel lenses, $m_{Fresnel}$, is similarly a ratio of focal lengths

$$m_{Fresnel} = \frac{f_{output-Fresnel}}{f_{input-Fresnel}} \qquad \text{Eqn. 5-2}$$

The total size magnification, m_{size}, of the screen system is found by combining these two equations

$$m_{size} = (m_{Fresnel})(m_{Lenticular}) \qquad \text{Eqn. 5-3}$$

while the angular magnification, m_{angle}, is the same as the lenticular magnification

$$m_{angle} = m_{Lenticular} \qquad \text{Eqn. 5-4}$$

This optical design for the projection screen seems to have the capability to dramatically widen the view zone for the projection polarization tracking design. It is also capable of doing this in a very compact profile, as the components are simply Fresnel lenses and lenticular arrays. In addition, it is anticipated that this projection screen system can be used for the other projection designs to be described below, as well as possibly having uses in other fields.

5.2.2 Projection Intensity Tracking Design

The LCD technology most often used today is the polarization based liquid crystal light valve system described in Section 5.1.3. In a 3-D display design using this common type of display as the left- and right-eye image bearing devices, the light entering and leaving the display is naturally polarized, making the display design a good candidate for the polarization tracking method. However, there are several other liquid crystal display technologies, as well as many display technologies which do not use liquid crystals, that are not polarization based. The polarization tracking method would therefore be difficult or impossible to implement for a display design using these types of display technologies. An alternate 3-D projection design was therefore created in an attempt to utilize a viewer tracking method that was polarization independent.

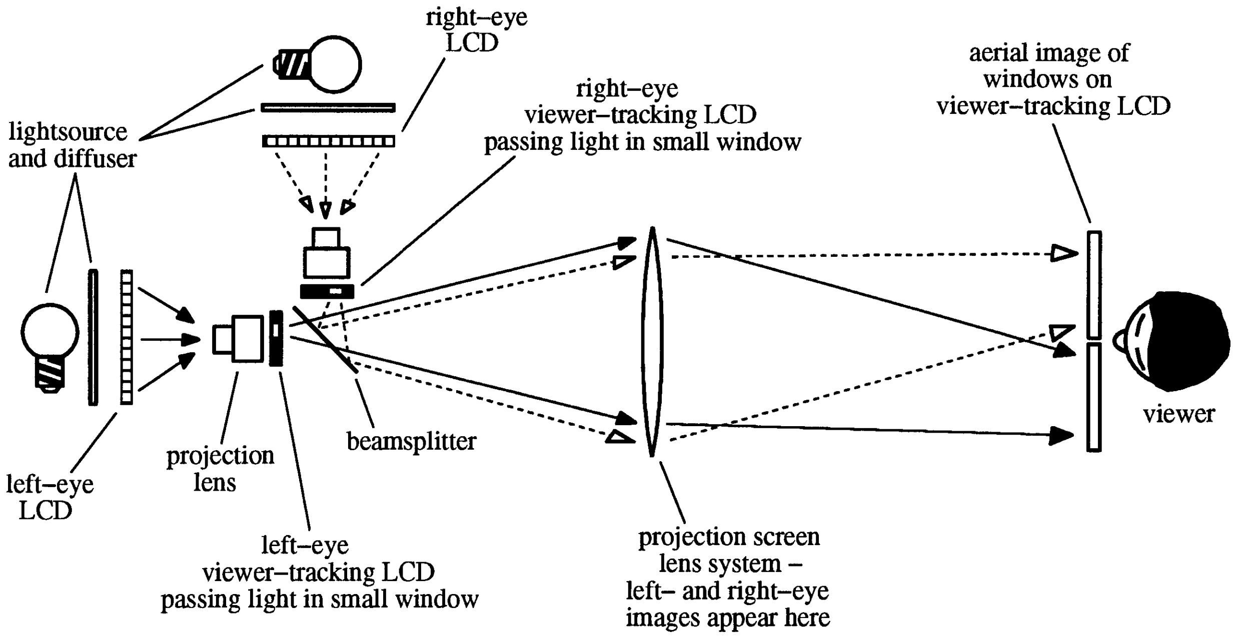

Figure 14 - Optical layout for the new projection intensity tracking display design.

An adaptation to the system described in Section 5.2.1 was designed by going back to the Hattori display and realizing that the polarization dependent technique had been implemented when trying to reduce the viewer tracking system to only a single element. At the expense of going back to the idea of a separate viewer tracking element for each image LCD, the polarization dependence could be avoided. Thus, rather than having a single projection lens and viewer tracking LCD for the two image LCDs, each image LCD has its own projection lens and viewer tracking LCD (see Fig. 14). The viewer tracking LCDs can now be operated as intensity controlling devices, passing a small square of light corresponding to a viewing zone and blocking the light outside of this viewing zone. The light passing through the viewing zone for each separate viewer tracking LCD is then combined along the same optical axis and focused by the projection screen lens system to two separate viewing zones in the viewing area. If the viewing zones are positioned such that only one goes to each eye of the viewer, then the proper stereo view can be seen. As a new viewer enter the viewing area, a new square is created on each viewer tracking LCD to provide the proper stereo view for this person.

This adaptation of the earlier projection design was created for the specific purpose of utilizing a different display technology than the standard LCDs as the left- and right-eye image bearing devices. In fact this design could be used with almost any display technology from ordinary CRTs to dispersive liquid crystal displays to electro-luminescent displays. The design is therefore extremely versatile. In addition, it should be pointed out that this design meets all of the criteria for a "television-like" display, and is capable of bringing the 3-D images out from behind the beamsplitter. However, there is a downside to the display's versatility, resulting in a combination of the problems initially seen in the Hattori and the Ezra designs. For instance, the display must now have two separate viewer tracking LCDs performing nearly identical tasks, as well as two projection lenses. Because the system no longer utilizes only a single viewer tracking element, the display must either use an arbitrary tracking method for locating the viewer and telling the viewer tracking LCDs where to position the square viewing zones, or the original Hattori method of two infra-red illuminators and two cameras must be employed. Either choice adds an extra layer of complexity to the system.

5.3 Single LCD Designs

In all of the above designs, two separate image LCDs have been used, one for the left-eye image and one for the right-eye image. The combination of the two stereo images in this manner can be referred to as spatial multiplexing, with the left- and right-eye images residing on two different, spatially separated, display sources and being combined, or multiplexed, by the beamsplitter. This configuration allows excellent image quality for each of the left- and right-eye images, and minimizes or eliminates any "flickering" of the image since each image has its own dedicated display source. However, in some circumstances it might be advantageous to sacrifice maximum image quality in exchange for a display that utilizes only one display source. For example, in situations where display cost or display size is an overriding issue, a 3-D display design with only a single image LCD might be the best solution. Such a solution would also require a different form of multiplexing, since both images for the stereo-pair will now be coming from the same image LCD.

5.3.1 Autostereoscopic "Crystal Eyes" Design

This first single LCD autostereoscopic design was arrived at by analyzing the well-known Crystal Eyes, or shutter goggles, technology from a new perspective. In Section 5.2.1, the projection polarization tracking system was described as being a traditional 3-D display that required polarized glasses to see the three-dimensional images, except that the display system placed a virtual pair of polarized glasses in front of the viewer's eyes rather than having the viewer wear an actual pair of glasses. A similar design was envisioned for using the Crystal Eyes technology, with the display system placing a virtual pair of shutter goggles in front of the viewer's eyes rather than polarized glasses.

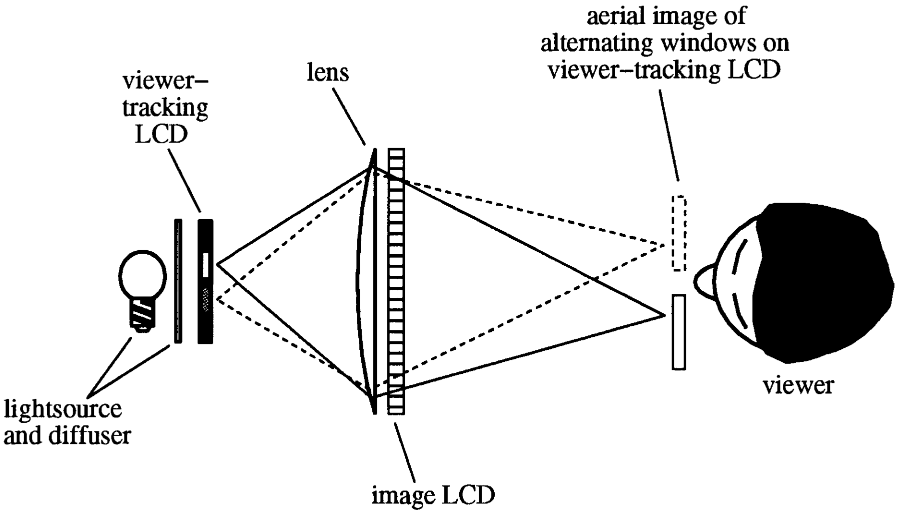

Figure 15 - Optical layout for the new autostereoscopic Crystal Eyes display design.

The system layout is pictured here in Fig. 15, and is centered around a single image LCD. Because both the left- and right-eye images must now come from this one image LCD, a different form a multiplexing the images must be used, called time multiplexing. The individual left- and right-eye images are displayed on the image LCD in a rapid succession, alternating back and forth between the left-eye image and the right-eye image. Each image is now being separated by time as opposed to being physically, or spatially, separated on two different LCDs. A person looking directly at the image LCD would see only a blur of left- and right-eye images resulting in a blending together of the two separate channels of information. However, if a person wore the proper synchronized Crystal Eyes goggles, or shutter goggles, the left eye lens of the goggles would only be open during the time that the left-eye image was on the image LCD, and the right eye lens of the goggles would only be open during the time that the right-eye image was on the image LCD. Thus the person would only see left-eye information with his or her left eye and only right-eye information with the right eye, resulting in a three-dimensional image.

