

Display Technology:

Stereo & 3D Display Technologies

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Introduction

Recently there have been rapid advancements in 3D techniques and technologies. Hardware has both improved and become considerably cheaper, making real-time and interactive 3D available to the hobbyist, as well as to the researcher. There have been major studies in such areas as molecular modeling, photogrammetry, flight simulation, CAD, visualization of multidimensional data, medical imaging, tele-operations such as remote vehicle piloting and remote surgery, and stereolithography. In computer graphics, the improvements in speed, resolution, and economy make interactive stereo an important capability. Old techniques have been improved, and new ones have been developed. True 3D is rapidly becoming an important part of computer graphics, visualization, virtual-reality systems, and computer gaming. Numerous 3D systems are granted patents each year, but very few systems move beyond the prototype stage and become commercially viable. Here we treat the salient 3D systems.

We first discuss the major depth cues that we use to determine depth relationships between objects in a scene.

Depth Cues

The human visual system uses many depth cues to disambiguate the relative positions of objects in a 3D scene. These cues are divided into two categories: physiological and psychological.

Physiological depth cues

Accommodation.

Accommodation is the change in focal length of the lens of the eye as it focuses on specific regions of a 3D scene. The lens changes thickness due to a change in tension from the ciliary muscle. This depth cue is normally used by the visual system in tandem with convergence.

Convergence.

Convergence, or simply *vergence*, is the inward rotation of the eyes to converge on objects as they move closer to the observer.

Binocular disparity.

Binocular disparity is the difference in the images projected on the left and right eye retinas in the viewing of a 3D scene. It is the salient depth cue used by the visual system to produce the sensation of depth, or *stereopsis*. Any 3D display device must be able to produce a left and right eye view and present them to the appropriate eye separately. There are many ways to do this as we will see below.

Motion parallax.

Motion parallax provides different views of a scene in response to movement of the scene or the viewer. Consider a cloud of discrete points in space in which all points are the same color and approximately the same size. Because no other depth cues (other than binocular disparity) can be

used to determine the relative depths of the points, we move our head from side to side to get several different views of the scene (called *look around*). We determine relative depths by noticing how much two points move relative to each other: as we move our head from left to right or up and down; the points closer to us appear to move more than points further away.

Psychological depth cues

Linear perspective.

Linear perspective refers to the change in image size of an object on the retina in inverse proportion to the object's change in distance. Parallel lines moving away from the viewer, like the rails of a train track, converge to a vanishing point. As an object moves further away, its image becomes smaller, an effect called *perspective foreshortening*. This is a component of the depth cue of retinal image size.

Shading and shadowing.

The amount of light from a light source illuminating a surface is inversely proportional to the square of the distance from the light source to the surface. Hence, surfaces of an object that are further from the light source are darker (shading), which gives cues of both depth and shape. Shadows cast by one object on another (shadowing) also give cues to relative position and size.

Aerial perspective.

Distant objects tend to be less distinct, appearing cloudy or hazy. Blue, having a shorter wavelength, penetrates the atmosphere more easily than other colors. Hence, distant outdoor objects sometimes appear bluish.

Interposition.

If one object occludes, hides or overlaps (interposes) another, we assume that the object doing the hiding is closer. This is one of the most powerful depth cues.

Retinal image size.

We use our knowledge of the world, linear perspective, and the relative sizes of objects to determine relative depth. If we view a picture in which an elephant is the same size as a human, we assume that the elephant is further away since we know that elephants are larger than humans.

Texture gradient.

We can perceive detail more easily in objects that are closer to us. As objects become more distant, the texture becomes blurred. Texture in brick, stone, or sand, for example, is coarse in the foreground and grows finer as the distance increases.

Color.

The fluids in the eye refract different wavelengths at different angles. Hence, objects of the same shape and size and at the same distance from the viewer often appear to be at different depths because of differences in color. In addition, bright-colored objects will appear to be closer than dark-colored objects.

The human visual system uses all of these depth cues to determine relative depths in a scene. In general, depth cues are additive; the more cues, the better able the viewer is to determine depth. However, in certain situations some cues are more powerful than others, and this can produce conflicting depth information. Our interpretation of the scene and what we perceive the depth relationships to be as a result of our knowledge of the world can override binocular disparity.

A Technology Taxonomy

The history of 3D displays is well summarized in several works. Okoshi [1], and McAllister [2] each present histories of the development of 3D technologies. Those interested in a history beginning with Euclid will find [3] of interest.

Most 3D displays fit into one or more of three broad categories: Stereo pair, holographic, and multiplanar or volumetric.

Stereo pair based technologies distribute left and right views of a scene to the left and right eyes of the viewer independently. Often special viewing devices are required to direct the appropriate view to the correct eye and block the incorrect view to the opposite eye. If no special viewing devices are required then the technology is called *autostereoscopic*. The human visual system processes the images and if the pair of images is a stereo pair, described below, most viewers will perceive depth. Only one view of a scene is possible per image pair which means that there is no ability for the viewer to change position and see a different view of the scene. We call such images “virtual.” Some displays include head tracking devices to simulate head motion or “look around.” Some technologies allow display of multiple views of the same scene providing motion parallax as the viewer moves the head from side to side. We discuss these technologies below.

In general, holographic and multiplanar images produce “real” or “solid” images, in which binocular disparity, accommodation, and convergence are consistent with the apparent depth in the image. They require no special viewing devices and hence are autostereoscopic. Holographic techniques are discussed elsewhere. Multiplanar methods are discussed in section 6 below.

Stereo Pairs

The production of stereoscopic photographs (stereo pairs or *stereographs*) began in the early 1850’s. Stereo pairs simulate the binocular disparity depth cue by projecting distinct (normally flat) images to each eye. There are many techniques for viewing stereo pairs. One of the first was the stereoscope, which, with the stereo card images, can still be found in antique shops. A familiar

display technology, which is a newer version of the stereoscope, is the View-Master and its associated circular reels (Fig. 1).

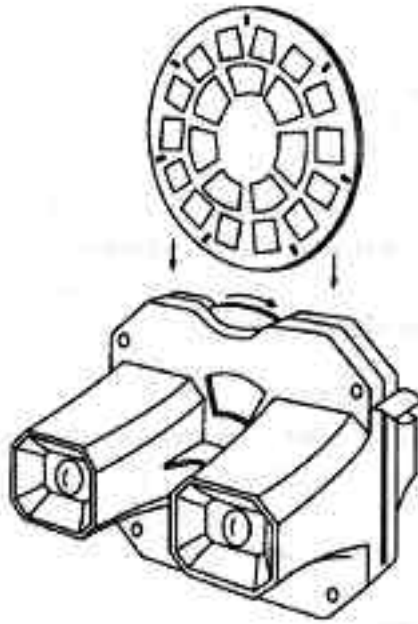


Figure 1 View Master

Since some of the displays described are based on the stereo pair concept, some stereo terminology is appropriate.

Terminology.

Stereo pairs are based on the presentation of two different images, one for the left eye (L) and the other for the right eye (R). Stereo images produced photographically normally use two cameras that are aligned horizontally with identical optics, focus, and zoom. To quantify what the observer sees on the two images, we relate each image to a single view of the scene.

Consider a point P in a scene being viewed by a binocular viewer through a window (such as the film plane of a camera). A point P in the scene is projected on the window surface, normally a plane perpendicular to the observer's line of sight, such as the camera film plane, the face of a CRT or a projection screen. This projection surface is called the *stereo window* or *stereo plane*.. We

assume the y axis lies in a plane that is perpendicular to the line through the observer's eyes. The distance between the eyes is called the *interocular distance*. Assigning a Cartesian coordinate system to the plane, the point P will appear on the left eye view with coordinates (x_L, y_L) and in the right eye view with coordinates (x_R, y_R) . These two points are called *homologous*. The horizontal parallax of the point P is the distance $x_R - x_L$ between the left-and right-eye views, the vertical parallax is $y_R - y_L$ (Fig. 2).

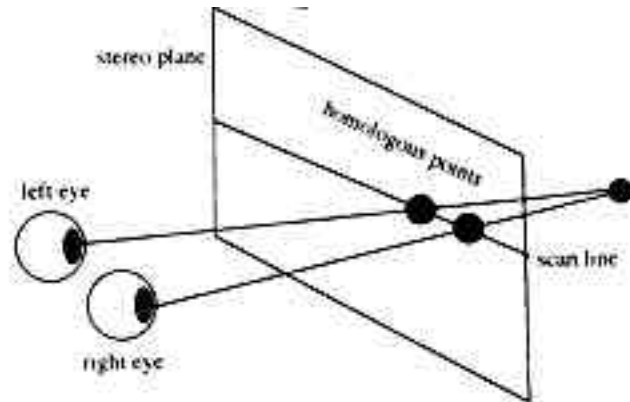


Figure 2 Horizontal Parallax

Positive parallax occurs if the point appears behind the stereo window, the left-eye view being to the left of the right-eye view. Zero parallax occurs if the point is at the same depth as the stereo window, indeed, zero parallax defines the stereo window, and negative parallax occurs if the point lies in front of the stereo window (Fig. 3).

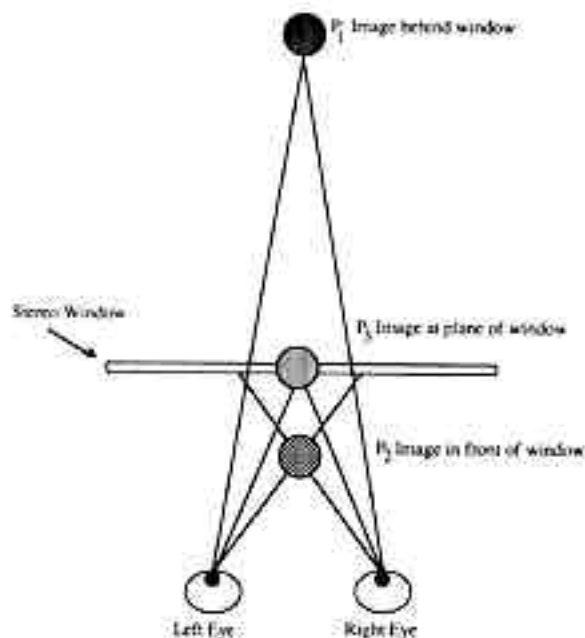


Figure 3 Positive/Negative parallax

Given the geometrical assumptions above, vertical parallax or *vertical disparity* should always be zero. Misaligned cameras can produce nonzero vertical parallax. Observers differ on how much they can tolerate before getting side effects such as headache, eye strain, nausea or other uncomfortable physical symptoms. Henceforth, the term *parallax* will mean horizontal parallax.

