Not Just 3-D Graphics, Practical 3-D Displays with Depth

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Three-dimensional displays have been a part of our popular culture since the stereoscope was first invented in the 1830s. 3-D movies, ViewMaster brand toys, and holographic pictures enjoy a widespread popularity. As with the ViewMaster stereoscope, Tek Labs' three-dimensional display gives users a sense of presence and reality not possible with an ordinary flat display. But more important, this display can form the heart of a more powerful and productive user interface. Tek businesses can explore this interface with the 3dAT system.

Although three-dimensional techniques have been applied to computer-generated images for many years now, true three-dimensional displays have not gained wide acceptance as engineering tools. Flickering images, dim displays and hard-to-handle devices have all delayed user acceptance and, for the effort expended, produced a poor payback. Recently, this situation has begun to change.

A new optical switch is being used to display 3-D information. Developed by Tek's Liquid Crystal Shutter group, this *stereo switch*, when coupled with an appropriate computer-graphics system, produces bright, easy-to-view, three-dimensional images. The liquid-crystal stereo switch (LCSS) has the potential of making a three-dimensional display an everyday engineering tool.

Let's first briefly examine 3-D computer graphics and several 3-D display techniques. Then, with this background, we will discuss how Tek's stereo switch operates. Finally, we will look at several promising applications for 3-D displays.

Displaying Three-Dimensional Information

Many high-performance computer graphics systems today are described as "three dimensional." One example is the Tektronix 4129 Color Graphics Workstation. In this context, "three-dimensional" means that *objects*—that is, points, lines and polygons—are described to the system as sets of three-dimensional coordinates. The graphics system reduces these three-dimensional objects to two-dimensional points, lines and polygons, for display. To help the user interpret the three-dimensional information, a variety of depth cues are often added, to enhance the displayed information. Examples are shading, perspective, head-motion parallax and hidden line removal. But even more powerful depth cues can be used, cues that are not available in ordinary graphics systems. The most important of these cues are *binocular disparity* and *accommodation*. It is binocular disparity that distinguishes Tek Labs' three-dimensional display from ordinary computer graphics.

Each of your eyes views the world from a slightly different position, and therefore receives slightly different information. Our brains use this *binocular disparity*, as one way to determine the distance of the objects we see. In video and film virtually everything described as "3-D" employs binocular disparity. To do so, two views resembling those we would see looking at a real object must be generated and presented, one to each eye. A three-dimensional display that incorporates these two views is called stereoscopic.

When looking at real-world objects, we also get depth cues from the muscles that focus our eyes. As our eyes *accommodate*, or focus, to different depths in a three-dimensional space or display, we get information from this process that helps us interpret the picture. While only binocular disparity cues are available in stereoscopic displays, holograms and varifocal mirror displays also allow accommodation cues to be used.

There is a great deal of excitement connected with holograms used as interactive display devices. A number of research groups are trying to generate holograms with computers. There is significant promise in these efforts, but much remains to be done. The algorithms and even computing architectures used to calculate the complex interference patterns which make up the hologram are far too slow for real-time, interactive computer graphics. In addition, no display has the resolution and the update speed to display holographic interference patterns.

Varifocal mirror displays have been used in oil exploration and medicine. With this technique, three-dimensional images are created by reflecting CRT images from a vibrating mirror (see figure 1). The curvature of the mirror, which is typically a very thin aluminized mylar membrane, varies smoothly from concave to flat to convex. For each position of the mirror, points displayed at that moment on the CRT appear at a unique depth. During one cycle of the mirror, a volume is scanned in display space Θ. Intriguing as this technique is, it has not gained wide acceptance. The images are dim, lack full color, and are difficult for a group to view.[1]

The shortcomings of the other 3-D techniques, leave the field mostly to stereoscopic (binocular-disparity) displays, at least for the next five to ten years.