In order to simulate this shutter goggles system in the current design, alleviating the viewer from the trouble of wearing any glasses or goggles, a viewer-tracking LCD is positioned behind the single image LCD to create a virtual pair of shutter goggles. With the aid of a viewer-tracking mechanism, the viewer-tracking LCD creates two small windows corresponding to the position of the viewer's eyes, alternating these windows on and off in synchronization with the alternating images on the image LCD. A lens is placed just behind the image LCD to take the light coming from the viewer-tracking LCD and focus it out to the viewing area.

The alternating cycle of the design starts with the viewer-tracking LCD, which passes light from the light source through only a small window corresponding to the viewer's left eye as determined by the tracking mechanism. The light passing through this window illuminates the image LCD, where the left-eye image is currently being displayed, and the lens just behind the image LCD then focuses this light out to the viewing area. Because the small window on the viewer-tracking LCD has been positioned to correspond with the left eye of the viewer, the light focused out to the viewing area is only directed to an area near the left eye of the viewer and nowhere else. Next, the viewer-tracking LCD and image LCD synchronously change images, so that the viewer-tracking LCD is displaying only a window corresponding to the viewer's right eye and the image LCD is displaying the right-eye image. The lens behind the image LCD takes the light coming from the viewer-tracking LCD and now focuses it to only the area near the viewer's right eye. The system has now completed one full cycle, and starts the process over again with the left eye. If the display performs this cycle of alternating images and windows at a high enough frequency, the viewer will be able to see a proper three-dimensional image on the single image LCD.

The obvious difficulty with this system is that the single image LCD must now do the work of what previously took two LCDs. A large concern is "flickering" of the image due to insufficient refresh rates of the image LCD. An image LCD displaying only a single channel of information needs to be updates at about 60 Hertz in order to provide a flicker-free image. Because the image LCD in this system must handle the displaying of two different channels of information, one for the left eye and one for the right, the LCD must be able to handle refresh rates of approximately 120 Hz. If the image LCD, and likewise the viewer-tracking LCD, is not capable of such refresh rates, the images will exhibit noticeable flicker, deteriorating the quality of the images and the 3-D scene. An additional concern is proper illumination for the display. Because the system must now split its time between alternately displaying the left- and right-eye images instead of delivering them both simultaneously, the display can only deliver half of the previous brightness to each of the left- and right-eye images. In order to compensate for this fact, the single image LCD must now be provided with the same illumination power required for a two image LCD system, but in a single illumination beam. This result is not intolerable, but it might raise light source lifetime issues and heat management concerns that could cause difficulties for the system.

Despite these problems, this design is extremely simple while still providing the viewer with a reasonably good quality three-dimensional image. In fact, this display design is capable of meeting all of the "television-like" criteria except for one, the scaleability criteria. The size of the 3-D images is limited by the size of the image LCD, which currently is only available commercially in sizes less than about 300 mm (12 inches). However, advances in LCD technology may soon result in larger LCDs at reasonable costs and yields, as well as rapidly updatable LCDs, ameliorating two of the concerns for this system, scaleability and flicker. An additional advantage to this system design is that there is no beamsplitter between the three-dimensional image and the viewer. The direct view nature of the display allows the viewer to now be in much closer interaction with the 3-D images without the added hardware necessary for a projection design.

5.3.2 Projection "Crystal Eyes" Design

Another single LCD design was arrived at through a synthesis of the projection intensity tracking system, described in Section 5.2.2, and the Crystal Eyes technology. The design begins by eliminating one entire leg of the design in Section 5.2.2, which removes one of the image LCDs, one of the viewer-tracking LCDs, one of the projection lenses, and the beamsplitter from the system. The remaining components form an in-line projection system, with the addition of a viewer-tracking LCD near the projection lens. In order to use this design to display stereo images, the technique described above involving time multiplexing of the images was employed, again similar to the Crystal Eyes stereo viewing system.

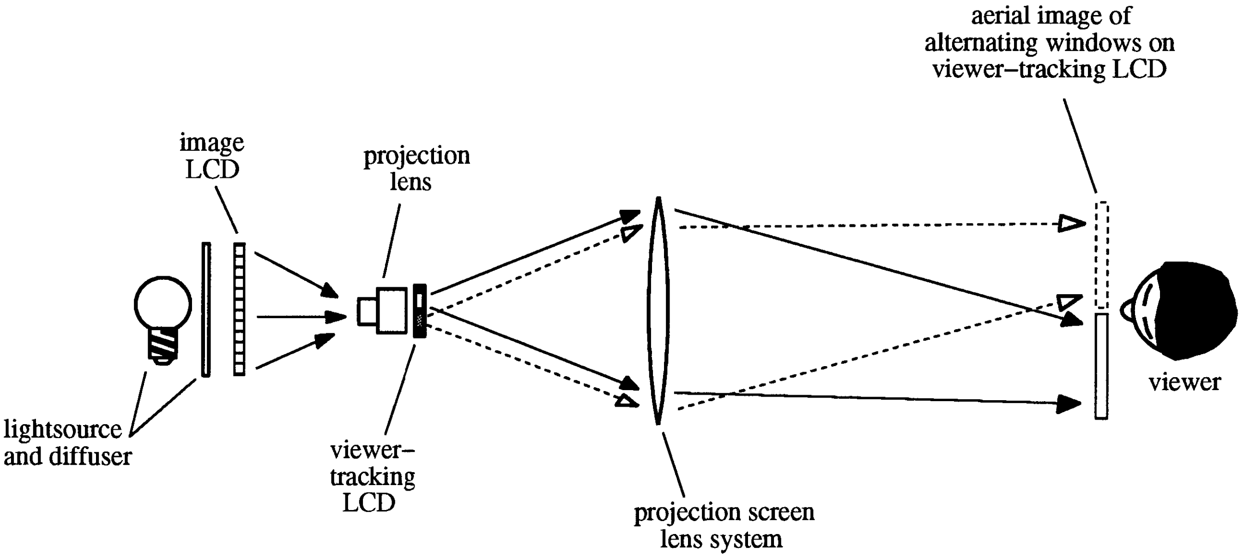

Figure 16 - Optical layout for the new projection autostereoscopic Crystal Eyes display design.

The design starts with the left-eye image being displayed on the image LCD. The viewer-tracking LCD, which is synchronized with the image LCD, receives the light coming from the left-eye image on the image LCD and only passes it through a small window corresponding to the left eye of the viewer, as determined by a viewer tracking system. The left-eye image is then projected by the projection lens onto the screen, which the viewer is observing. The projection screen now takes this light, which is coming from the small window on the viewer-tracking LCD, and focuses it out to the area near the left eye of the viewer. For the next half of the cycle, the image LCD rapidly changes to display the right-eye image, and the viewer-tracking LCD changes in synch to pass only a small square corresponding to the viewer's right eye. The right-eye image is projected onto the projection screen, and this light is directed to only a small area near the viewer's right eye. As in the previous design, if this cycle is continuously performed at a high enough frequency, the viewer will be able to perceive the proper three-dimensional image.

The problems and pluses of this system are almost exactly the same the design of Section 5.3.1. However, one additional benefit has been gained through the projection design of this system, which is the ability to have a much larger image size. Because the image LCD is projected onto a screen rather than viewed directly, the three-dimensional images are not bound by the size of the image LCD, and can be substantially larger. This design is now capable of meeting all of the "television-like" criteria, including scaleability.

6 Experimental Prototype Results

The previous chapter has described the conceptual designs for seven new three-dimensional autostereoscopic displays. The next step in this research is to take these conceptual ideas and move them into the real world to see how they fare. In this way it can be found if the conceptual ideals hold up to the litmus test of practicality. This section will begin by treating the prototype of the design outlined in Section 5.1.3, the new polarization tracking design. The first two designs of Section 5.1 have been omitted here as they are only minor modifications to the Ezra, et al. and Hattori, et al. display designs. While these modifications do improve these systems, their inclusion here would bring little new insight.

6.1 Prototype of the Polarization Tracking Design

The initial prototype put together for testing the polarization tracking design started with a few initial parameters. The first, which wound up driving the general size of the overall display, was the desire to use image LCDs of approximately 250-300 mm (10-12 inches) in diagonal size. LCDs of this size will allow a reasonably large display while also being achievable with off-the-shelf components. One other parameter was to create a compromise between the viewing distance of the viewer from the display and the size of the viewing zone. These two factors are closely connected, as they are both dependent on the lenses immediately behind the image LCDs.

The lens law

$$\frac{1}{o}+\frac{1}{i}=\frac{1}{f} \qquad \text{Eqn. 6-1}$$

combined with the magnification equation

$$m=\frac{i}{o} \qquad \text{Eqn. 6-2}$$

dictates that as the view zone gets larger the viewer must be positioned farther and farther away from the display in order to be at the proper viewing distance.

With these parameters in mind, the prototype depicted in Fig. 17 was constructed. In order to simplify the testing of this initial prototype, the viewer-tracking LCD was replaced by two pieces of polarizer material placed side by side with their polarization orientations opposite to each other. This would effectively simulate a situation where the viewer-tracking LCD had half of its pixels turned "on" and half of its pixels turned "off." In order to give the largest possible viewing zone for the system while maintaining a reasonably compact footprint, the simulated viewer-tracking LCD size was chosen to be roughly equal to that of the image LCDs; approximately 250 mm (10 inches) diagonally. The choice of an f = 335 mm (13.2 inch) Fresnel lens behind each image LCD would then focus this simulated viewer-tracking LCD out to the viewing area with approximately a 1:1 magnification. This proved to be the best compromise between view zone size and viewing distance, resulting in a lateral view zone size of about 200 mm (8 inches) and a viewing distance of approximately 600 mm (24 inches) from the image LCDs. The resulting viewing angle is about 19 degrees. This viewing distance was chosen on the basis of statistical viewer information which shows that viewers are most comfortable sitting at a distance from a television set that is 3-5 times the height of the set. The image LCD height in the case of the prototype is approximately 150 mm (6 inches), placing the average comfortable viewing distance at about 600 mm (24 inches), or 4 times the LCD height.