If the horizontal parallax is too large and exceeds the maximum parallax, in order to view the points our eyes must go *wall-eyed*, a condition where the eyes each move to the outside to view the image. After lengthy exposure, this can produce disturbing physical side effects. Images in which the parallax is reversed are said to have *pseudo stereo*. Such images can be very difficult to fuse; the human visual system will have difficulty recognizing the binocular disparity. Other depth cues compete and overwhelm the visual system.

Parallax and convergence are the primary vehicles for determining perceived depth in a stereo pair; the observer focuses both eyes on the plane of the stereo window. Hence, accommodation is fixed. In such cases accommodation and convergence are said to be “disconnected,” and the image is “virtual” rather than “solid” (see the section on volumetric images below). This inconsistency between accommodation and convergence can make stereo images difficult for some viewers to fuse. If you cannot perceive depth in a stereo pair, you may be a person who is “stereo-blind” and cannot fuse stereo images (interpret as a 3D image rather than two separate 2D images). There are many degrees of stereo-blindness and the ability or inability to see stereo may depend on the presentation technique, whether the scene is animated, color consistency between the L/R pair and many other considerations.

Computation of Stereo Pairs.

Several methods have been proposed for computing stereo pairs in a graphics environment. Certain perception issues eliminate some techniques from consideration.

A common technique for computing stereo pairs involves the rotation of a 3D scene about an axis parallel to the sides of the viewing screen followed by a perspective projection. This process can cause vertical displacement because of the foreshortening that occurs with a perspective projection. Hence, the technique is not recommended.

Although parallel projection will not produce vertical displacement, the absence of linear perspective can create a "reverse" perspective as the result of a perceptual phenomenon known as Emmert's law: objects that do not obey linear perspective can appear to get larger as the distance from the observer increases. The preferred method for computing stereo pairs is to use two off-axis centers of perspective projection (corresponding to the positions of the left and right eyes). This method simulates the optics of a stereo camera where both lenses are parallel. For further details see [McAL93].

Display Technologies Overview

Separating Left and Right Eye Views

When viewing stereo pairs, a mechanism is required so that the left eye sees only the left eye view and the right eye sees only the right eye view. There are many mechanisms which have been proposed to accomplish this. The ViewMaster uses two images each directed to the appropriate eye by lenses. The images are shown in parallel and there is no way one eye can see any part of the other eye view.

It is common in display technologies to use a single screen to reflect or display both images either simultaneously (time parallel) or in sequence (time multiplexed or field sequential). The technologies used to direct the appropriate image to each eye while avoiding mixing the left and right eye images require sophisticated electro-optics or shuttering. Some of the more common methods are described below.

Cross talk

Stereo cross talk occurs when a portion of one eye view is visible in the other eye. In this case the image can appear blurred or a second or double image appears in regions of the scene being viewed creating a phenomenon called *ghosting*. Cross talk can create difficulty in fusing L/R views. When using the same display surface to project both eye views, cross talk can be a problem. When stereo displays are evaluated, the cross talk issue should be addressed.

Field Sequential Techniques

A popular method for viewing stereo on a single display device is the field-sequential or time multiplexed technique. The L/R views are alternated on the display device, and a blocking mechanism to prevent the left eye from seeing the right eye view and vice versa is required. The technology for field-sequential presentation has progressed rapidly. Historically, mechanical devices were used to occlude the appropriate eye view during display refresh. A comparison of many of these older devices can be found in [4]. Newer technologies use electro-optical methods such as liquid-crystal plates. These techniques fall into two groups: those that use active vs. passive viewing glasses.

In a passive system, a polarizing shutter is attached to the display device as in the case of a CRT or the screen produces polarized light automatically as in the case of an LCD panel. The system polarizes the left and right eye images in orthogonal directions (linear or circular), and the user wears passive polarized glasses where the polarization axes are also orthogonal. The polarizing

lenses of the glasses combine with the polarized light from the display device to act as blocking shutters to each eye. When the left eye view is displayed, the light is polarized along an axis parallel to the axis of the left eye lens and the left eye sees the image on the display. Since the axis is orthogonal to the polarizer of the right eye, the image is blocked to the right eye.

The passive system permits several people to view the display simultaneously and allows a user to easily switch viewing from one display device to another since no synchronization with the display device is required. It also permits a larger field of view (FOV). The drawback is that the display device must produce a polarized image. Projector mechanisms must have polarizing lenses and CRT or panel displays must have a polarizing plate attached to or hanging in front of the screen or the projector. When projecting an image on a screen, the screen must be coated with a material (vapor deposited aluminum) that does not depolarize the light (the commercially available "silver" screen). Polarization has the added disadvantage that the efficiency or *transmission* is poor; the intensity of the light to reach the viewer compared to the light emitted from the display device is very low, often in the range of 30%. Hence, images appear dark.

LCD's can also be used as blocking lenses. An electronic pulse provided by batteries or a cable cause the lens to "open" or admit light from the display device. When no electronic pulse is present, the lens is opaque, blocking the eye from seeing the display device. The pulses are alternated for each eye while the display device alternates the image produced. The glasses must be synchronized to the refresh of the display device normally using an infrared signal or a cable connection. For CRT based systems this communication is accomplished using the stereo-sync or Left/ Right (L/R) signal. In 1997 the Video Equipment Standards Association (VESA) called for the addition of a standard jack that incorporates the L/R signal along with a + 5 volt power supply output. With this new standard, stereo equipment can be plugged directly into a stereo-ready video card that has this jack.

Active glasses have an advantage that the display device does not have to polarize the light before it reaches the viewer. Hence, efficiency is higher and back projection can be used effectively. The disadvantage is obviously the synchronization requirement.

While the initial cost of the passive system is higher the cost to add another user is inexpensive. This makes the passive system a good choice for theaters and trade shows, for example, where one does not want to expose expensive eyewear to abuse.

In both systems, if the images are delivered at a sufficiently fast frame rate (120 Hz) to avoid flicker, the visual system will fuse the images into a three-dimensional image. Most mid- to high-end monitors can do this. A minimum of 100 Hz is acceptable with active eyewear systems. One may be able to use 90 Hz with a passive system without perceiving flicker even in a well-lit room.

Time-Parallel Techniques

Time-parallel methods present both eye views to the viewer simultaneously and use optical techniques to direct each view to the appropriate eye.

3D movies often used the *anaglyph* method, which requires the user to wear glasses with red and green lenses or filters. Both images were presented on a screen simultaneously; hence, it is a time-parallel method. Many observers suffered headaches and nausea when leaving the theater, which gave 3D, and stereo in particular, a bad reputation. (A phenomenon called ghosting or cross talk was a significant problem. Colors were not adjusted correctly and the filters did not completely eliminate the opposite-eye view, so that the left eye saw not only its image but sometimes part of the right-eye image as well. Other problems included poor registration of the left and right eye images causing vertical parallax and projectors out of synch.) The View Master is another example of a time-parallel method.

An early technique for viewing stereo images on a CRT was the half-silvered mirror originally made for viewing microfiche [4]. The device had polarizing sheets, and the user wore polarized glasses that distributed the correct view to each eye.

Polarizing filters can also be attached to glass-mounted slides. Incorrect positioning of the projectors relative to the screen can cause *keystoning*, in which the image is trapezoidal shaped caused by foreshortening resulting in vertical parallax.

If more than one projector is used, as is often the case when projecting 35 mm. stereo slides, for example, orthogonal polarizing filters are placed in front of each projector and both left and right eye images are projected onto a nondepolarizing screen simultaneously. Hence, the technique is time-parallel. The audience wears passive glasses in this case. Using more than one projector always brings with it the difficulties of adjusting the images. L/R views should be correctly *registered*; there must be minimal luminosity differences, minimal size differences, minimal keystoneing, minimal vertical parallax, minimal ghosting, and so forth.

Most non-autostereoscopic display systems use one of the above methods. We indicate which method below.

3D Displays

Viewing Devices required

Hardcopy

Anaglyphs

The anaglyph method has been used for years to represent stereo pairs and it was a salient technique in old 3D movies and comic books. Colored filters cover each eye, red/green, red/blue or red/cyan filters being the most common. One eye image is displayed in red and the other in green, blue or cyan so that the appropriate eye sees the correct image. Since both images appear simultaneously, it is a time-parallel method. The technique is easy to produce using simple image

processing techniques and the cost of viewing glasses is very low. Grayscale images are most common. Pseudo color or *poly-chromatic* anaglyphs are becoming more common. If correctly done, anaglyphs can be an effective method for presenting stereo images.

Vectographs

Polaroid's Vectograph process was introduced by Edwin Land in 1940. The earliest Vectograph images used extensively were black-and-white polarizing images formed by iodine ink applied imagewise to oppositely oriented polyvinyl alcohol (PVA) layers laminated to opposite sides of a transparent base material. The iodine forms short polymeric chains that readily align with the oriented polymeric molecules and stain the sheet. The chemistry is analogous to that of uniformly stained iodine polarizers, such as Polaroid H-sheet, used in polarizing filters for stereo projection and in 3-D glasses used for viewing stereoscopic images (see [2] for more details).