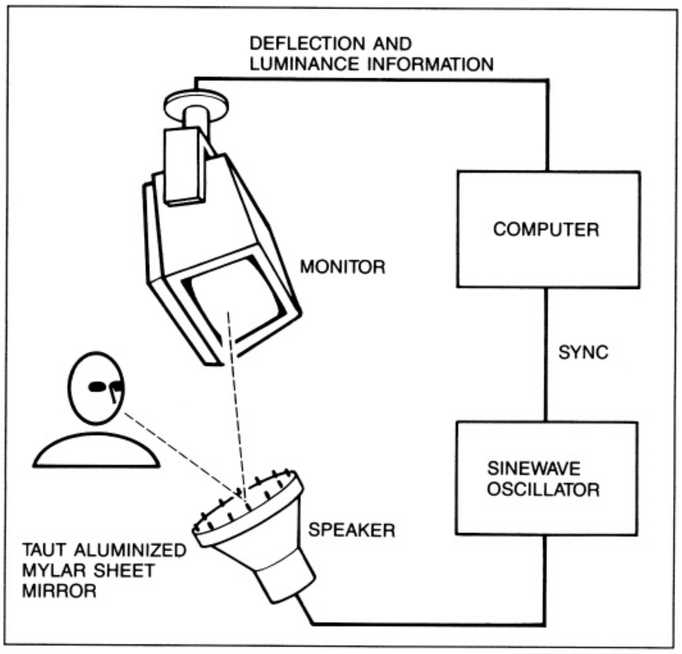

Figure 1. Among display devices, the varifocal mirror is truly dynamic—the display medium literally moves. An aluminized membrane flexes in and out in response to speaker-generated sound waves. At each instant, images unique to the depth plane to be displayed are displayed on the CRT and reflected to the viewer. Unfortunately, this simple technique produces dim, color-limited results.

The Mathematics of Stereoscopic Displays

All stereo displays require two views. In computer-generated images, these two views are produced by two viewing transformations.[1] These two transformations are geometrically related in such a way to produce two views that closely resemble the binocular views that the viewer would observe in similar real scene. The geometry we use for constructing a stereo image on a computer graphics screen is shown in figure 2. The viewer is at a distance D from the display screen and has an eye separation of S. The left and right eye views are created by rotating the database by:

$$\text{stereo angle} = 2^{*}\arctan[(S/2)/D] \qquad \text{eq. (1)}$$

For the typical viewing distance of 24 inches and the average eye separation of 2.5 inches, the stereo angle is 6 degrees. This six-degree rotation applies only when these values are used. For other viewing distances and eye separations, the angular separation will differ. If the object is at the same depth as the display screen, the left and right views will occupy about the same position, superimposed on the screen. At any other depth, the left- and right-eye views will be separated by a parallax P. If the object is behind the screen the left-eye view, L, is to the left of the right view, R, and if the object is in front of the screen, the left-eye view is to the right of the right view. The two disparate images, L and R, produce an apparent object distance of Z (see figure 2).

In the real world, our eyes cross at the same distance as they focus. However in a stereo display as the parallax P increases, our eyes remain focused on the display screen. This fixed focus limits the "distance" over which our eyes can follow binocular-disparity clues. If this apparent distance is too great, our eyes will no longer be able to fuse the stereo pair into a single image. This limits the range of depths a stereoscopic display can present. Valyus[2] determined that when an observer's eyes are focused at a distance D, the observer's eyes will be able to cross and fuse images if parallax P is less than or equal to 0.03 the eyes' distance to the display screen.

$$P \leq 0.03^{*}D \qquad \text{eq. (2)}$$

Stereoscopic Display Techniques

Literally hundreds of ways to display information in 3-D have been patented. Most never saw the light of day again. Poor images, uncomfortable viewing, and mechanical complexity killed off these devices. However, over the years several techniques continue to resurface—sort of like bad 3-D movies. It is these poor methods that have produced the negative impression many people have about stereoscopic displays.

Entertainment continues to be the largest market for stereoscopic displays. This market accepts images of far lower quality than engineers and scientists require. Of all 3-D entertainment techniques, color-encoded stereoscopic television is the worst. Several 3-D movies, made for viewing with polarized glasses in theaters, have been remastered as *anaglyphs*, or color-encoded 3-D movies intended for home television viewing. With this technique, the picture intended for the left eye is transmitted in blue, while the picture for the right eye is transmitted in red. The viewer wears a pair of glasses with one blue and one red lens—very crude, but very cheap.

Viewing anaglyphs strains the visual system. Since one eye sees only blue and the other only red, a conflict called *retinal rivalry* is produced. Although uncomfortable for most viewers, economics have made anaglyphs the only viable technique for 3-D television.