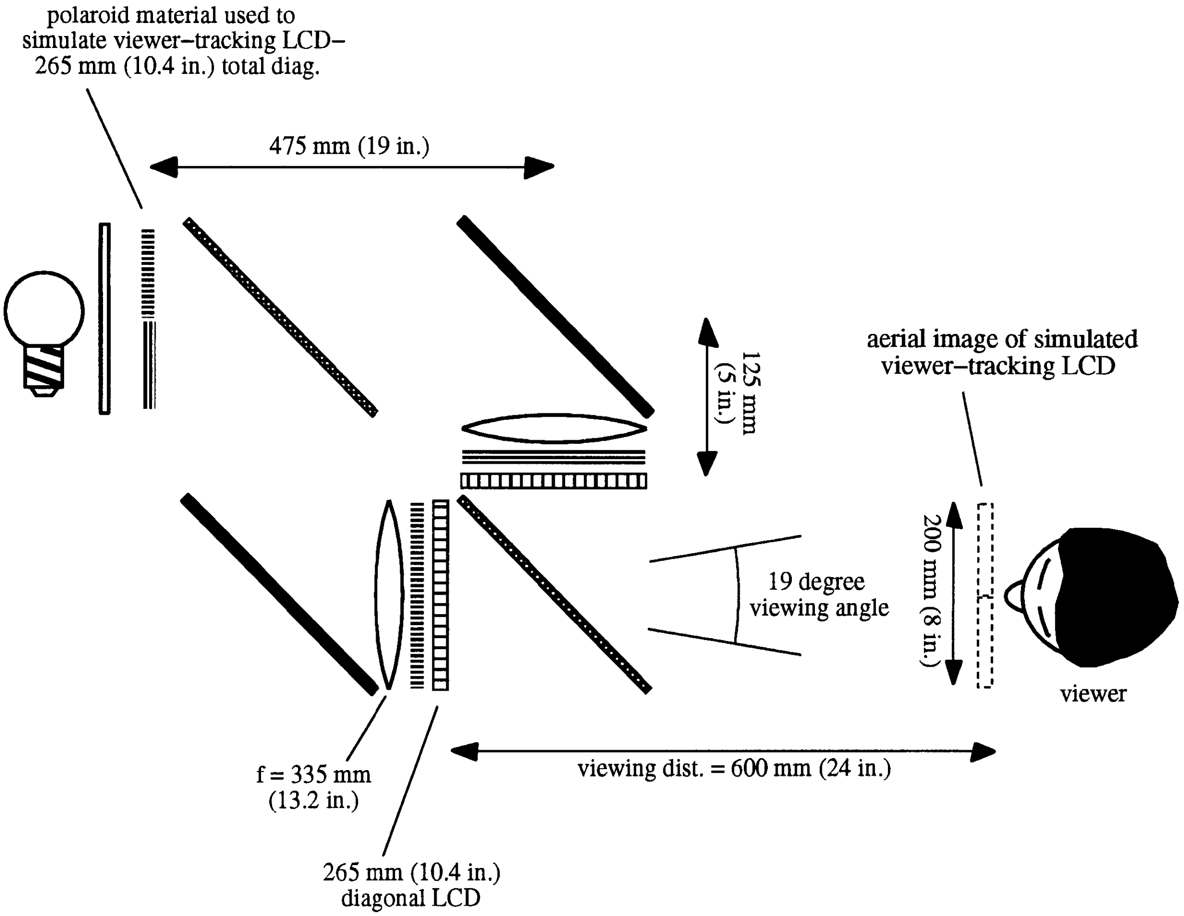

Figure 17 - Dimensions and specifications for the first prototype of the polarization tracking display.

With the conceptual design implemented in this configuration, on technical difficulty immediately rose to the surface. This difficulty involved the polarization transmission and reflection characteristics of the beamsplitters and the front surface mirrors used in the display. When the polarizers making up the simulated viewer-tracking LCD were oriented such that the light passing through them was either horizontally polarized (p-polarized) or vertically polarized (s-polarized) (see Fig. 18, a)), the left- and right-eye images on the two image LCDs were found to have slightly different colorations. The problem in this case was that the multi-layer dielectric beamsplitter that split the light coming from the viewer-tracking LCD had different spectral reflectance and transmittance characteristics when the viewer-tracking polarizers were oriented in this way. While the transmitted beam always had a relatively even coloration, the result of a flat spectral transmittance curve, the reflected beam always appeared to be slightly yellowish. It was discovered that this type of 50/50 multi-layer beamsplitter had poor reflection characteristics in the blue region of the spectrum. The result was that less of the blue component of the light was reflected off of the beamsplitter, creating a yellowish tint to the reflected beam. While this slight coloration was not an overwhelming problem when considering the left- and right-eye images independently, when the two images were viewed together as a stereo-pair the difference in coloration had a tendency to create viewer discomfort.

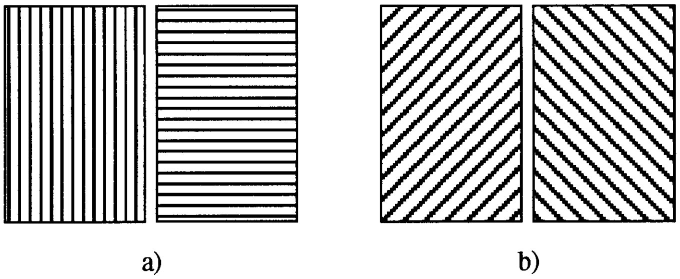

Figure 18 - Polarization orientations for the simulated viewer-tracking LCD.
a) s- and p-polarization orientations.
b) orthogonal 45 degree orientations.

In an effort to avoid these coloration problems, the polarizers serving as the viewer-tracking LCD were positioned so that their orientations were at opposite 45 degree angles with respect to the horizontal, rather than horizontal and vertical (see Fig. 18, b)). This approach did yield a more even spectral response in the reflected and transmitted beams coming from the 50/50 beamsplitter. However, difficulties were now encountered with the front surface fold mirrors used to direct the light from the beamsplitter towards the rear of the image LCDs. These aluminized front surface mirrors, similar to the beamsplitter, had difficulties in the blue region of the spectrum, having a tendency to slightly depolarize wavelengths in this region. The result of this slight depolarization meant that the left-eye image LCD would not only be illuminated by the left-eye portion of the viewer-tracking LCD, but would also be slightly illuminated by the right-eye section of the viewer-tracking LCD. The viewer's right eye would now be able to see a faint image of the left-eye image LCD in addition to the right-eye image LCD, creating cross-talk between the left- and right-eye channels and causing difficulty in fusing the stereo-pair images into a three-dimensional scene.

A reasonable solution for each of these cases was found. In the case of the horizontal and vertical orientations of the viewer-tracking LCD, a special beamsplitter coating, known as an inconel coating, was used to give a more even spectral reflectance and transmittance. The cost of this improved beamsplitter is a slight hit in the overall efficiency of the system. The inconel beamsplitter has a slight dark tint to it, resulting in a beam ratio of closer to 30/30 as opposed to 50/50. The beamsplitter does do an effective job, however, with the left- and right-eye image LCDs now being illuminated with equal color and creating a three-dimensional image which can be seen without viewer strain.

In the case of the viewer-tracking polarizers being oriented at opposing 45 degrees, a sheet of polaroid material was placed between the beamsplitter and each fold mirror to serve as a pre-polarizer (see Fig. 19). These pre-polarizers are each aligned with the input polarizer of the image LCD which follows them. In the leg of the system containing the left-eye image LCD, the pre-polarizer performs the function of blocking all of the light coming from the right-eye section of the viewer-tracking LCD and transmitting almost all of the light from the left-eye section of the viewer-tracking LCD. Because none of the light from the right-eye section of the viewer-tracking LCD makes it past the pre-polarizer, the front-surface fold mirror never has a chance to de-polarize this light. Light from the left-eye section of the viewer-tracking LCD that gets de-polarized by the front-surface mirror will be effectively blocked by the input polarizer of the left-eye image LCD. The system again takes a hit in overall efficiency, as the pre-polarizers absorb approximately 20-30 percent of the light in the polarization orientation that it is supposed to pass, but the technique is effective in cancelling almost all of the cross-talk that would otherwise be present. One interesting note to point out is that most commercial LCDs have their polarizers oriented at 45 degrees from the horizontal. The pre-polarizer technique is therefore the favorable choice if the system is to be built with readily available components.