In 1953 Land demonstrated three-color Vectograph images formed by successive transfer of cyan, magenta, and yellow dichroic dyes from gelatin relief images to Vectograph sheet. Unlike StereoJet digital inkjet printing described below, preparation of Vectograph color images required lengthy, critical photographic and dye transfer steps. Although the process produced excellent images, it was never commercialized.

StereoJet

The StereoJet process, developed at the Rowland Institute for Science in Cambridge, Massachusetts, provides stereoscopic hardcopy in the form of integral, full-color polarizing images. StereoJet images are produced by inkjet printing, forming polarizing images by the use of inks formulated with dichroic dyes. Paired left-eye and right-eye images are printed onto opposite surfaces of a multilayer clear substrate, as shown in Fig. 4.

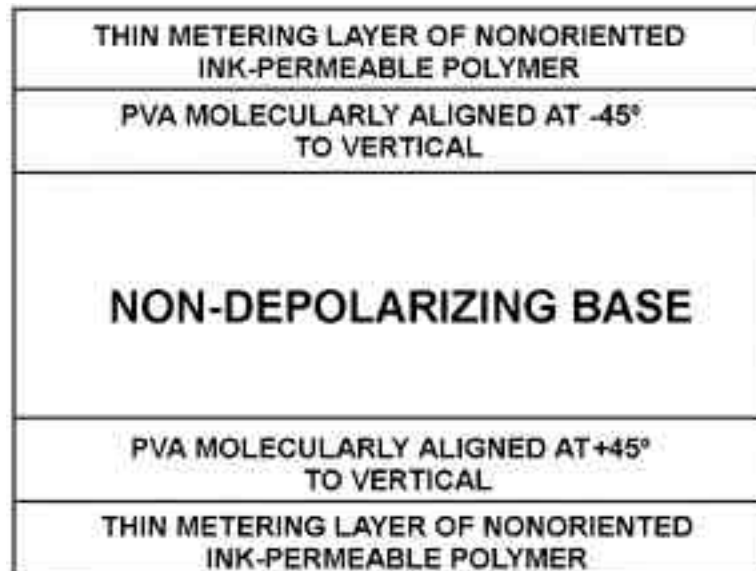


Figure 4 StereoJet substrate

The two outer layers, formed of an ink-permeable polymer such as carboxymethylcellulose, meter the ink as it penetrates the underlying image-receiving layers. The image-receiving layers are formed of polyvinyl alcohol (PVA) molecularly oriented at 45 degrees to the edge of the sheet. As the dye molecules are adsorbed they align with the oriented polymer molecules and assume the same orientation. The two PVA layers are oriented at 90 degrees to one another, so that the images formed have orthogonal polarization.

StereoJet transparencies are displayed directly by rear illumination or projected by overhead projector onto a non-depolarizing screen, such as a commercially available lenticular “silver” screen. No attachments to the projector are needed, as the images themselves provide the polarization. StereoJet prints for viewing by reflected light have aluminized backing laminated to the rear surfaces of StereoJet transparencies.

ChromaDepth

Chromostereoscopy is a phenomenon in optics commercialized by Richard Steenblik [2]. The technique originally used double prism-based glasses which slightly deflect different colors in an

image, laterally displacing the visual positions of differently colored regions of an image by different amounts. The prisms are oriented in opposite directions for each eye, resulting in different images being presented to each eye, thereby creating a stereo pair (Fig. 5). Production chromostereoscopic glasses, marketed under the name ChromaDepth 3-D, utilize a unique micro-optic film that performs the same optical function as double prism optics without the attendant weight and cost. Images designed for viewing with the ChromaDepth 3-D Glasses use color to encode depth information. A number of color palettes have been successfully employed, the simplest of which is the RGB on Black palette: on a black background red will appear closest, green in the middleground, and blue in the background. Reversal of the optics results in the opposite depth palette: BGR on Black.

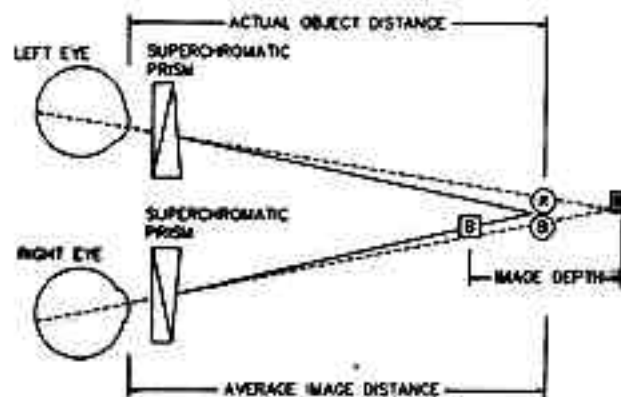


Figure 5 Superchromatic glasses

A peculiar feature of the ChromaDepth 3-D process is that the user does not have to create a stereo pair. A single ChromaDepth 3-D color image contains X, Y, and Z information by virtue of the image contrast and the image colors. The stereo pair seen by the user is created by the passive optics in the ChromaDepth 3-D Glasses. The primary limitation of the ChromaDepth 3-D Process is that the colors in an image cannot be arbitrary if they are to carry the image's Z dimension, so the method will not work on arbitrary images. The best effects are obtained with images that are specifically designed for the process and with natural images, such as underwater reef photographs, that have natural coloring fitting the required palette.

Another limitation is that some color “fringing” can occur when viewing CRT images. The light emitted from a CRT consists of different intensities of red, green, and blue; any other color created by a CRT is a composite of two or more of these primary colors. If a small region of a composite color, such as yellow, is displayed on a CRT, the ChromaDepth 3-D Glasses optics may cause the composite color to separate into its primary components, blurring the region. ChromaDepth 3-D High Definition Glasses reduce this problem by placing most of the optical power in one eye, leaving the other eye to see the image clearly.

The ChromaDepth 3-D technique can be used in any color medium. It has found wide application for use with laser shows and with print, video, television, computer graphic, photographic slide, and Internet images. Many areas of research have benefited from the use of ChromaDepth 3-D, including interactive visualization of geographic and geophysical data

Transparency Viewers

Cheap plastic and cardboard slide viewers are available for viewing 35 mm. stereo slides from many companies like Reel 3D Enterprises (<http://stereoscopy.com/reel3d/index.html>). The user places the left eye view in the left slot and the right eye view in the right slot and then holds them up to the light. This is a standard technique for checking the mounding of slides for correct registration.

Field Sequential Devices

StereoGraphics Systems

Although there are many manufacturers of active and passive glasses systems, StereoGraphics is a well known company that has produced high quality CRT and RGB projector based stereo systems for years. The quality of their hardware is excellent and we report on it here.

The active StereoGraphics shutters called CrystalEyes (Fig. 6) are doped, twisted-nematic devices. They “open” in about 3 ms and “close” in about 0.2 ms. The shutter transition occurs within the vertical blanking period of the display device and is all but invisible. The principal figure of merit for such shutters is the dynamic range, which is the ratio of the transmission of the shutter in its open state to its closed state. The CrystalEyes system is in excess of 1000:1. The transmission of the shutters is commonly 32%, but because of the 50% duty cycle the effective transmission is half that. Their transmission should be neutral and impart little color shift to the image being viewed.

The field of view (FOV) varies also. Ninety-seven degrees is typical. SGI can operate at a speed of up to 200 fields per second. The cost for eyewear and emitter is \$1000.



Figure 6 Active Glasses CrystalEyes System

Passive systems have a lower dynamic range than active eyewear systems. The phosphor afterglow on the CRT causes ghosting, or image cross talk, in this type of system. In order to minimize the time that the modulator is passing an unwanted image, electrode-segmentation can be used. The modulator's segments change state moments before the CRT's scanning beam arrives at that portion of the screen. The consequence of this action is a modulator that changes state just as the information is changing. This increases the effective dynamic range of the system and produces a high quality stereo image. This technique is used by StereoGraphics in their ZScreen system (Fig. 7). A Monitor ZScreen system costs \$2200



Figure 7 Passive Glasses ZScreen System

On personal computers that do not have a stereo sync output, the above-and-below format is used. The left image is placed on the top half of the CRT screen and the right image on the bottom half, thus reducing the resolution of the image. Chasm Graphics makes a software program called Sudden Depth that will format the images in this way. Now, the stereo information exists but needs an appropriate way to send each L/R image to the proper eye. The StereoGraphics EPC-2 performs this task.

The EPC-2 connects to the computer's VGA connector and intercepts the vertical sync signal. When enabled, the unit adds an extra vertical sync pulse halfway between the existing pulses. The result causes the monitor to refresh at twice the original rate. This in effect stretches the two images to fill the whole screen and show field sequential stereo. The EPC-2 acts as an emitter for CrystalEyes or can be used a device to create a left / right signal to drive a liquid crystal modulator

or other stereo product. The EPC-2 is the same size as the other emitters and has approximately the same range. The cost is \$400.

The Pulfrich Technique

Retinal sensors require a minimum number of light photons to fire and send a signal to the visual system. By covering one eye with a neutral density filter (like a lens in a pair of sunglasses), the light from a source will be slightly time delayed to the covered eye. Hence, if an object is in motion in a scene, the eye with the filter cover will see the position of the object later than the uncovered eye. Therefore, the images perceived by the left and right eyes will be slightly different and the visual system will interpret the result as a stereo pair.

If the motion of an object on a display device is right to left and the right eye is covered by the filter, then a point on the object will be seen by the left eye before the right eye. This will be interpreted by the visual system as positive parallax and the object will appear to move behind the stereo window. Similarly, an object moving from left to right will appear in front of the display device. The reader can implement the technique easily using one lens of a pair of sunglasses while watching TV.