In the movie theater, things are not much better. 3-D projectors are troublesome and often misaligned. Many in the audience suffer eye strain due to misaligned images. Sometimes the left and right images are even reversed.[3]

Poor 3-D images are not necessary. Excellent 3-D images are indeed practical. It is performance compromises and poor techniques, and not the state of the art, that yield the eye-straining presentations that have tarnished the public's opinion of "3-D." There are, in fact, three methods that produce good, even excellent, images: (1) The side-by-side method, (2) the dual-monitor method, and (3) the field-sequential method.

The Side-By-Side Display

The side-by-side display simply employs the left half of the display screen for the left-eye views, and the right half for the right-eye views. So viewers can merge the images easily, most

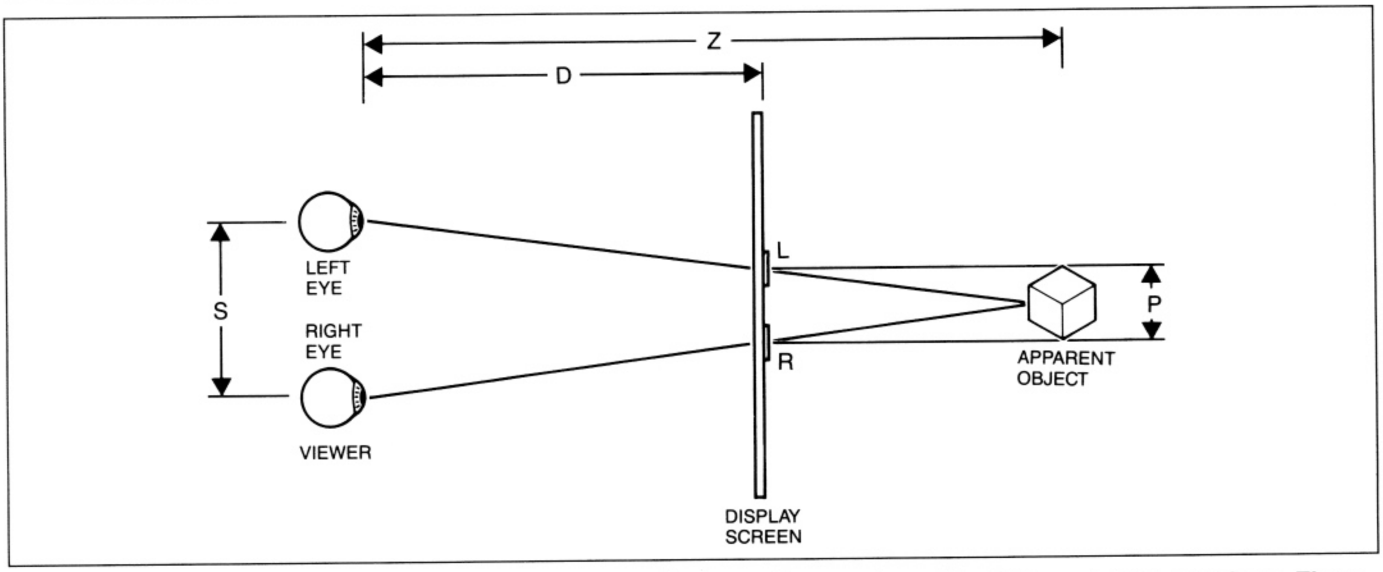

Figure 2. From this geometry, the software in a stereo display system creates virtual left- and right-eye views. These views enable the viewer to perceive depth in a displayed image. (Equations given in text.)

use a stereoscope like the device in figure 3. As with the anaglyphic display for TV, the major advantage of the side-by-side display is its easy application to virtually any computer-graphics system. Only software is needed to generate the stereo pair from the graphic database. Viewing side-by-side displays, however, can be tiresome. Depth addressability is somewhat limited because each view can employ only half the horizontal display capacity of the screen.

The Dual-Monitor Display

In the dual-monitor approach, two monitors are placed at right angles with a half-silvered mirror between (see figure 4). A vertical polarizer is placed in front of one monitor and a horizontal polarizer in front of the other. Each view presented is therefore uniquely polarized. With corresponding polarizing glasses, the user's left eye sees a left view; the right eye sees a right view. Although image quality can be excellent, images are correctly registered at only one viewing position, that is for one viewer. Needless to say, requiring two graphics systems per person can be expensive.