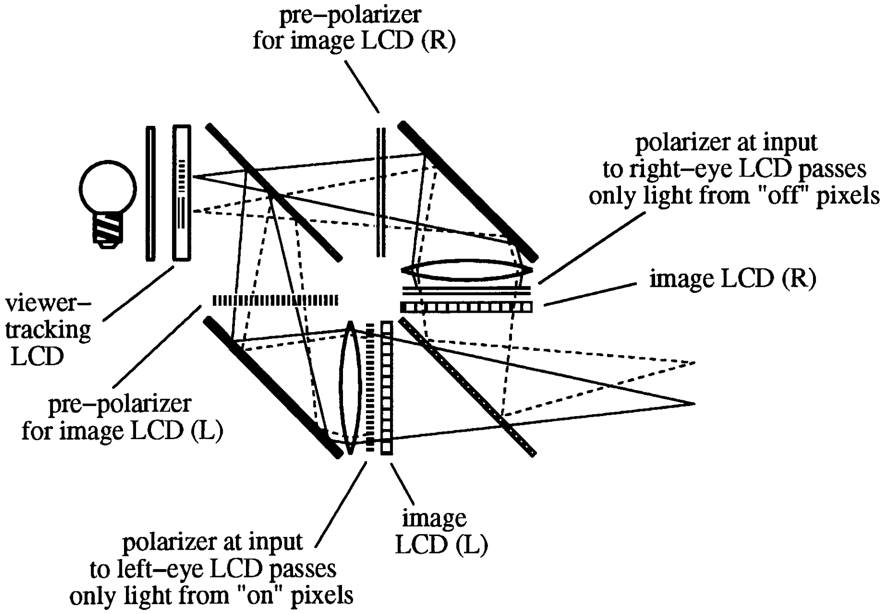

Figure 19 - Optical layout for polarization tracking display using pre-polarizers.

Although the technical feasibility of this design has been convincingly demonstrated by the prototype, two issues still caused concern, eventually prompting the design of the projection systems. The first issue is a more practical one dealing with the viewing zone size associated with this display. Because the viewer-tracking LCD must be positioned beyond the fold mirrors and the input beamsplitter, the lenses just behind the image LCDs have a minimum object distance which is quite large. In order to get even a small magnification of the viewer-tracking LCD, the image distance from these lenses must be still larger. The result, as discussed earlier, is that a larger view zone size necessitates the viewer to be positioned farther and farther away from the display for optimal viewing conditions. If the viewing constraints are maintained such that the viewer must be located at a distance of approximately 3-5 times the height of the display, then the only means for increasing the view zone size is to increase the size of the viewer-tracking LCD. While adding a slightly larger viewer-tracking LCD, upwards of approximately 380 mm (15 inches) diagonal, would be possible, the set distances of the viewer-tracking LCD and the viewer from the image LCDs means that the increase in viewer-tracking LCD size yields only an equivalent increase in view zone size. The resulting view zone would be about 300 mm (12 inches) wide with a viewing angle of about 28 degrees using the same optical layout as Fig. 17. A 300 mm (12 inch) wide view zone size is not sufficient if this is truly to be a multiple-viewer 3-D display.

The other issue detracting from the acceptability of this display is that the three-dimensional images must all be viewed through the output beamsplitter of the system. While this does not create any overt problems with the display and certainly does not hinder the perception of the 3-D images, the three-dimensional impact is minimized due to the images being physically separated from the viewer. As mentioned in earlier chapters, effective 3-D images often elicit the "reach out and touch" response from viewers. The output beamsplitter of this system has the tendency of counteracting this response and detracting from the overall effectiveness of the 3-D display.

Thus the practical implementation of the new polarization tracking design has yielded a workable, yet not optimal 3-D display. The limited view zone capabilities, while possibly acceptable for a computer monitor type display, need to be improved if this is to be a "television-like," multiple-viewer display. It is this issue, combined with the uncomplimentary effects of the beamsplitter that led from this prototype to the design of the projection polarization tracking design.

6.2 Prototype of the Projection Polarization Tracking Design

Construction of the first prototype projection display started by borrowing many of the components of the polarization tracking prototype from Section 6.1. This meant that while smaller image LCD sizes could be utilized for this projection system, the readily available 265 mm (10.4 inch) LCDs were used in the prototype. These LCDs have a polarization orientation at 45 degrees from horizontal, and based on the polarization experiments from section 6.1 therefore require the use of the special inconel beamsplitter to ensure equal coloration for both of the LCD images. The polarization orientation of each of the image LCDs was rotated so that the LCDs had orthogonal polarization directions when viewed through the beamsplitter.

Following the trend of convenience and ease of availability, the choice of projection lens and viewer-tracking LCD was determined on the basis of what was available in the laboratory. The projection lens chosen has a focal length equal to 240 mm (9.54 inches), which allowed the projection lens to be positioned just beyond the beamsplitter and deliver an image of approximately 300-350 mm (12-14 inches) diagonal. This image size does not fully take advantage of the projection design, which is capable of much larger images. However, an image of this size turned out to be very convenient for the sake of using off-the-shelf Fresnel lenses, easily available in a size of 280 x 280 mm (11 x 11 inches), as the projection screen for the prototype. The first prototype used one of these Fresnel lenses with a focal length of f = 610 mm (24 inches). The viewer-tracking LCD was also a piece of equipment readily available and borrowed from the laboratory. It was extremely critical that this LCD be of the active matrix type, as this would give the high contrast required for minimizing or eliminating cross-talk between the left- and right-eye channels. The choice of a black-and-white LCD was also important for maintaining efficiency in the system. The viewer-tracking LCD is serving simply as a mechanism to pass or block light coming from the image LCDs, a type of two-channel shutter or light valve, and therefore does not need to add or remove any color characteristics to the light passing through it.

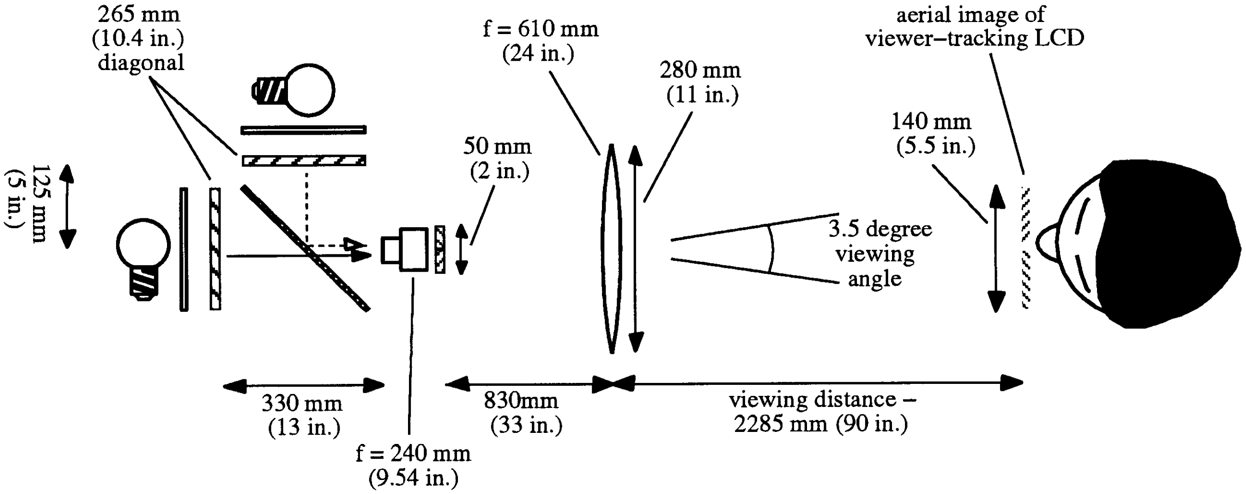

Figure 20 - Dimensions and specifications for the projection polarization tracking prototype.

The resulting prototype layout can be seen here in Fig. 20. As can be seen from this diagram, the viewing distance from the projection screen is larger than the 300 mm (12 inch) diagonal image necessitates. This distance of approximately 2285 mm (90 inches) between the projection screen and the viewer was chosen for two reasons. The first reason, and probably the most critical, was to use the largest possible viewing distance to allow a larger magnification of the viewing zone. The viewer-tracking LCD being used in this prototype is only about 50 mm (2 inches) in width. In order to get a reasonably large magnification of this small sized viewer-tracking LCD, it was necessary for the viewing distance to be substantially longer than the 830 mm (33 inch) distance between the viewer-tracking LCD and the projection screen. The other reason for a 2285 mm (90 inch) viewing distance was the anticipation of a much larger projection screen of approximately 760 mm (30 inches) diagonal. The image height for a screen this size would be approximately 460 mm (18 inches), resulting in a preferred viewing distance of approximately 3-5 times this height, or 2285 mm (90 inches) at the farthest comfortable distance. At this view zone distance, the view zone size is about 140 mm (5.5 inches) wide, and has a viewing angle of about 3.5 degrees.

Because the shuttering or light valve action of the viewer-tracking LCD was the key factor in minimizing cross-talk in the system, it was important to examine exactly how well the viewer-tracking LCD was performing this function. An experimental method was needed to quantify this feature. The system was first set up with the right-eye image LCD blocked by a black card, and a spot meter looking backwards through the viewer-tracking LCD toward the exposed left-eye image LCD. The viewer-tracking LCD was then switched between states of displaying a full screen of "off" pixels and displaying a full screen of "on" pixels. In one state, the viewer-tracking LCD would fully transmit the light coming from the left-eye image LCD, while in the other state the viewer-tracking LCD would fully block the light coming from the left-eye image LCD. By using the spot meter to measure the intensity of the light passing through the viewer-tracking LCD in each of these transmitting and blocking states, an extinction ratio can be found which quantifies how effectively the viewer-tracking LCD is able to turn the left-eye image channel on and off. Next, the left-eye image LCD is blocked, and the same experiment is performed for the right-eye image channel. The two extinction ratios derived from this test, one for the left-eye image channel and one for the right-eye image channel, can now serve as a figure of merit for how well the system is minimizing cross-talk.

The above tests were performed on the prototype projection polarization tracking system. The results gave a left-eye channel extinction ratio of 14.0, and a right-eye extinction ratio of 9.9. Analysis of the 3-D image displayed by the system seems to support the idea that these are acceptable extinction ratios, as the left- and right-eye channels appear to be clearly separated and the images are easy to fuse into a three-dimensional scene.

