Vibrating varifocal mirrors for 3-D imaging

To relieve some of the complexity that exists between man and machines, a three-dimensional interface is needed. A practical 3-D system is not available, but here is a technique that satisfies many autostereoscopic requirements

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As technology advances, the interactions between man and machine become more complex. A reliable three-dimensional man–machine interface could help alleviate some of the complexity; but an effective 3-D display has, so far, eluded technologists. Thus, we have been forced to make unnatural compromises when dealing with data that are essentially three-dimensional in nature. This article describes a system that may meet the autostereoscopic display requirements in many situations.

A miniature television camera held by an astronaut made the beauty of the moon and earth vivid for millions of viewers. This same camera, when focused on instruments and controls within the Apollo 10 cabin, testified to the complexity of man–machine interactions.

Much of the data involved in these interactions are three-dimensional in nature; and technologists have continually stressed the need for a good three-dimensional man–machine interface. The lack of such a device has forced us into unnatural compromises in data handling. For example, the three-dimensional positions of aircraft in the vicinity of an airport are presented on a two-dimensional interface—a cathode-ray tube (CRT). If the aircrafts' altitudes are shown, they are represented by numbers painted beside the radar echo marks. Like the air traffic controller, the submarine commander who operates in a three-dimensional environment would probably be happier if he could replace his two-dimensional CRT sonar display with an equivalent three-dimensional man–machine interface. In short, he would like an autostereoscopic projector. Recently, the use of vibrating varifocal mirrors for stereoscopic display[1-3] have made important additions to 3-D projection techniques.

Autostereoscopic displays

Stereoscopic display systems can be divided into two broad classes: those that are autostereoscopic and those of the stereo pair type.[4] Stereo-pair-type devices use two slightly different images, and an optical system that directs one image to each eye [Fig. 1(A)]. Home stereo viewers are of this class, as were the ill-fated 3-D movies of a few years ago. Autostereoscopic display systems (holograms are perhaps the best known example) project the light rays that emanate from a reconstructed image over a relatively wide solid angle; and can therefore be viewed by several observers, over a range of distances and from any direction within the solid angle [Fig. 1(B)]. Another example of an autostereoscopic process is integral photography (Fig. 2), which was invented in 1908 by Gabriel Lippmann.[5] Since then, interest in integral photography has languished due to the lack of suitable "fly's-eye" lenses. However, the availability of high-quality plastic lens arrays has recently stimulated activity in this area.[6-9] A modified form of the integral photograph, in which the fly's-eye array of spherical lenslets is replaced by an array of plastic cylindrical lenses, is known as a parallax panoramogram.[10]

A third example of an autostereoscopic projection technique, and the one from which the vibrating varifocal mirror display has evolved, makes use of a rapidly vibrating or rotating screen on which is projected a sequence of images.[11-15] Figure 3(A) shows one form of the device.[12] A rotating projection screen is illuminated by a high-brightness CRT and a projection lens positioned on the rotation axis. The motion of the screen spreads these images throughout the three-dimensional volume swept by the screen; if the periodic motion of the screen is at a high enough frequency (about 15 Hz or higher), persistence of vision creates the impression of a three-dimensional image. A related display device[15] [Fig. 3(B)] makes use of a flat projection screen that oscillates, piston-like, toward and away from the viewer. The mechanics of the system limit the oscillation amplitude, and hence the depth of the three-dimensional image volume swept out by the screen.

A vibrating varifocal mirror display system is basically an oscillating screen that relieves several mechanical problems by oscillating the image of the screen instead of the screen itself.