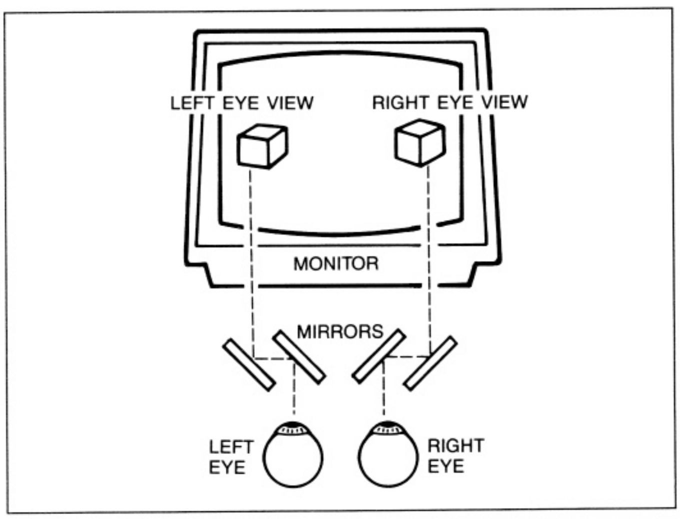

Figure 3. By split-screen display and mirrors, the side-by-side technique presents left- and right-eye images to the viewer. Although simple in concept, depth addressability is halved. Viewing is tiring.

Field-Sequential Stereo Display

The Tek LCSS-based 3-D display is a field-sequential system. Field-sequential stereo alternately presents the right- then the left-eye view. A single graphics system and a single video monitor can be used. A complete stereo picture, or frame, comprises either two or four fields, depending on the refresh scheme. In our computer-generated images, we use two fields per frame. During field 1, the right-eye view is displayed, followed by the left-eye view during field 2. Each view is stored in its own buffer, and alternately displayed by the graphics system.

Since at low frame rates, for example 30 Hz, image flicker can be quite noticeable, the frame rate, or refresh rate, is one figure of merit for field-sequential stereo displays. For computer-generated images, especially those with high spatial frequencies (such as wire-frame images with single-pixel-wide elements), a frame rate of 60 Hz or more may be necessary to eliminate flicker.

A way to alternately prevent each eye from seeing the other eye's view is essential in all field-sequential stereo systems. This can be accomplished by a pair of shutters, one for each eye. One prevents the left eye from viewing the monitor while the image for the right eye is being displayed, and vice versa. Both mechanical and electro-optic shutters have been in use for several years.