This design yielded excellent results. The viewer-tracking LCD, for the moment, was not driven by any tracking mechanism but was instead driven by a laser disc player continually providing a single frame to the viewer-tracking LCD which has half "on" and half "off." The image LCDs could be driven by input from either a computer displaying stereo-pair images or by two real-time cameras capturing stereo-pair video and feeding it immediately to the image LCDs. The result was a clear, three-dimensional image that was larger than the previous prototype and which was no longer separated from the viewer by a beamsplitter. Despite its simple design, the projection polarization tracking prototype was extremely effective.

The primary concern with this prototype was that the view zone size was still too small to adequately support more than one viewer. While a number of advantages had been found with this system, including a simpler overall design, a design capable of compact size, a much larger image size, and an image accessible to the viewer, an improvement to the view zone size was still critical. Two approaches to this problem were possible. The first approach realizes that the size of the projection lens and viewer-tracking LCD within the system is proportional to the size of the view zone. By enlarging the aperture size of the projection lens and increasing the size of the viewer-tracking LCD, the view zone could be significantly increased. However, larger components, particularly the projection lens, could prove very expensive for each system as well as increasing the bulk and size of the system. It is important, though, to realize that this would be a viable option for improving the display's view zone. A second approach is also possible which would place the focus of widening the view zone on the projection screen instead of the projection lens. This approach seemed to be a more elegant solution to the problem, allowing the rest of the system to remain simple and compact while achieving the goal of expanding the viewing zone, and is described in the following section.

6.3 Projection Screen System

Drawing on the conceptual design outlined in Section 5.2.1.a, I started to put together a projection screen system which would fit both the prototype of the projection polarization tracking system and, later, the prototype of the projection intensity tracking system. The specifications for the projection screen components (see Fig. 21), including an input Fresnel lens, one positive and one negative lenticular, and an output Fresnel lens, were chosen for a screen which could display an image of approximately 760 mm (30 inches) in diagonal size, with a 3:4 aspect ratio.

With the screen size in mind, the focal length of the output Fresnel lens was the obvious starting point. Since viewer statistical information shows that the most comfortable viewing distance from a display is approximately 3-5 times the height of the display, a viewing distance of about 1830 mm (72 inches), or 4 times the display height of 460 mm (18 inches), would be optimal. The output Fresnel lens in the projection screen will be imaging the view zone, or an image of the viewer-tracking LCD, at one focal length's distance. The focal length of the output Fresnel should therefore coincide with the optimal viewing distance, giving this lens a focal length of 1830 mm (72 inches). The dimensions of the lens should be large enough to accommodate the entire 760 mm (30 inch) diagonal image, or at least 460 x 600 mm (18 x 24 inches).

The input Fresnel lens was the next to be specified. This lens will be positioned so that it is one focal length away from the output of the projection lens and the viewer-tracking LCD, which means that the focal length of the input Fresnel will be equal to the projection distance, or image distance, of the projection lens. To find this image distance, the prototype of the projection polarization tracking system was used as a model. The image LCDs for this prototype were 265 mm (10.4 inches) diagonal, requiring a projection magnification of 2.9 times for a 760 mm (30 inch) image, and the projection lens had a focal length of 240 mm (9.54 inches). Using a combination of the magnification equation and the lens law, the image distance, or projection distance, was found to be approximately 940 mm (37 inches) from the projection lens to the projection screen. In order to account for the physical length of the projection lens and the addition of the viewer-tracking LCD just after the projection lens, a conservative figure of 760 mm (30 inches) was chosen for the focal length of the input Fresnel lens. The dimensions of the lens should again be at least 460 x 600 mm (18 x 24 inches) to accept the entire projected 760 mm (30 inch) image.

At this point, the projection screen system already has a magnification equal to the focal length of the output Fresnel lens divided by the focal length of the input Fresnel lens, or

$$m_{Fresnel} = \frac{f_{Fresnel-out}}{f_{Fresnel-in}} = \frac{1830mm}{760mm} = 2.4 \qquad \text{Eqn. 6-3}$$

The next step is to add the lenticular Galilean telescope system between the input and output Fresnel lenses to increase this magnification. A lenticule pitch of 1/mm was chosen for the lenticular system as an initial starting point. This size was chosen as a compromise between the resolution deteriorating effects of a larger lenslet size and the diffraction effects of a smaller lenslet size.

The goal for specifying the focal lengths of the positive and negative lenticulars was to achieve the highest magnification possible without adding cross-talk to the system. Because the magnification of the lenticular Galilean telescope system is a ratio of the two focal lengths of the lenticulars,

$$m_{lenticular} = \frac{f_{positive}}{f_{negative}} \qquad \text{Eqn. 6-4}$$

maximizing the magnification depends in part on choosing a focal length for the negative array which is as short as possible. The manufacturer contacted for the custom fabricating of these micro-lens arrays stated that the fastest lenslets possible with their fabrication technique were about f/2.5, resulting in a minimum focal length of -2.5 mm for our negative array with 1/mm pitch.

Specifying the focal length for the positive array was the most critical part of the projection screen system for minimizing cross-talk caused by the screen. If the focal length was too large, light from one positive lenticule would form an oversized image of the viewer-tracking LCD, spilling light over to more than one negative lenticule and creating cross-talk. The result would prevent the stereo-pair from being properly fused into a three-dimensional image. However, if the focal length of the positive array was too small, the view zone size would not be magnified to its fullest capability. The specification also had to take into account not only the angles of the light coming from the viewer-tracking LCD, but also the diffraction due to the input Fresnel lens and the positive lenticular array which would cause light spilling over to several negative lenslets again.

According to the specifications for the input Fresnel lens, the viewer-tracking LCD will be positioned at the focal point of the input Fresnel, or about 760 mm (30 inches away). With the prototype projection tracking system as a model, the viewer-tracking LCD is measure to have a width of about 50 mm (2 inches). Light is therefore entering the input Fresnel lens from the viewer-tracking LCD with a horizontal half-angle of about 1.91 degrees. This light will be collimated by the Fresnel lens, but will also be diffracted by the grooves of the Fresnel lens, increasing the half-angle spread of the light. Referencing a catalog of Fresnel lenses, a groove pitch of 50/mm was taken as a typical frequency of the features on a Fresnel lens. This frequency, f_{groove}, was used to calculate the increase of the half-angle spread using the equation

$$\sin\theta_{out} - \sin\theta_{in} = \lambda f_{groove} \qquad \text{Eqn. 6-5}$$

with $\sin\theta_{in} = 1.91$ degrees and $\lambda = 600$ nm. The new half-angle spread, $\sin\theta_{out}$, is 1.98 degrees, and this light enters the positive lenticular array. Using the same diffraction equation, but with $f_{array} = 1/\text{mm}$ instead of f_{groove}, the half-angle spread increases again to 2.01 degrees. It is this light that must be focused by each of the positive lenslets into only one negative lenslet in order to avoid any cross-talk. By considering the half-angle spread of 2.01 degrees to be the most extreme angle of a light ray passing through the positive lenslets, and by noting the half-width of the negative lenslets, the simple geometry expressed by the equation

$$\tan(half-angle) = \frac{half-width_{neg}}{f_{pos-max}} \qquad \text{Eqn. 6-6}$$

leads to the maximum focal length possible for the positive lenslets before light begins to spill over to more than one negative lenslet. This focal length, $f_{pos\text{-}max}$, is 14.2 mm. For experimental purposes I chose to have two test positive lenticulars fabricated, one with f = 15 mm and the other with f = 10 mm. The f = 15 mm array would push the view zone to its largest possible size while also possibly exhibiting a little cross-talk, and the f = 10 mm array would assure minimum cross-talk at the expense of not fully magnifying the view zone.

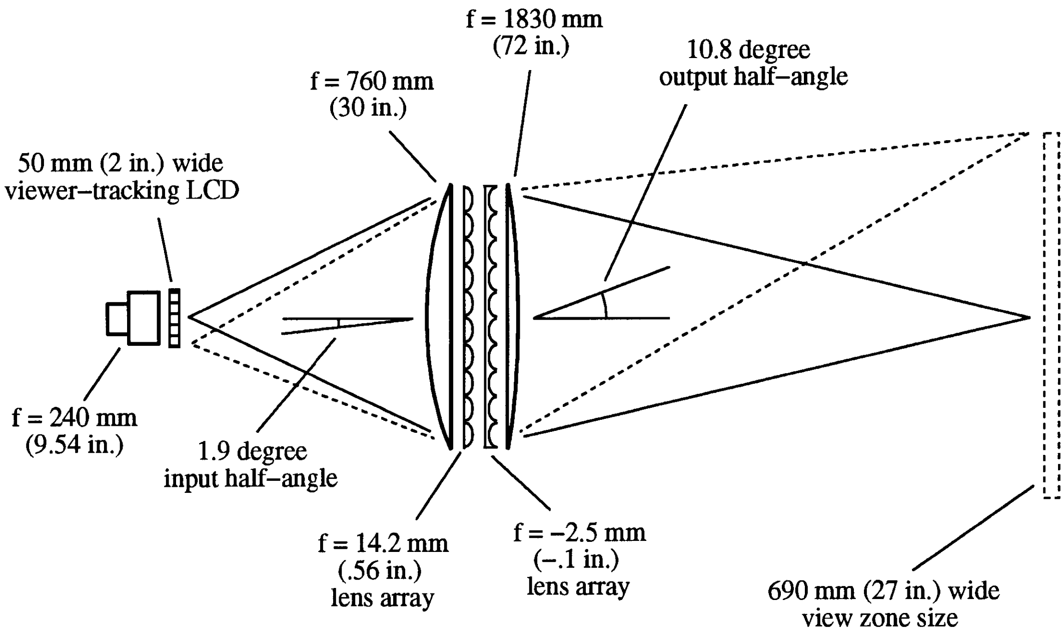

Figure 21 - Specifications for projection screen system.