The Fakespace PUSH Display

Fakespace Lab's PUSH desktop display uses a box shaped binocular viewing device with attached handles which is mounted on a triad of cylindrical sensors (Fig. 8) The device allows the user to move the viewing device and simulate limited movement within a virtual environment. The field of view can be as large as 140 degrees on CRT based systems. The cost is \$25,000 US for the 1024x768 CRT and \$9,995 US for the 640x480 LCD version

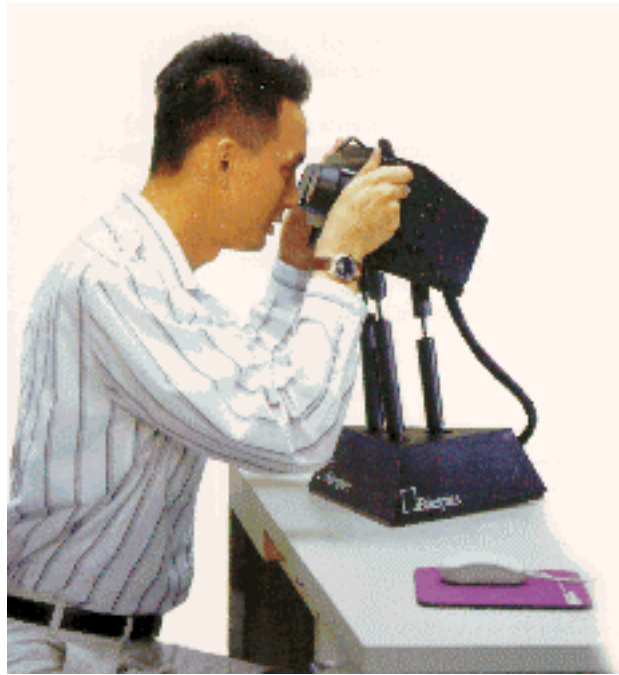


Figure 8 The Fakespace Lab's PUSH Desktop Display

A variation which permits more viewer movement is the Boom (Fig. 9). The binocular viewing device is attached to a large arm configured like a 3D digitizer that signals the position of the viewer using sensors at the joints of the arm. The viewer motion is extended to a circle with 6' diameter. Vertical movement is limited to 2.5'. The Boom sells for \$60,000 US. A hands free version is available for \$85,000 US.



Figure 9 Fakespace Lab's Boom

Work Bench Displays

Smaller adjustable table based systems such as the Fakespace ImmersaDesk R2 and ImmersaDes M1 are available (fig. 10). The systems use the active glasses stereo technique. The fully portable R2 sells for approximately \$140,000 US, including tracking. The Mini WorkBench sells for \$62,995 US.



Figure 10 Fakespace ImmersaDesk R2

VREX Micropolarizers

VREX has patented what they call the μ Pol (micropolarizer) technology, an optical device that can change the polarization of an LCD display on a line by line basis. It is a periodic array of microscopically small polarizers that spatially alternate between mutually perpendicular polarizing states. The size of each micropolarizer can be as small as 10 millionths of a meter. Hence, a μ Pol could have more than 6 million micropolarizers of alternating polarization states per square inch in a checkerboard configuration of over 2500 lines per inch in a one-dimensional configuration. In practice, the μ Pol encodes the left eye image on even lines and the right eye image on odd lines. Passive polarized glasses are needed to view the image.

The format requires a single-frame stereoscopic image format that combines a left-eye perspective view with a right-eye perspective view to form a composite image, which contains both left and right-eye information alternating on a line-by-line basis. VREX provides software utilities

to combine left and right eye views into a single image. All VREX hardware supports this image format.

The advantages of μ Pol include the ability to run at lower refresh rates since both eyes are presented with a (lower resolution) image simultaneously and hence the presentation is time-parallel.

Large Format Displays

One of the objects of virtual reality is to attempt to give the user the feeling of immersion in a scene. This has been accomplished in various ways, head mounted displays being a common solution. In general, head mounted displays have a limited field of view and are low resolution. In addition, allowing the user to move in space requires position tracking which has been a difficult problem to solve. Position tracking results in image lag which is a result of the times required to sense that the viewer's position has changed, signal the change to the graphics system, render the scene change and then transmit it to the head mounted display. Any system that must track the viewer and change the scene accordingly must treat this problem. The lag can produce motion sickness in some people.

Projection systems have been developed that use large projection surfaces to simulate immersion. In some cases the user is permitted to move about. In others, the user is stationary and the scene changes.

IMAX

Most readers are familiar with the large screen IMAX system that employs a large flat screen to give the illusion of peripheral vision. When projecting stereo, IMAX uses the standard field-

sequential polarized projection mechanism where the user wears passive glasses. Similar techniques are used in the Kodak flat screen 3D movies at Disney.

Fakespace Systems Displays

Fakespace Systems markets immersive displays that are similar to immersive technologies produced by several other companies.

An extension of flat screen stereo is the walk-in, fully immersive CAVE. The Cave system was developed at the Electronic Visualization Lab at the U. of Illinois where the user is in a 10' x 10' room with flat walls (Figs. 11, 12). A separate stereo image is back projected onto each wall, the floor and possibly the ceiling giving the user the feeling of immersion. Image management is required so that the scenes on each wall fit together seamlessly to replicate the single surrounding environment. Since the system uses back projection, it requires active shuttering glasses. The user can interact with the environment using 3D input devices such as gloves and other navigational tools. The system sells for approximately between \$325,000 and \$500,000 US, depending on the projection systems used.

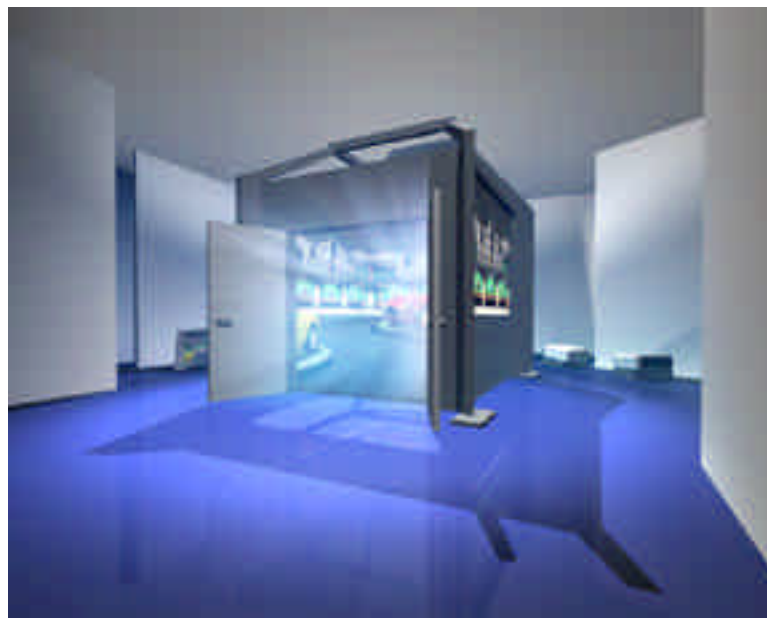


Figure 11 Fakespace CAVE, Front View



Figure 12 Fakespace CAVE - Inside

Fakespace also produces an immersive WorkWall with a screen size of up to 8' x 24' (Fig. 13). The system uses two or more projectors with images blending to create a seamless image. As in the CAVE, the user can interact with the image using various 2 and 3D input devices. Cost is approximately \$290,000 US for an 8' by 24' 3 projector system.



Figure 13 The Fakespace WorkWall

The VisionDome

Elumens Corporation Vision Series displays ([5],[6], [7], [8]), use a hemispherical projection screen with a single projection lens. Previous dome-based systems relied on multiple projectors and seamed-together output from multiple computers, making them both complicated to configure and prohibitively expensive. The high cost, complexity, and non-portability of these systems made them suitable for highly specialized military and training applications, but they were impractical and out of reach for most corporate users. Available in sizes from 1.5 to 5 meters in diameter which accommodate from one to forty people, the VisionDome systems range in price from US \$15,000 to US \$300,000.

The projector is mounted with a patented "fisheye" lens that provides a 180-degree field of view. This single projection source completely fills the concave screen with light. Unlike other fisheye lenses, whose projections produce focal "hot spots" and non-linear distortions, the Vision Series lens uses linear angular projection to provide uniform pixel distribution and uniform pixel size across the entire viewing area. The lens also provides an infinite depth of field, so images remain in focus on screens from .5 meters away to theoretical infinity at all points on the projection surface.

The single-user VisionStation displays 1024x768 pixels at 1000 lumens, while larger 3 to 5 meter VisionDomes display up to 1280x1024 pixels at 2000 lumens (Fig. 14).

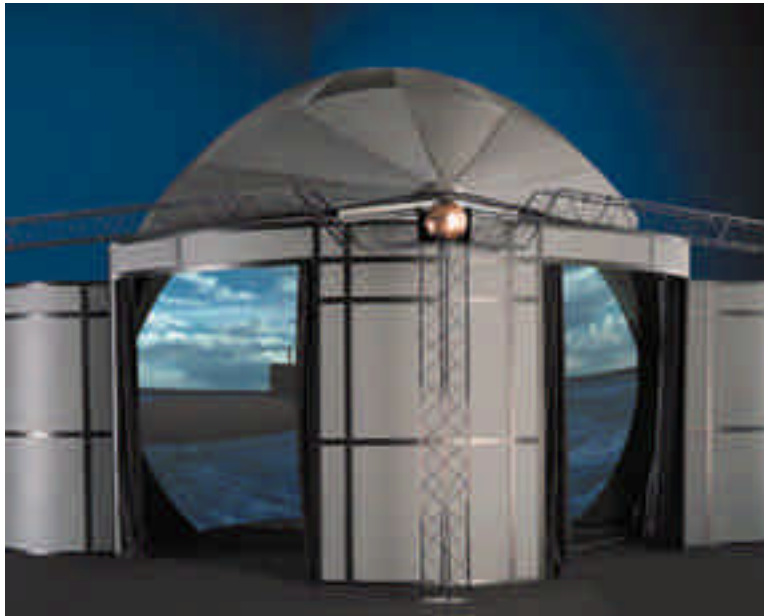


Figure 14 The VisionDome

Elumens provides an application programming interface called SPI (Spherical Projection of Images). Available for both OpenGL and DirectX applications, SPI is an image-based methodology for the display of 3D data on a curved surface. It enables off-axis projection, permitting arbitrary placement of the projector on the face plane of the screen. The image-based projection is dependent on viewer position; if the viewer moves, the image must change accordingly or straight lines become curved. The number of viewers within the viewing “sweet spot” increases with the screen diameter.