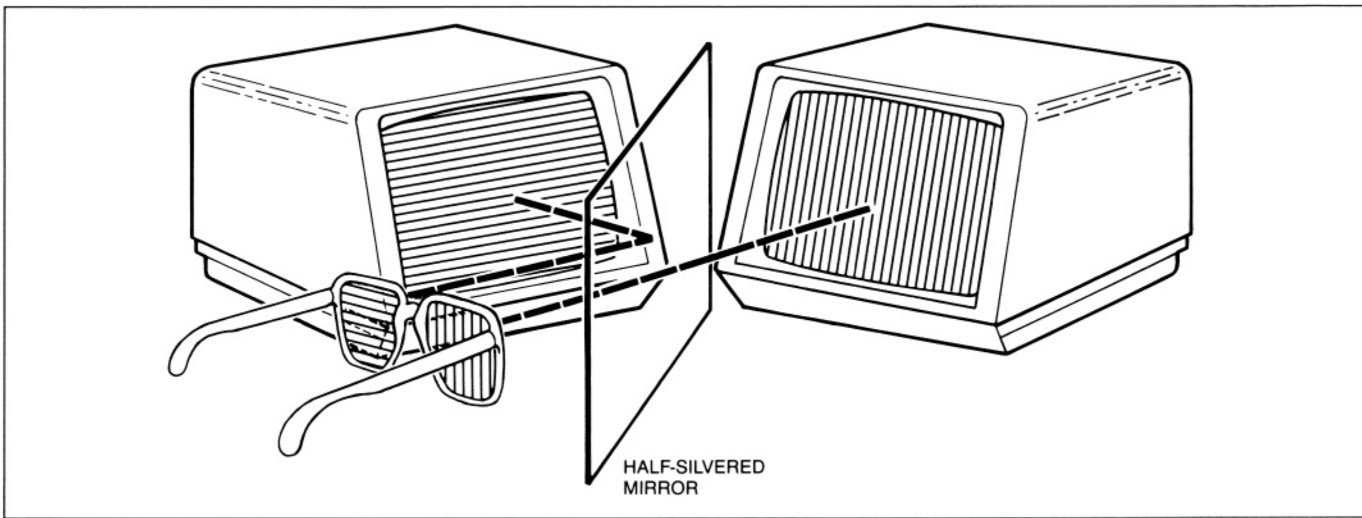

Figure 4. The dual-monitor approach produces good depth perception—but only at one viewing position. Two graphic systems make for more expense, and since only one viewer can use a complete system at a time, additional viewers require additional systems.

Rotating Cylinder

One popular mechanical-shutter consists of a double tube, each containing a set of apertures (see figure 5). A motor synchronized to the display rotates the tube so that while the right-eye view is displayed, the right-eye slots line up and an opaque section in the left side of the tube blocks the left-eye view. The situation reverses when the left-eye view is displayed. The light transmission is excellent (100%) when the slots line up and nil when they don't. However, since the slots for each eye line up only briefly, light transmission to the user is less then 30%. There are three disadvantages: (1) The device is electromechanical, requiring power and synchronization to the display. (2) Each viewer requires a tube, resulting in a tangle of cords with even a few users. (3) The rotating tube is cumbersome to use for extended periods.

PLZT Shutter

The PLZT (lead lanthanum zirconate titanate) shutter employs two electrically controlled solid state optical switches, as shown in figure 6. The user wears the shutters much as eye glasses. Unfortunately they are expensive and fragile, and they must be removed for viewing anything other than display viewing. Each switch is controlled independently and allows each eye to see only the view intended for it. When ON, a PLZT switch in a field-sequential stereo system transmits about 6% of the light from the CRT, and about 1% when turned off. It is a solid-state device. It contains no moving parts. But, because the light transmission is quite low, PLZT shutters work best in a dim room.

The Liquid-Crystal Stereo Switch

The liquid-crystal stereo switch (LCSS), like the PLZT, is an electro-optic switch. But in the LCSS the system consists of two pieces (see figure 6). One, the liquid-crystal shutter module (figure 7), mounts on the front of the video display. Timed by a synchronization signal provided by the graphics hardware, the shutter encodes each of the eye-view images by circularly polarizing the light, left circular for the left eye and right circular for the right eye. The second part of the system is essentially a pair of polarized sunglasses modified to decode the correct view for each eye.

Any field-sequential stereo system has two advantages: (1) Just one graphics system and one video monitor are needed. (2) The horizontal resolution of a full screen is available for each eye view.

To these advantages, Tek's LCSS adds four advantages of its own: (1) The shutter has no moving parts. (2) The expensive piece, the shutter itself, is safely out of the user's hands. (3) All that's required for several users to view a system are individual pairs of inexpensive glasses. (4) Since the glasses are circularly polarized, users can do other work away from the display while wearing the glasses.

In an LCSS system, light transmission is good enough to be useful in typical graphic work environments. Of all the light emitted by the CRT, 12% actually reaches each eye. Since the field-sequential duty cycle has already halved the CRT light available, and the polarizing glasses attenuates light further, that 12% net represents excellent light transmission by the LCSS itself.

When several LCSS 3-D systems are in use in a work area, any viewer can glance from display to display. No resynchronizing of glasses is necessary. This and the preceding advantages make Tek's LCSS system a convenient and clear way to present data and structures in three dimensions.