Test pieces were fabricated for each of the three lenticulars, f = -2.5 mm, f = 15 mm, and f = 10 mm, in a size of approximately 50 x 50 mm (2 x 2 inches). Using these small test samples, along with Fresnel lenses of the appropriate focal lengths in a size of about 280 mm (11 x 11 inches), a series of experiments were set up to examine how well the projection screen system performed compared to its conceptual design.

The first experiment was to simply determine the proper alignment and separation of the positive and negative lenticulars for the Galilean telescope configuration. A laser beam was made to be parallel to the table surface at a height of a few inches, and then one of the positive lenticulars and the negative lenticular were aligned by retro-reflection of this beam to make each lenticular perpendicular to the beam. In this manner, the two lenticulars could be made parallel to each other. Next, lateral translation was adjusted on one of the lenticulars so that light from each positive lenslets went to only one negative lenslet. This could be determined by placing a white card beyond the two lenticulars and adjusting the lateral translation until the transmitted laser beam was centered horizontally on the card. Finally, the z-axis translation was adjusted, moving the lenticulars closer together or farther apart, and the transmitted laser beam was examined on the white card beyond the lenticulars. As the spacing between the lenticulars approached the optimal position, the laser beam on the card would shrink from a horizontal line of light to a slightly elongated spot. This demonstrated that the array of Galilean telescopes, formed with the f = 15 mm positive lenticular and the negative lenticular or the f = 10 mm positive lenticular and the negative lenticular, were effectively working as a single unit to pass the laser beam without added noise or scatter. This experiment also proved an effective method for aligning the lenticulars for many of the other tests.

The next important factor to determine was whether or not the system was magnifying the view zone as well as anticipated, and to check for cross-talk. Using the above technique for laser alignment, the lenticular system was properly positioned and the input and output Fresnels were added to examine the projection screen system as a whole. Due to difficulties finding Fresnel lenses with the exact focal lengths specified above, the input and output Fresnel lenses for this test did not have the proper f = 760 mm (30 inches) and f = 1830 mm (72 inch) focal lengths. In fact the longest focal length Fresnel lens that was readily available from several different sources had a focal length of only f = 600 mm (24 inches), and this lens was therefore used for both the input and output Fresnel lens for this test. After properly positioning the Fresnel lenses, a light source of approximately the same size as the viewer-tracking LCD was placed behind the input Fresnel lens at its focal point, and a large white card was placed at the focal point of the output Fresnel lens. The light passing through the projection screen system was then blocked off so that it only passed through the 50 x 50 mm (2 x 2 inch) section of the screen containing the lenticulars. The result was an image of the light source on the white card which was greatly magnified horizontally and slightly magnified vertically.

In order to measure the magnification of the screen system and compare it to the theoretical design, the input light source was measure to have a circular diameter of 41 mm (1.625 inches). When the f = 15 mm positive lenticular was used in the system, the image of the light source on the white card measured 280 mm (11 inches) horizontally and 50 mm (2 inches) vertically. This translates to a horizontal magnification of 6.8 and a vertical magnification of 1.2. According to the theoretical design, and remembering that this test is using an input and output Fresnel lens with f = 600 mm (24 inches), the horizontal magnification for this system should be $m_{\text{screen-horz}} = 6$, and the vertical magnification should be $m_{\text{screen-vert}} = 1$, which is in reasonably close agreement with the measured magnifications. When the f = 10 mm positive lenticular was used, the image of the light source was 185 x 50 mm (7.25 x 2 inches), giving a magnification of 4.5 horizontally and 1.2 vertically. The theoretical magnifications with this positive lenticular are $m_{screen\text{-}horz} = 4$ and $m_{screen\text{-}vert} = 1$, again in close agreement with the measured data.

In an attempt to more closely match the specifications outlined above for the screen system, one additional test of the spreading light source was performed using different Fresnel lenses. The output Fresnel lens specification of f = 1830 mm (72 inches) was approximately created using two lenses in combination, one positive and one negative, to give a longer focal length than originally possible with only a single Fresnel lens. The two lenses had focal lengths of f = 335 mm (13.2 inches) and f = -420 mm (-16.5 inches), which when placed back to back next to each other created a lens with f = 1680 mm (66 inches). This combination of lenses was used as the output Fresnel lens for the screen system, while the input Fresnel lens was still the same as before at f = 600 mm (24 inches). A test with the light source and the f = 15 mm positive lenticular was performed again, with the white card now being placed 1680 mm (66 inches) from the output Fresnel lens. The image of the light source was measured to be 740 x 130 mm (29 x 5.25 inches), for a magnification of 17.8 horizontally and 3.2 vertically. The theoretical magnification for this set-up is 16.5 horizontally and 2.75 vertically. This test shows the additional magnification added to the system by the Fresnel lens magnification.

These light spreading experiments proved very encouraging, showing that the system is working as designed and illustrating that the large magnifications necessary for a large view zone are possible. If the screen specifications from the previous paragraph are used in conjunction with the projection polarization tracking prototype of Section 6.2, the projection screen system would be starting with a viewer-tracking LCD width of about 50 mm (2 inches) and an input angle of about 4 degrees. Using the horizontal magnification figure above of 17.8, the resulting view zone size after the screen system would be 36 inches wide, with a viewing angle of about 28 degrees. This view zone size is definitely large enough to comfortably fit two viewer side-by-side, and it might be possible to fit 4 viewers if two sit and two stand.

However, the most important factor is amount of cross-talk due to the screen. If the screen does cause sufficient amounts of cross-talk between the left- and right-eye images, the large magnification of the view zone will be worthless. To test this, a type of knife-edge test was performed with the above set-up. The vertical edge of a black card was translated horizontally across the face of the light source, while the magnified image of the light source was examined. If the system were working perfectly, a single, sharp vertical edge corresponding to the edge over the actual light source should be seen in the image on the white card.

What initially appeared on the white card, with both the f = 15 mm positive lenticular and the f = 10 mm positive lenticular, was an image of three edges moving across the image of the light source. One of these images was darker and more distinct, while the other two were fainter. This was a clear indication of cross-talk, with a single feature on the input side of the projection screen resulting in several images of the feature on the output side of the screen. However, it was found that by adjusting the lateral translation of one of the lenticulars relative to the other and by changing the spacing between the lenticulars that the two extra images could be removed, leaving only one sharp edge in the image. As would be expected, this adjustment was much easier with the f = 10 mm positive lenticular system, resulting in a clean edge in the image with only minor changes in alignment. The f = 15 mm positive lenticular system proved more difficult to achieve perfect alignment, but in the end did seem to give acceptable results of only a single edge in the image.

The final step was to test the projection screen system with the projection polarization tracking prototype. It was important to see how the screen system affected the images that were projected on it, and to examine how it handled a real viewer-tracking LCD rather than a light source. The prototype was assembled as shown in Fig. 22.

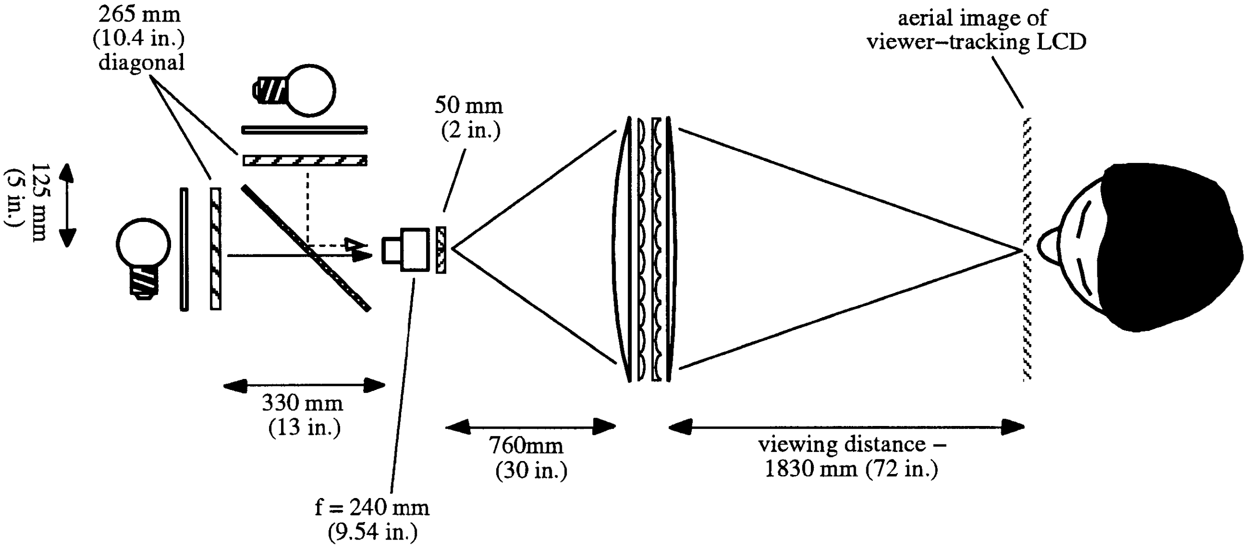

Figure 22 - Dimensions and specifications for the projection polarization tracking prototype.

With the projection screen system using the f = 15 mm positive lenticular, it was evident that there was some cross-talk interfering with the images. Scanning one eye across the viewing zone, the main transition where the left-eye image changed over to the right-eye image could be readily identified, however faint ghosts of the right-eye image could be seen occasionally in the left-eye image zone and vice versa. Adjusting the lenticulars did not seem to alleviate the problem, only shift the cross-talk from one part of the viewing zone to another. The system using the f = 10 mm positive lenticular, on the other hand, worked quite well. The left- and right-eye channels were clearly separated, and a 3-D image was viewable within the small 50 x 50 mm (2 x 2 inch) area of the projection screen system.