Frame sequential stereo imaging with synchronized shutter glasses is supported on Elumens products. The maximum refresh rate currently supported is 85 Hz (42.5 Hz stereo pair). Passive stereo, projecting left and right eye images simultaneously but with opposite polarizations, is currently under development.

Autostereoscopic Displays

No viewing devices required

Hardcopy

Free Viewing

With practice, most readers can view stereo pairs without the aid of blocking devices using a technique called *free viewing*. There are two types of free viewing, distinguished by how the left and right eye images are arranged. In *parallel*, or *uncrossed* viewing the left eye image is to the left of the right eye image. In *transverse* or *cross* viewing, they are reversed and crossing the eyes to form an image in the center is required. Some people can do both types of viewing, some only one, some neither. In Fig. 15, the eye views have been arranged in left/right/left order. To parallel view, look at the left two images. To cross view, look at the right two images.

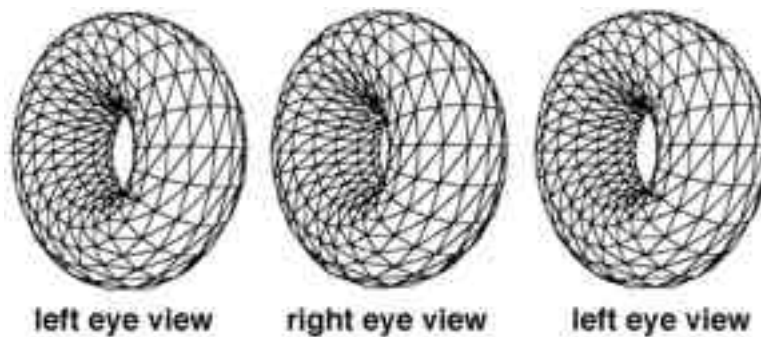


Figure 15 Free viewing examples

Figure 16 is a *random dot autostereogram* in which the scene is encoded in a single image as opposed to a stereo pair [9]. There are no depth cues other than binocular disparity. Using cross viewing, merge the two two dots beneath the image to view the functional surface. Crossing your eyes even further will produce other images. (See [10] for a description of how to generate these interesting images).

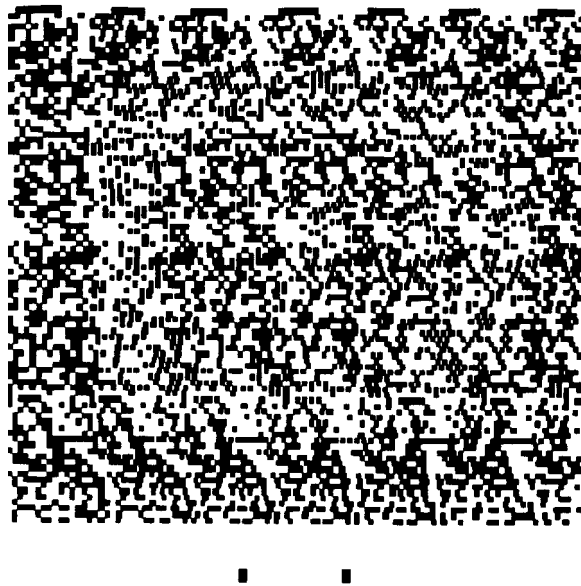


Figure 16 A random dot autostereogram

$$\text{Cos}[(x^2 + y^2)^{(1/2)}] \text{ for } -10 \leq x, y \leq 10$$

Holographic Stereograms

Most readers are familiar with holographic displays, which reconstruct solid images. Normally a holographic image of a three dimensional scene will have the “look around” property. A popular combination of holography and stereo pair technology, called a *holographic stereogram*, involves recording a set of 2D images, often perspective views of a scene, on a piece of holographic film. The film can be bent to form a cylinder so the user can walk around the cylinder

to view the scene from any aspect. At any point the left eye will see one view of the scene and the right eye another or the user is viewing a stereo pair.

Conventional display holography has long been hampered by many constraints such as limitations with regard to color, view angle, subject matter limitations, and final image size. Even with the proliferation of holographic stereogram techniques in the 1980s, the majority of the constraints remained. Zebra Imaging, Inc. expanded on the developments in one-step holographic stereogram printing techniques and has developed the technology to print digital full-color reflection holographic stereograms with a very wide view angle (up to 110°), unlimited in size, and with full parallax.

Zebra Imaging's holographic stereogram technique is based on creating an array of small (1mm or 2mm) square elemental holographic elements (hogels). Much like the pixels of two-dimensional digital images, hogel arrays can be used to form complete images of any size and resolution. Each hogel is a reflection holographic recording on pan-chromatic photopolymer film. The image recorded in each hogel is of a two-dimensional digital image on a spatial light modulator (SLM) illuminated with laser light in the three primary colors: red, green, and blue (Figure 17)

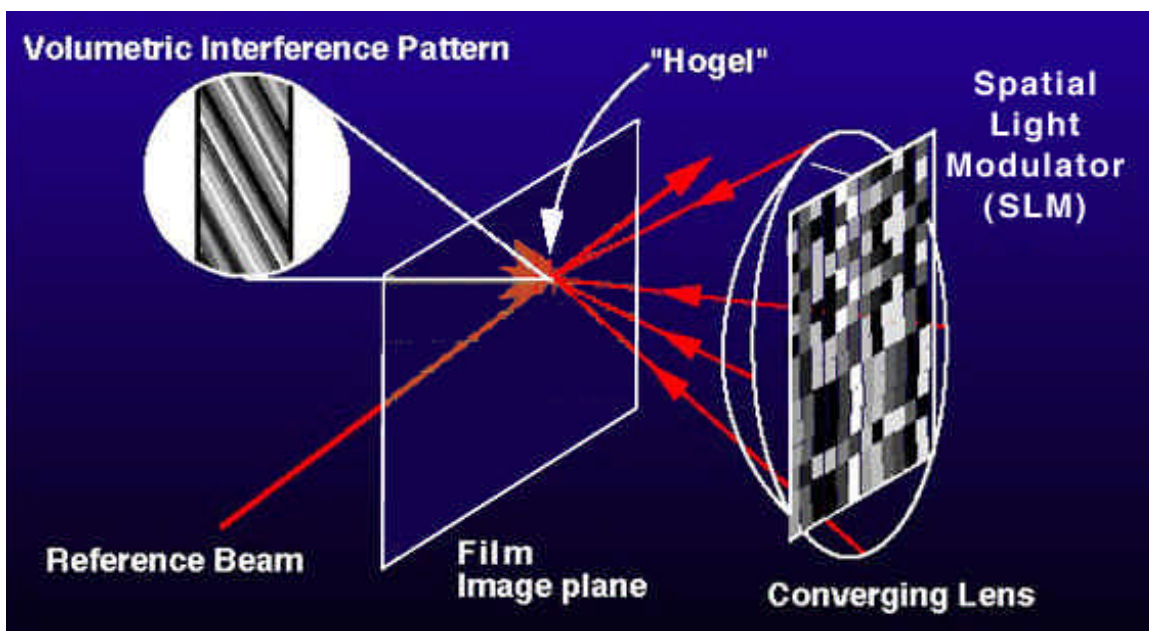


Figure 17 Zebra Imaging holographic stereogram recording

Parallax Barrier Displays

A parallax barrier [2] consists of a series of fine vertical slits in an otherwise opaque medium. The barrier is positioned close to an image that has been recorded in vertical slits and back lit. If the vertical slits in the image have been sampled with the correct frequency relative to the slits in the parallax barrier, and the viewer is the required distance from the barrier, then the barrier will occlude the appropriate image slits to the right and left eyes respectively and the viewer will perceive an autostereoscopic image (Fig. 18). The images can be made panoramic to some extent by recording multiple views of a scene. As the viewer changes position, different views of the scene will be directed by the barrier to the visual system. The number of views is limited by the optics and, hence, moving horizontally beyond a certain point will produce “image flipping” or a cycling of the different views of the scene.

High resolution laser printing has made it possible to produce very high quality images: the barrier is printed on one side of a transparent medium and the image on the other. This technique was pioneered by Artⁿ in the early 1990's to produce hard copy displays and is now being used by Sanyo for CRT displays.

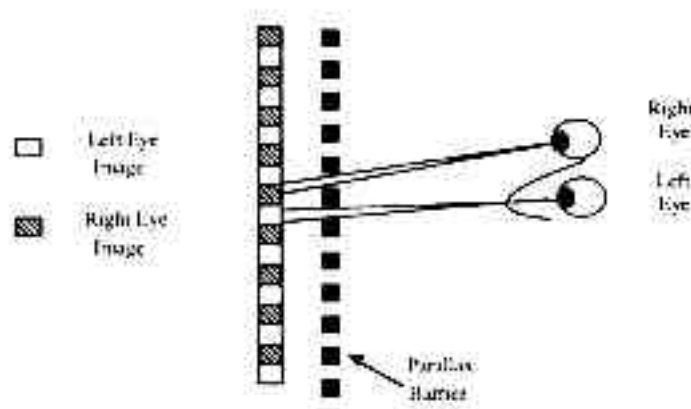


Figure 18 Parallax Barrier Display

Lenticular Sheets

A *lenticular sheet* ([1], [2]) consists of a series of semi-cylindrical vertical lenses called “lenticles,” typically made of plastic. The sheet is designed so the parallel light entering the front of the sheet will be focused onto strips on the flat rear surface (Fig. 19). By recording an image in strips consistent with the optics of the lenticles as in the case of the parallax barrier display, an autostereoscopic panoramic image can be produced. Because the displays depend on refraction vs. occlusion the brightness of a lenticular sheet display is usually superior to the parallax barrier and requires no back-lighting. Such displays have been mass produced for many years for such hardcopy media as postcards.