The 3dAT — A Stereo Research Tool

To enable engineers to investigate product possibilities, Tek Labs' Imaging Research Laboratory developed 3dAT, a stereoscopic computer-graphic system incorporating the liquid-crystal stereo switch. 3dAT has three major pieces: a 3-D monitor, a graphics controller, and the software for displaying two, interrelated viewing transformations. The monitor is a 19-inch, 512-

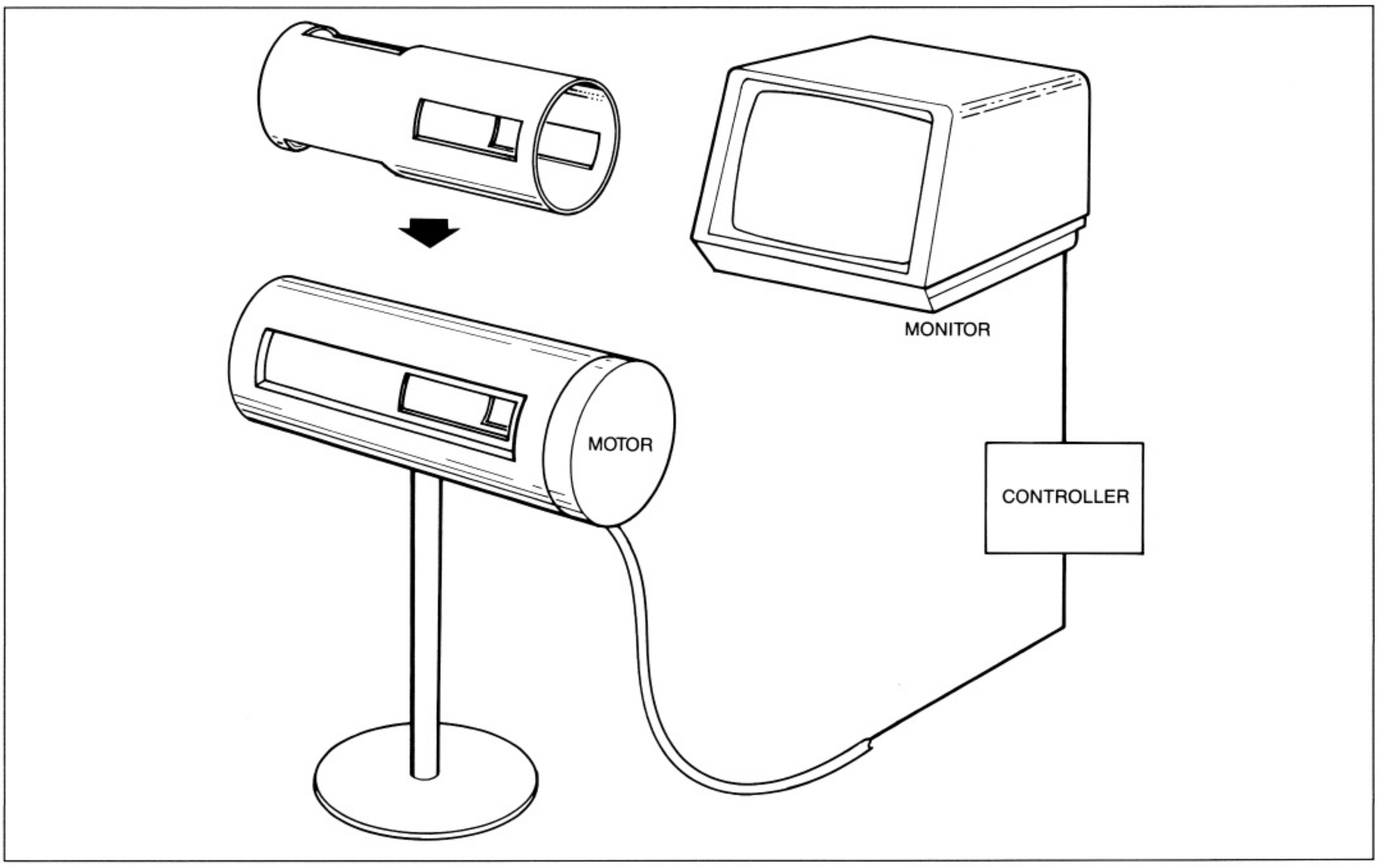

Figure 5. The rotating cylinder alternates views of field-sequential displays by blocking the appropriate "other" eye. Simple, yes—but burdened by difficulties inherent in linking a mechanical system to an otherwise electronic system.