Two problems were noticed with the projection screen system used as part of the whole prototype 3-D display. The first was that the lenticular part of the screen system had the effect of adding thin, dark vertical lines to the image. On the 50 x 50 mm (2 x 2 inch) area of the screen system, however, it could not be determined if this was just a harmless by-product of the screen, or if this actually adversely affected the image quality of the projected images. The second problem was the fact that the images were much dimmer with the projection screen system than with just a simple Fresnel lens serving as the projection screen. Part of the explanation for this dimmer image is that the light for the display is now being spread over a larger view zone, and therefore requires more light in order to keep the same brightness as a smaller view zone. The other part of the explanation is that the projection screen system has introduced 8 optical surfaces into the image, rather than the 2 optical surfaces of a simple Fresnel lens. Each uncoated surface has a surface reflection of approximately 4%, resulting in a loss of about 28% of the light just due to all the surfaces in the screen system. Both of these brightness problems can be handled by simply supplying the images with brighter sources of illumination. The current illumination system of fluorescent backlighting leaves much room for improvement, so this is not a difficult obstacle to overcome.

One important factor which has not yet been tested with the projection screen system is the off-axis characteristics of the screen. Because the test lenticular pieces were only fabricated in a 50 x 50 mm (2 x 2 inch) size, only the paraxial characteristics of the system were effectively tested. While theoretically the screen system should not change as the light moves farther from the optical axis, it is unclear as to how well the Fresnel lenses behave in this region and therefore how they will affect the screen design as a whole.

6.4 Prototype of the Projection Intensity Tracking Design

The prototype for this design has only recently been started, and there is therefore very little in the way of results to include here. However, the preliminary construction can be discussed. As mentioned in Section 5.2.2, this design was created to take advantage of image sources which are not naturally polarized, as most LCDs are. A relatively new display technology which has been emerging over the past several years is the Deformable Mirror Device (DMD) developed at Texas Instruments. This device is a reflective display source, boasting an extremely high optical efficiency and a fully digital image control system. In an effort to use this latest technology in combination with projection intensity tracking design, two DMD projectors have been purchased as the display engines for the prototype. Each projector already has a powerful light source and a projection lens incorporated into its system, so the only additions that should be necessary to complete a projection intensity tracking system are two viewer-tracking LCDs, a beamsplitter, and a projection screen system. The prototype will be laid out as shown here in Fig. 23.

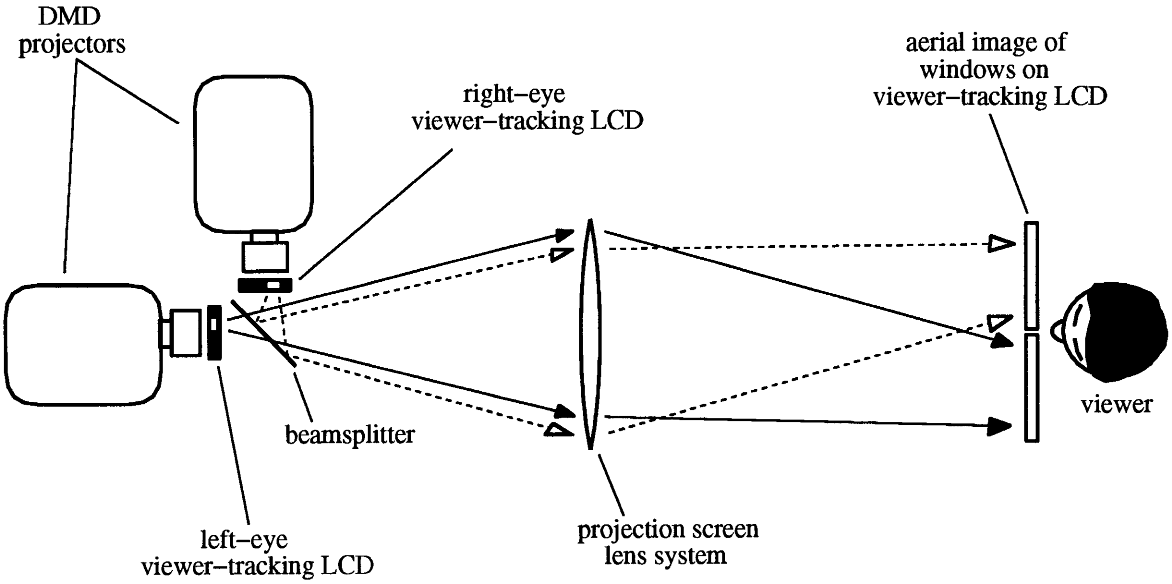

Figure 23 - Conceptual layout for projection intensity tracking prototype using DMD projectors.

7 Conclusions and Future Work

The work outlined in these chapters began with the establishment of six criteria for reaching the goal of a “television-like” three-dimensional display. These criteria put forth such ideas as complete viewer freedom, simultaneous viewing with multiple viewers, and even manufacturing concerns such as 2-D compatibility and scaleability. The remainder of the text was dedicated to analyzing and creating three-dimensional displays on the basis of these criteria. However, even if the display designs presented here are replaced by other designs in the future, it is hoped that the criteria established here will continue to help define what is necessary for an effective "television-like" three-dimensional display.

With all this being said, it is the author's belief that the previous chapters have presented several new autostereoscopic display designs that hold excellent promise for successful “television-like” displays. The projection designs, especially, have great potential due to their combination of large 3-D image capabilities combined with a reasonably compact system. The ability to present the three-dimensional images directly in front of the viewer, without the interference of a beamsplitter, also adds viewer appeal to the design, tempting the viewer to “reach-out-and-touch.”

A number of the display designs may also be effective in a variety of uses other than “television-like” displays. For example, the single LCD designs would work quite well as “computer monitor-like” displays, with the direct view nature of these systems being well suited for computer work. The compact, single image LCD and single viewer-tracking LCD layout would additionally fit quite easily into a desktop monitor-type package. Other uses for the designs described in this thesis might extend from 3-D video conferencing that allows greater freedom of speakers to move about naturally, to 3-D arcade-style video games that combine the rendered, three-dimensional computer graphics of today's games with the “no-glasses,” three-dimensional feel and impact of tomorrow's technology.

In the opinion of the author, the designs of this thesis meet the outlined "television-like" criteria better than any other 3-D display currently available or under research. However, three problem areas cannot be overlooked, and deserve discussion here as well as further research investigation:

- View zone size. This factor is extremely critical to every 3-D display, and particularly to a “television-like” display. The goal of viewer freedom dictates that the view zone should allow a reasonably wide range of viewing locations, and thus a relatively wide viewing angle. Additionally, the multiple-viewer and viewer-tracking capabilities of the systems mean little if there is not enough view zone space to comfortably accommodate several viewers or to move around. While the projection designs in combination with the projection screen system do seem capable of approaching a viewing angle of approximately 30 degrees, this is only temporarily adequate. A design allowing a viewing angle of about 60 degrees begins to enter the range where the view zone is no longer a limiting factor on the display.

- Viewer depth tracking. As mentioned earlier, this variable was purposely left out of the considerations of this thesis in an effort to focus more intently on other areas of development, such as autostereoscopic viewing, lateral viewer tracking, and multiple-viewer tracking. However, depth tracking cannot be continually left out of consideration, as it applies directly to the viewer freedom issue. A few research efforts have attempted to tackle this problem, with varied success. These attempts have always been for only a single viewer, though, and the methods by which several viewers might be appropriately tracked both in the lateral direction and in distance from the display is still an unknown quantity.

- Viewer-locating methods. A number of viewer-locating methods for finding the viewer's face and the division between his or her eyes were outlined here, but each with its own unique deficiencies. A technique is needed that can function in a variety of lighting conditions, does not depend substantially of the viewer's skin tone, and that can handle the locating of several viewers without difficulty. All this must be done while maintaining a high degree of accuracy and speed. While the display designs themselves have been developed independently of the viewer-locating method, allowing them to be compatible with almost any of the methods described in this thesis or any new methods developed in the future, the 3-D displays cannot be completely independent of the viewer-locating methods. Therefore, the optimal operation of these displays depends on the development of a robust viewer-locating method to fully take advantage of the display's capabilities.

In light of these difficulties, further work is still necessary for the full completion of a "television-like" three-dimensional display. However, the display designs put forth in this text have not only defined what is necessary for a "television-like" display, but have created the real possibility of reaching this goal. The realization of three-dimensional television displays has now been placed within striking distance.