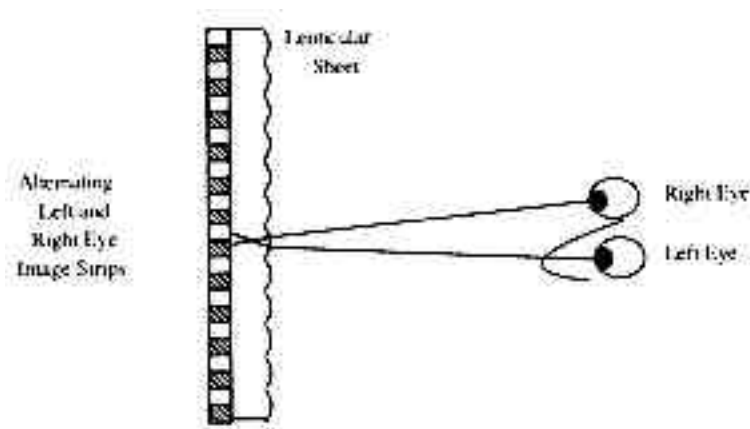


Figure 19 Lenticular Sheet Display

In these two techniques the image is recorded in strips behind the parallax barrier or the lenticular sheet. Although the techniques are old, recent advances in printing and optics have increased their popularity for both hardcopy and autostereoscopic CRT devices.

In both the lenticular and parallax barrier cases, multiple views of a scene can be included providing motion parallax as the viewer moves his/her head from side to side creating what is called a *panoramagram*. Recently, parallax barrier liquid-crystal imaging devices have been developed that can be driven by a microprocessor and used to view stereo pairs in real time without glasses. Some of these techniques are discussed later.

Alternating Pairs

The output from two vertically mounted video cameras are combined. A integrating circuit was designed to merge the two video streams by recording a fixed number of frames from one camera followed by the same number of frames from the other camera. The technique imparts a vertical rocking motion to the image. If the scene has sufficient detail and the speed of the rocking motion and the angle of rotation is appropriate for the individual viewing the system, most viewers will fuse a 3D image. The system was commercialized under the name VISIDEP. The technique can be improved using graphical and image processing methods. More details can be found in [2].

Moving Slit Parallax Barrier

A variation of the parallax barrier is a mechanical moving slit display popularized by Homer Tilton he called the Parallactiscope [2]. A single vertical slit is vibrated horizontally in front of a point plotting output display such as a CRT or oscilloscope. The image on the display is synchronized with the vibrating to produce an autostereoscopic image. Many variants have been proposed but to date the author knows of no commercially viable products using the technique.

The DTI System

The Dimension Technologies, Inc. (DTI) illuminator is used to produce what is known as a multiperspective autostereoscopic display. Such a display produces multiple images of a scene, each of which is visible from a well defined region of space called a viewing zone. The images are all 2D perspective views of the scene as it would appear from the center of the zones. The viewing zones are of such a size and position that an observer sitting in front of the display always has one eye in one zone and the other eye in another. Since the two eyes see different images with different perspective, a 3D image is perceived.

The DTI system is designed for use with an LCD or other transmissive display. The LCD is illuminated from behind, and the amount of light passing through individual elements is controlled in order to form a full color image.

The DTI system uses an LCD back-light technology which they call parallax illumination [11]. Figs. 20 and 21 illustrate the basic concept. As shown in Figure 20, a special illuminator is located behind the LCD.

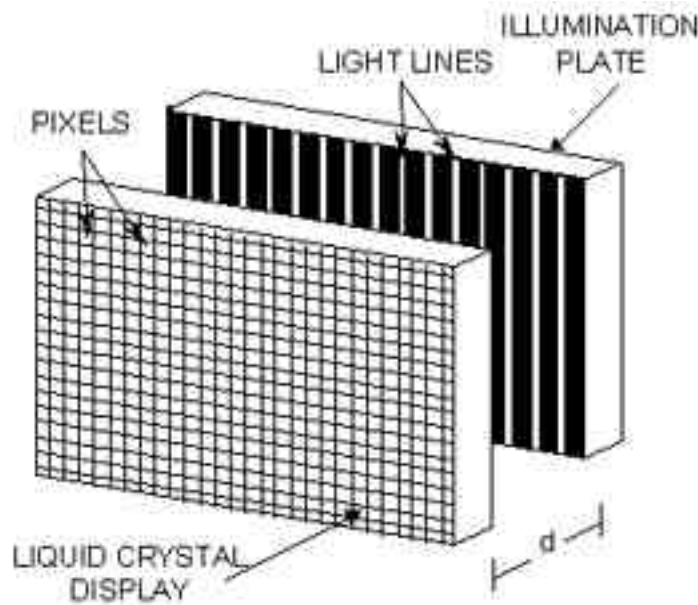


Figure 20 DTI Illuminator

The illuminator generates a set of very thin, very bright, uniformly spaced vertical lines. The lines are spaced with respect to pixel columns such that (because of parallax) the left eye sees all the lines through the odd columns of the LCD while the right eye sees them through even columns. There is a fixed relation between the distance of the LCD to the illumination plate, and the distance of the viewer from the display. This in part determines the extent of the "viewing zones." As shown in Fig. 21,

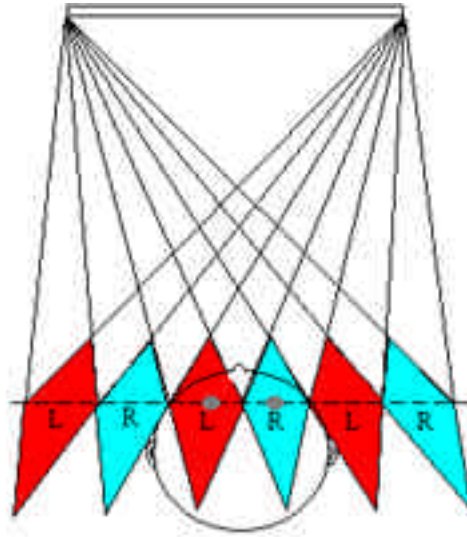


Figure 21 Viewing Zones

viewing zones are diamond shaped areas in front of the display where all the light lines are seen behind the odd or even pixel columns of the LCD.

To display 3D images, left and right eye images of a stereoscopic pair are placed on alternate columns of elements. The left image appears on the odd columns, while the right image is displayed on even columns. Both left and right images are displayed simultaneously and hence the display is time parallel. Since the left eye sees the light lines behind the odd columns, it only sees the left eye image displayed on the odd columns. Similarly, the right eye, sees only the right eye image displayed on the even columns.

The 2D/3D Back-light System

There are many ways to create the precise light lines described above. One method that is used in DTI products is illustrated in Figure 22 ([12], [13]). The first component is a standard off the shelf back-light of the type used for conventional 2D LCD monitors. This type of back-light uses one or two miniature fluorescent lamps as light sources in combination with a flat, rectangular light guide. For large displays, two straight lamps along the top and bottom of the guide are typically

used. For smaller displays a single U shaped lamp is typically used. An aluminized reflector is placed around the lamp(s) to reflect light into the light guide

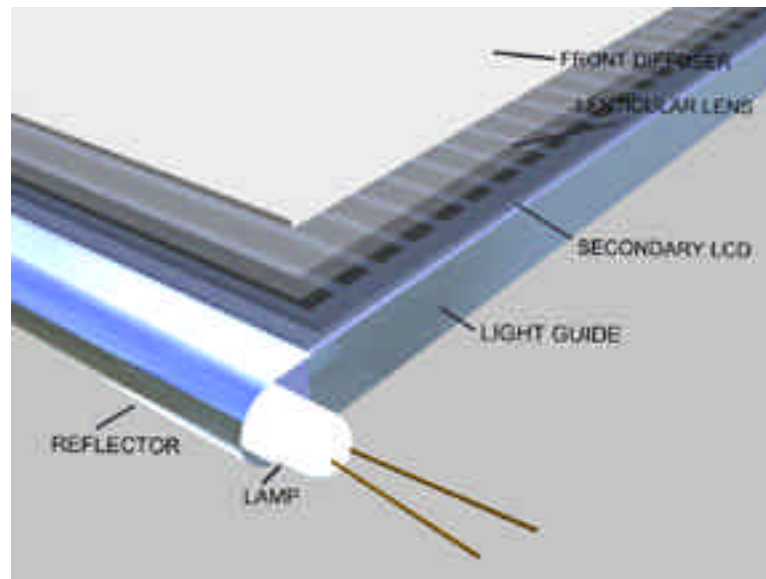


Figure 22 Back-light System

The flat, rectangular light guide is typically made of acrylic or some other clear plastic. Light from the lamp enters the light guide from the sides and travels through it due to total internal reflection from the front and back surfaces of the guide.

The side of the light guide facing away from the LCD possesses a pattern of reflective structures designed to reflect light into the guide and out the front surface. Several possible choices for such structures exist, but current manufacturers usually use a simple pattern of white ink dots applied to the rear surface of the light guide in combination with a white reflective sheet placed behind the light guide.

The second component is a simple, secondary LCD which, when in the “on” state, displays a pattern of dozens of thin, transparent lines with thicker opaque black stripes between them. These lines are used for 3D imaging as described in the previous section

The third major component is a lenticular lens, again shown in Figure 5.8. This lens consists of a flat substrate upon the front surface of which are molded hundreds of vertical, parallel cylindrical lenslets. Light coming through the dozens of thin transparent lines on the secondary LCD is re-

imaged into thousands of very thin, evenly spaced vertical lines by a lenticular lens array spaced apart from and in front of the secondary LCD. The lines can be imaged onto an optional front diffuser located in a plane at one focal length from the lenticular lenslets. The pitch (center to center distance) of the lines on the light guide and the lenticular lenses must be chosen so that the pitch of the light lines re imaged by the lenticular lenslets bears a certain relationship to the pitch of the LCD pixels.