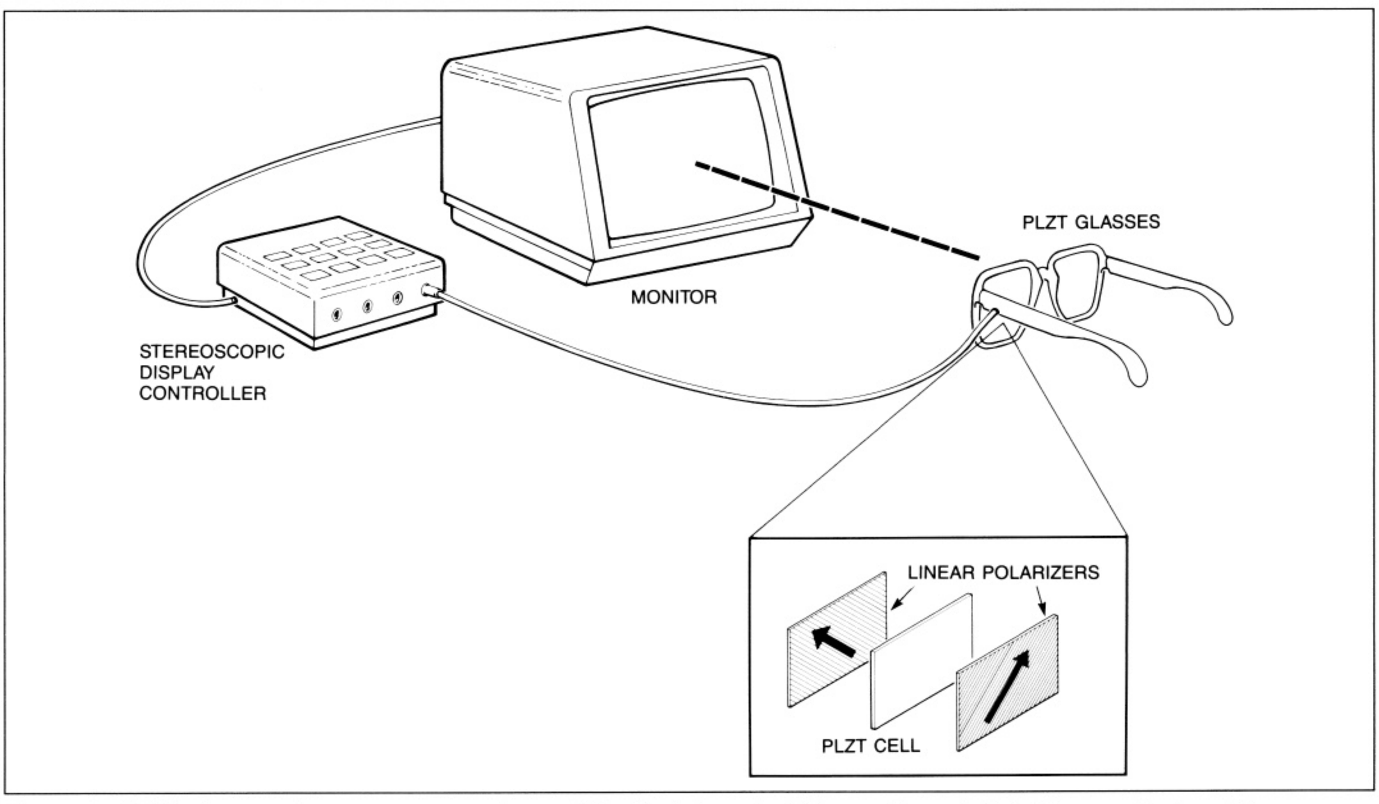

Figure 6. PLZT shutter glasses are expensive and fragile. They don't transmit much light from a displayed image even when "on."