Appendix A- Specifications for Prototype Components

Image LCD's	Sharp LQ10P341 260 mm (10.4 in.) diagonal 211.2(H) x 158.4(V) mm 640(H) x 480(V) x RGB pixels Active matrix
Viewer-tracking LCD	Masushita B&W 64 mm (2.5 in.) diagonal 50.8(H) x 38.1(V) mm 320(H) x 240(V) pixels Monochrome active matrix
Projection lens	Buhl Optical projection lens 240 mm (9.54 in.) focal length f/2.5 100 mm (4 in.) diameter
Beamsplitters	Coating 1 - inconel Coating 2 - MgFl 356 x 203 mm clear aperture 6.35 mm thickness
Fold mirrors	Coating - front-surface, AlSiO 356 x 203 mm clear aperture 6.35 mm thickness
Fresnel lenses	Optical grade acrylic 265 x 265 mm clear aperture 2.3 mm (.09 in.) thickness 20 grooves per cm (50/in.) 335 mm (13.2 in.), 610 mm (24 in.), and -420 mm (-16.5 in.) focal lengths

Polarizing film material	25% unpolarized light transmission 99% polarization efficiency Gray color .74 mm (.029 in.) thickness
Optical diffusing glass	Flashed “opal” coating 250 x 200 mm clear aperture 3.18 mm (.125 in.) thickness
Illumination	Fluorescent tube backlighting

Appendix B - Photographs of Projection Polarization Tracking Prototype

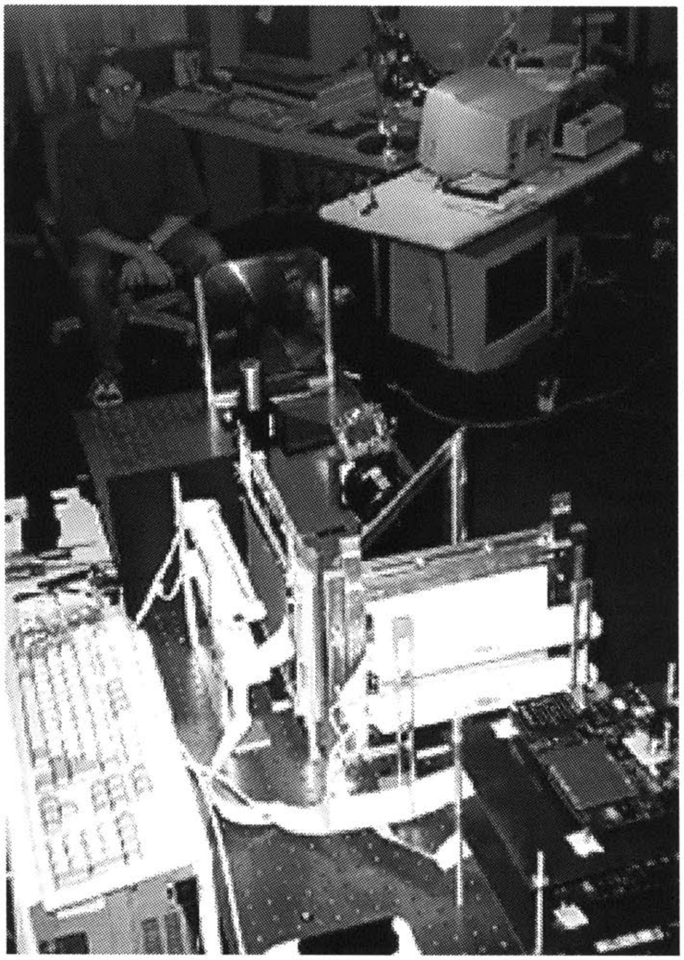

Figure 24 - Overhead view of projection polarization tracking prototype. Yes, that's me pretending to be a viewer.

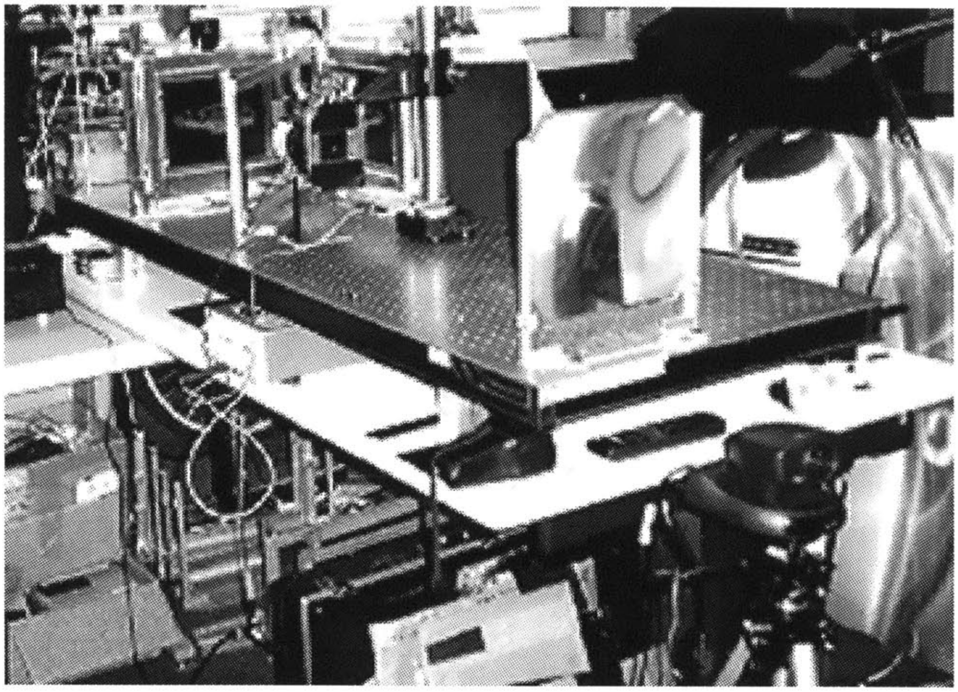

Figure 25 - Angled front view of projection polarization prototype. Notice (from right to left) black viewer-locating camera, Fresnel lens projection screen, small viewer-tracking LCD, projection lens, beamsplitter, and two image LCDs displaying a red car (upside-down).

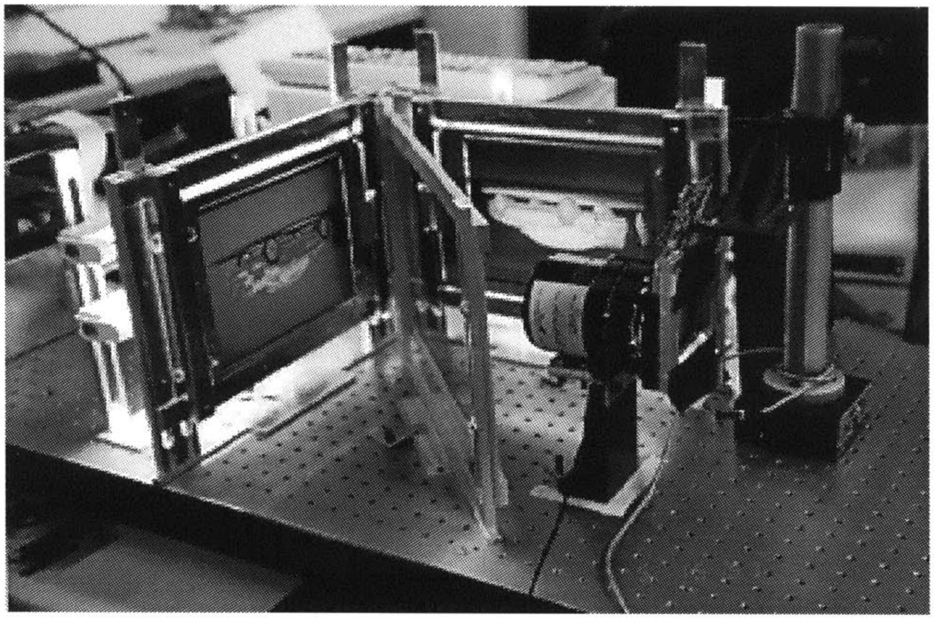

Figure 26 - Closer view of two image LCDs, beamsplitter, projection lens, and viewer-tracking LCD for projection polarization tracking prototype. Image is upside-down red car.

References

Benton, S. A. 1990. Experiments in Holographic Video Imaging. *SPIE Institute Series* Vol. IS 8.

Blundell, B. G., et al. 1993. Volumetric three-dimensional display systems -- their past, present and future. *IEE Science and Engineering Education.* Vol. 2 (5), pp. 196-200.

Collings, Peter J. 1990. *Liquid Crystals - Nature's Delicate Phase of Matter.* Princeton, New Jersey: Princeton University Press.

Ezra, David, et al. February 1995. New Autostereoscopic Display System. *SPIE Proceedings* #2409: Stereoscopic Displays and Applications VI.

Hattori, Tomohiko, et al. December 6, 1993. Stereoscopic Liquid Crystal Display. *Proceedings of the Telecommunications Advancement Organization (TAO) First International Symposium.* pp. S-5-4-3 to -7.

Ives, F. E. April 14, 1903. "Parallax Stereogram and Process for Making Same." U.S. Patent 725,567.

Kollin, J. June 1988. Design and Information Considerations for Holographic Television. Masters thesis, MIT Media Laboratory.

Lipton, Lenny, et al. Stereoscopic Television System. U.S. Patent No. 4,523,226, June 11, 1985.

Mahler, J. Feb. 26, 1935. Stereoscopic Apparatus. U.S. Patent #1,992,872.

Maxwell, James Clerk. 1868. On the Cyclide. *The Quarterly Journal of Pure and Applied Mathematics.* Vol. IX, pp. 111-126, esp. p. 115.

Omori, Shigeru, et al. December 6, 1993. Stereoscopic Liquid Crystal Display System. *Proceedings of the Telecommunications Advancement Organization (TAO) First International Symposium.* pp. E-2-1 to -2.

Potonniee, Georges. 1930. *Louis Ducos du Hauron, his life and work.*

Swan, H. December 4, 1862. Improvements in Stereoscopic Apparatus. British patent #3249.

Tetsutani, Nobuji, et al. November 1994. Wide-screen autostereoscopic display system employing head-position tracking. *Optical Engineering*. Vol. 44, No. 11, pp. 3690-7.

Travis, A. R. L., et al. 1995. Time-Multiplexed Three-Dimensional Video Display. *SID '95 Digest*. pp. 851-4.

Trayner, David J. and Edwina Orr. 1996. Autostereoscopic display using holographic optical elements. *SPIE Proceedings* Vol. 2653, pp. 65-74.

Wheatstone, Charles. On some remarkable, and hitherto unobserved, phenomena of binocular vision (Part the first). *Philosophical Transactions of the Royal Society of London*, 1838, 371-94.

Woodgate, Graham J., et al. 1997. Observer Tracking Autostereoscopic 3D Display Systems. *Preprint paper SPIE* Vol. 3012A.