Since the displays will likely all be used for conventional 2D applications (such a word processing and spreadsheets) as well a 3D graphics, the system must be capable of generating illumination in such a way that each eye sees all the pixels of the LCD so that a conventional full resolution 2D image can be displayed with conventional software.

Note that when the secondary LCD is off, in other words in the clear state where the lines are not generated, the even diffuse light from the back-light passes through it freely, and remains even and diffuse after being focused by the lenticular lens. Therefore, when the secondary LCD is off, no light lines are imaged and the observer sees even, diffuse illumination behind all the pixels of the LCD. Therefore, each of the observer's eyes can see all the pixels on the LCD and full resolution 2D images can be viewed.

DTI sells two displays: a 15" at \$1699, with optional video input at \$300 extra, and an 18.1" at \$6999 video included. Both have 2D and 3D modes and accept the standard stereo formats (field sequential, frame sequential, side by side, top/bottom).

Seaphone Display

Fig. 23 shows a schematic diagram of the Seaphone display ([14], [15], [16]).

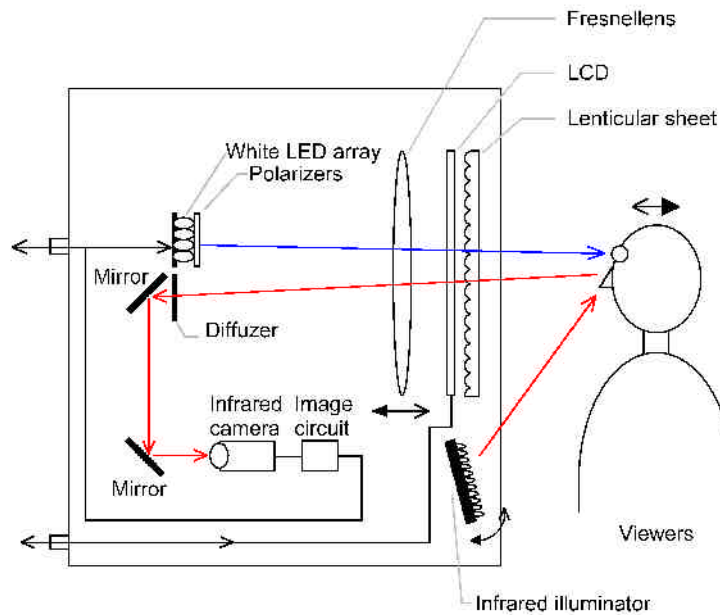


Figure 23 A schematic of the Seaphone Display

A special transparent μ Pol-based color liquid crystal imaging plate (LCD:SVGA 800x600) with a lenticular sheet and a special back-light unit is used to produce a perspective image for each eye. The lenticular sheet creates vertical optical scattering. Horizontal strips of two types of micropolarizers, with orthogonal polarization axes, are transmitted on odd vs. even lines of the LCD. The back-light unit consists of a large format convex lens and a white LED array filtered by the polarizers with the same axes of polarization of the μ Pol array. The large format convex lens is arranged so that an image of the viewers is focused on the white LED array.

The light from the white LED array illuminates the right half face of the viewer using the odd (or even) field of the LCD, when the geometrical condition is as indicated in Fig. 25. The viewers' right eyes perceive the large convex lens as a full-size bright light source, and the viewers' left eyes perceive it as dark one. Similarly for the left eye. (See Fig. 24)

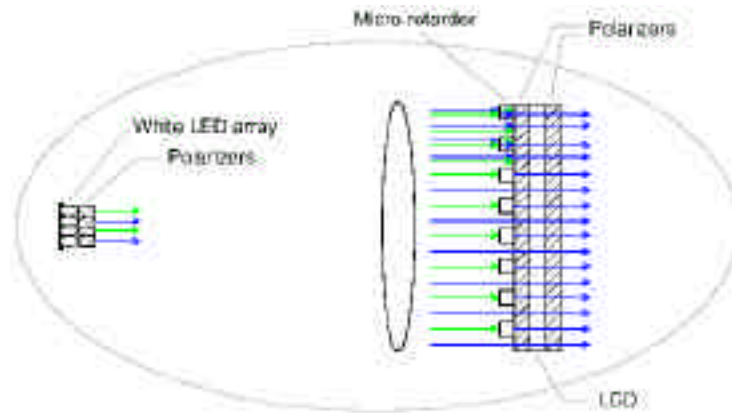


Figure 24 Each perspective back-light

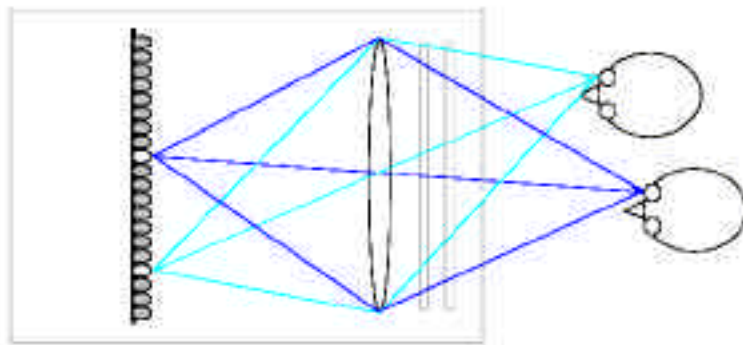


Figure 25 Plan view of a back-light unit

On the head tracking system the viewers' infrared image is focused on the diffuser by the large format convex lens and is captured by the infrared camera. An image circuit modulates the infrared image and produces binary half right and left face images of each viewer. The binary half face images are displayed on the appropriate cells of the white LED array. The infrared image is captured using the large convex format lens. There is no parallax between the captured infrared image with the image focused on the white LED array. Hence, the displayed infrared viewers' binary half Right face image (the appropriate cells) and the viewers' image that is focused by the large format convex lens are automatically superposed on the surface of the white LED array. The bright

areas of the binary half face images (the appropriate cells) are distributed to the correct eye of the viewers.

On the Seaphone display several viewers can perceive a stereo pair simultaneously and they can move independently without special attachments. The display is currently 1,492,000 YEN.

The Sanyo Display

The Sanyo display uses the LC technology for both image presentation and a parallax barrier [17]. Since the thermal expansion coefficients are the same, registration is maintained in different operating conditions. They call the parallax barrier part of the display the “image splitter.” They use two image splitters, one on each side of the LC (image presentation) panel (Fig. 26).

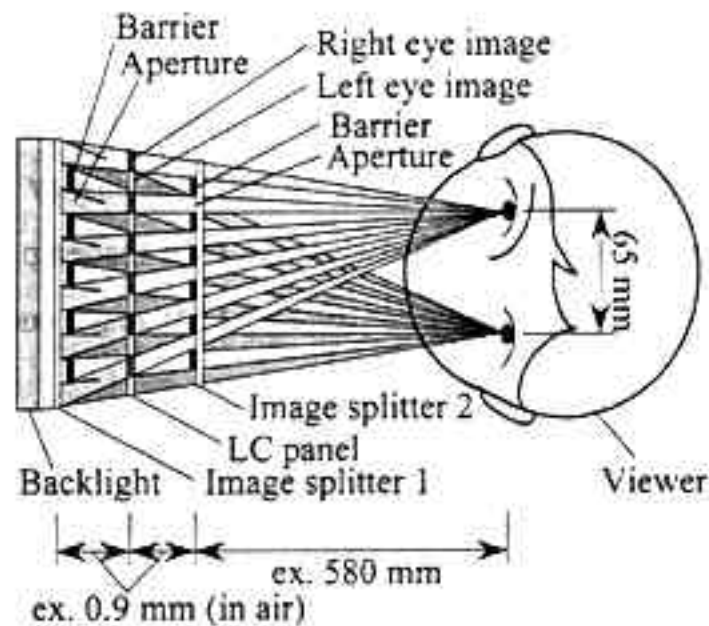


Figure 26 A double image splitter

The splitter on the back-light side is evaporated two-layer thin films of aluminum and chromium oxide. The vertical stripes are produced by etching. The stripe pitch is slightly larger than twice the dot pitch of the LC panel.

The viewer-side splitter is a low-reflection layer. The stripe pitch is slightly smaller than twice the dot pitch on the LC image presentation panel. Each slit corresponds to a column of the LC panel. They claim that the technique produces no ghosting.

They also have a head tracking system in which the viewer does not have to wear any attachments.

The HinesLab Display

An autostereoscopic display with motion parallax ([18], [19], [20]), has been developed by HinesLab, Inc. (www.hineslab.com) of Glendale, Calif. The display uses live or recorded camera images, or computer graphics, and displays multiple views simultaneously (Fig. 27). The viewer stands or sits in front of the display where the eyes fall naturally into two of multiple viewing positions. If the viewer shifts positions, the eyes move out of the two original viewing positions, into two different positions where views with the appropriate parallax are pre-positioned. This gives a natural feeling of motion parallax as the viewer moves laterally. An advantage of this approach is that multiple viewers can use the display simultaneously.

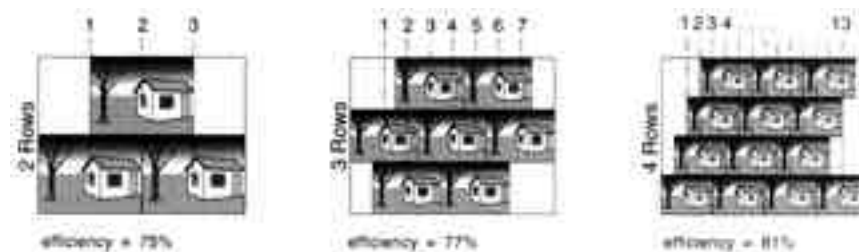


**Figure 27 HinesLab autostereoscopic computer display -
video arcade games.**

The technology provides from 3 to 21 eye positions, providing lateral head freedom and look-around ability, confirming the positions and shape of objects. The device is NTSC compatible and all images can be projected on a screen simultaneously, in full color, with no flicker.