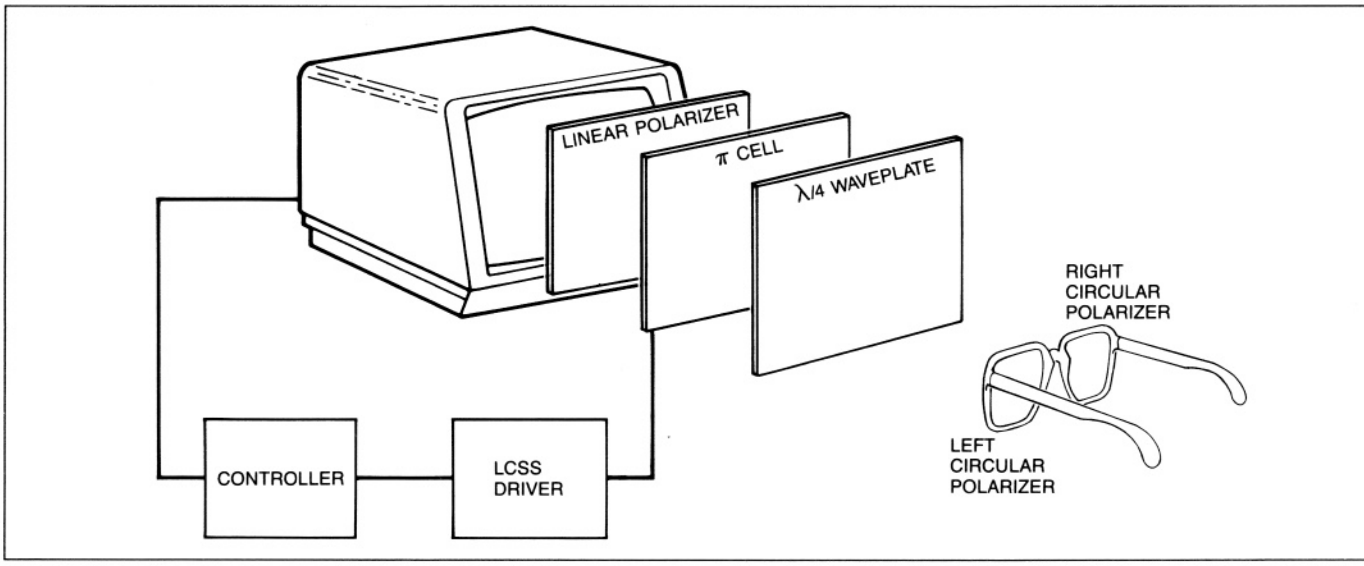

Figure 7. To view a Tek LCSS display system, the user wears glasses that are much like polarized sunglasses. Unlike user-worn devices in other field-sequential systems, these glasses do not restrict head movement or position. The viewer, wearing these glasses, can look elsewhere without restriction. Users are not tethered or harnessed to the 3-D system.

line/eye color monitor with a 60-Hz frame rate, coupled to a 19-inch liquid-crystal stereo switch. This is driven by a stereo graphics adapter (SGA) for the IBM PC/AT (hence, 3dAT). Special hardware in the adapter automatically alternates the image displayed between the left and right views. The hardware is accessed through a subroutine library, modeled after the 4129 command set, that accepts 3-D objects such as points and lines, and draws corresponding stereo image pairs. In addition, a 3-D Paint program allows quick evaluation of the 3-D display in new applications.

During the past year, the 3dAT has enabled us to evaluate a number of applications for the LCSS. So far, we have only scratched the surface. A small number of 3dAT systems are available to enable Tek businesses to explore their own applications.

Applications for Stereoscopic Displays

A good three-dimensional display can enhance the user's ability to see the relationships of things in a workspace, or to readily comprehend Z-axis-coded information in plots and tables.

By far the most prevalent use for 3-D is as a better user-interface to a three-dimensional workspace. Traditional uses—for example in underwater salvage or remote handling of materials—stress 3-D's power to increase an operator's ability to distinguish positions in the operating environment. Many engineering tasks have similar elements, for example, specifying mesh points on an irregular surface, or observing simulated tool paths.

Since the steroscopic display improves the user's understanding of a three-dimensional workspace, it can often replace the physical model. Architects can present options to clients quickly and easily without actually constructing models. In automobile design, 3-D may replace the expensive clay models currently used.

In medicine, the volumes of three-dimensional data generated by scanners are often difficult to interpret. Through computer processing and a stereoscopic display, medical researchers can derive and present clear summaries of complex data. In planning reconstructive surgery, for example, interactive, three-dimensional computer graphics can help the surgeon plan the best way to go about a cosmetically sensistive repair.

Each of these applications, as well as dozens more, are under development, using a wide variety of three-dimensional display techniques. But, what are possibly the most exciting applications are still to be developed. Because the stereo switch is convenient to use and highly functional, many applications are now feasible. The excellent images, along with the ease of use, may mean that a stereoscopic three-dimensional display will become essential to the next-generation engineering workbench.

For More Information

For more information, call Rick DeHoff, 627-5093 (50-320). □

References

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