The display is built around a single liquid crystal panel, from which multiple images are projected to a screen where they form the 3-D image.

The general approach used to create the autostereo display was to divide the overall area of the display source into horizontal rows. The rows were then filled with the maximum number of images, while maintaining the conventional 3:4 aspect ratio, and with no two images having the same lateral position (Fig. 28).



**Figure 28 Possible image arrangements
on the liquid-crystal projection panel**

The optical design for these configurations is very straight forward. Identical projection lenses are mounted to a common surface in the display housing, which project each image to the back of a viewing screen from unique lateral angles. Working in conjunction with a Fresnel field lens at the viewing screen, multiple exit pupils, or viewing positions, are formed at a comfortable viewing distance in front of the display. Fig. 29 shows an arrangement of seven images displayed on the LCD panel in three horizontal rows.

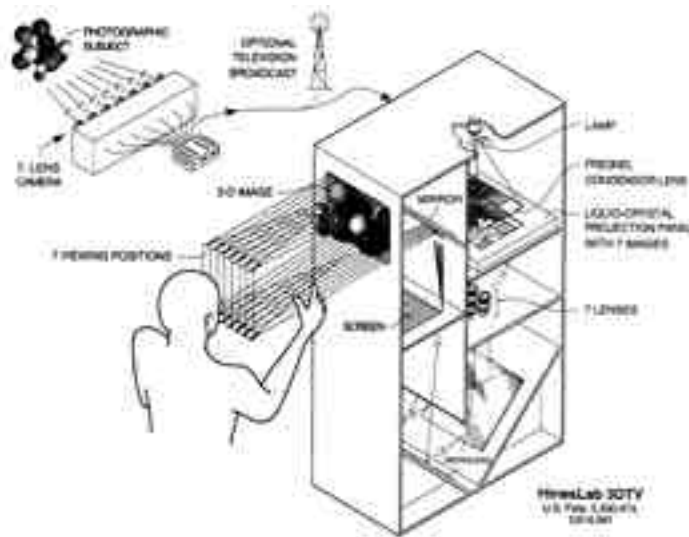


Figure 29 The 7-lens autostereo display.

Volumetric Displays

A representation technique used in computer visualization to represent a 3D object uses parallel planar cross sections of the object, e.g., CAT scans in medical imaging. We call such a representation a *multiplanar* image. *Volumetric* or multiplanar 3D displays normally depend on moving mirrors, rotating LEDs or other optical techniques to project or reflect light at points in space. Indeed, aquariums full of Jell-O with images drawn in ink inside the Jell-O have also been used for such displays. A survey of such methods can be found in [2] and [21].

A few techniques are worth mentioning. We first discuss the principle of the oscillating mirror.

Oscillating Planar Mirror

Imagine a planar mirror which is able to vibrate or move back and forth rapidly along a track perpendicular to the face of a CRT and assume that we are able to flash a point (pixel) on the CRT which decays very rapidly (Fig. 30).

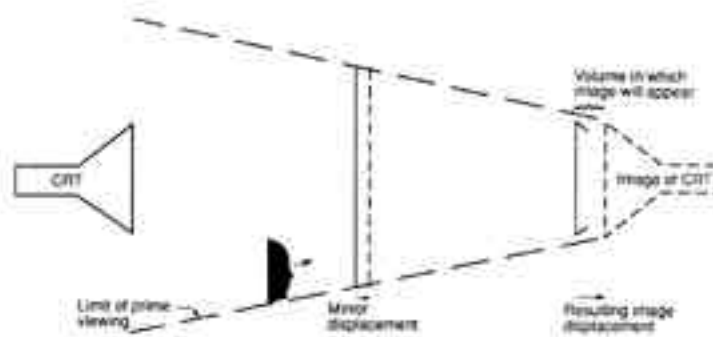


Figure 30 Vibrating Mirror

Let the observer be on the same side of the mirror as the CRT so the image in the CRT can be seen reflected by the mirror. If a point is rendered on the surface of the CRT when the mirror reaches a given location in its vibration, and the rate of vibration of the mirror is at least fusion frequency (30 Hz), the point will appear continuously in the same position in space. In fact, the point would produce a solid image in the sense that as we changed our position, our view of the point would also change accordingly. If the point is not extinguished as the mirror vibrates, then the mirror would reflect the point at all positions on its track and the viewer would see a line in space perpendicular to the face of the CRT. Any point plotted on the surface of the CRT would appear at a depth depending on the position of the mirror at the instant the point appears on the CRT. The space that contains all possible positions of points appearing on the CRT defines what is called the *view volume*.

All depth cues would be consistent and there would be no “disconnection” of accommodation and vergence as in the case of stereo pairs. The optics of the planar mirror produce a view volume depth twice that of the mirror excursion or displacement depth.

If the focal length of the mirror is changed also during the oscillation, dramatic improvement in view volume depth can be obtained.

Varifocal Mirror

The varifocal mirror was a commercially available multiplanar display for several years. The technique uses a flexible circular mirror anchored at the edges (Fig. 31). A common woofer driven at 30 Hz is used to change the focal length of the mirror. A 3D scene is divided into hundreds of planes, and a point-plotting electrostatic CRT plots a single point from each. The mirror reflects these points and the change in focal length of the mirror affects their apparent distance from the viewer. A software program determines which point from each plane is to be rendered so that lines appear to be continuous and uniform in thickness and brightness. The resulting image is solid. The view volume depth is approximately 72 times the mirror displacement depth at its center.

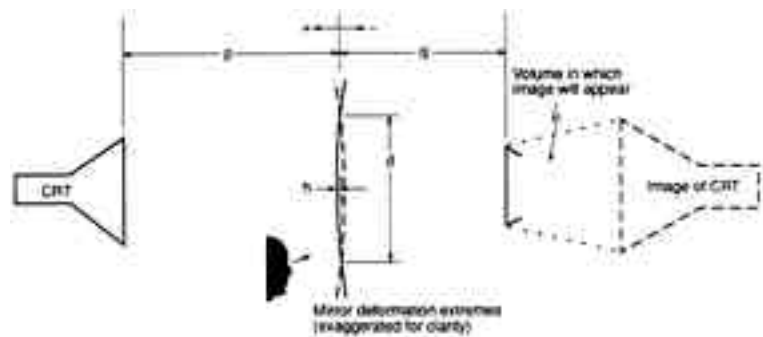


Figure 31 A varifocal Mirror

The images produced by the CRT would have to be warped to handle the varying focal length of the mirror. Such a mirror was produced by several companies in the past. At that time, only a green phosphor existed which had a sufficiently fast decay rate to prevent image smear.

Rotating Mirror

A variant of this approach developed by Texas Instruments using RGB lasers for point plotting and a double helix mirror rotating at 600 rpm as a reflecting device was commercially available also for a time under the name of Omniview (Fig. 32).

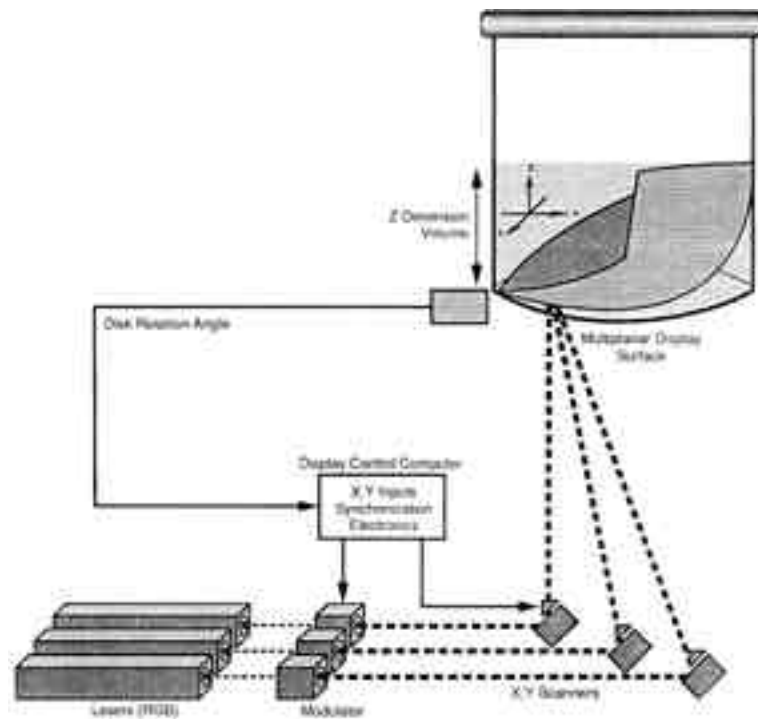


Figure 32 Omniview volumetric display

Some recent efforts have included LCD displays, but the switching times are currently too slow to produce useful images.

Problems and Advantages

A major advantage of the multiplanar displays is that they are “solid.” Accommodation and convergence are not disconnected as in viewing stereo pairs where the visual system focuses always at the same distance. Users who are stereo-blind can see the depth, and the image is viewable by several people at once

The primary problem with these mirror oriented technologies is that the images they produce are transparent. The amount of information they are able to represent before the user becomes confused is low because of the absence of hidden surface elimination although head trackers could be implemented for single view use. In addition they are limited to showing computer generated images.

Another major disadvantage of multiplanar displays has been that the electro-optics and point plotting devices used to produce the image are not sufficiently fast to produce more than a few points on a 3D object at a time, and laser grids are far too expensive to generate good raster displays. Hence, multiplanar or volumetric displays have been limited to wire frame renderings.

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Stephen Hines, HinesLab, Inc.

Mark Holzbach, Zebra Imaging, Inc.

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