Vibrating varifocal mirror display

In 1961, Muirhead[16] noted that a thin sheet of aluminized Mylar plastic film stretched taut over an airtight circular frame could be pneumatically distorted to form a good-quality concave or convex mirror, and that the curvature, and hence the focal length, of the mirror could be conveniently varied by decreasing or increasing the static air pressure on the Mylar's back surface. These "varifocal" mirrors were constructed with diameters up to 3.66 meters. A few years later, Dr. Alan Traub at Mitre Corporation recognized the potentialities of the varifocal

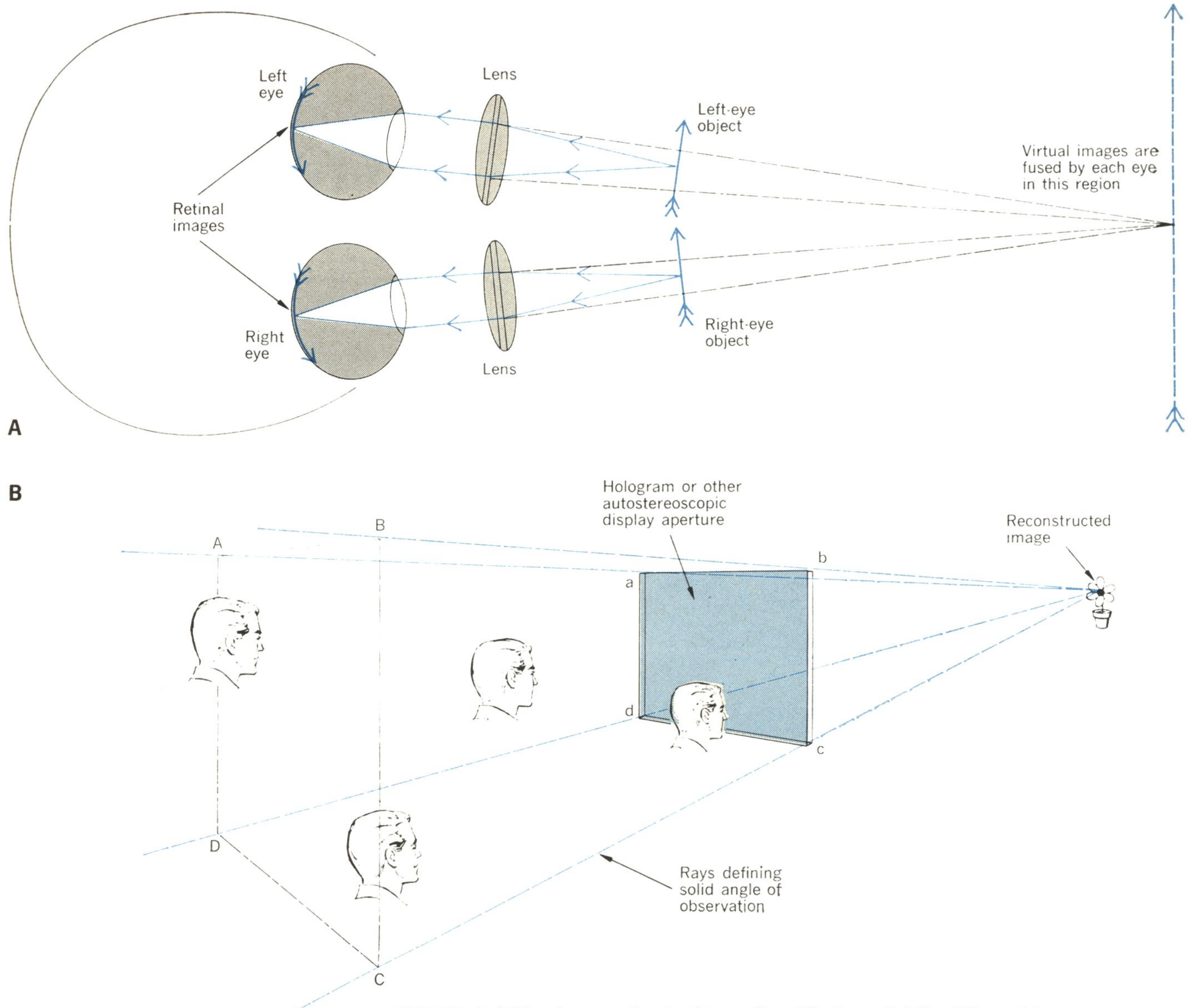
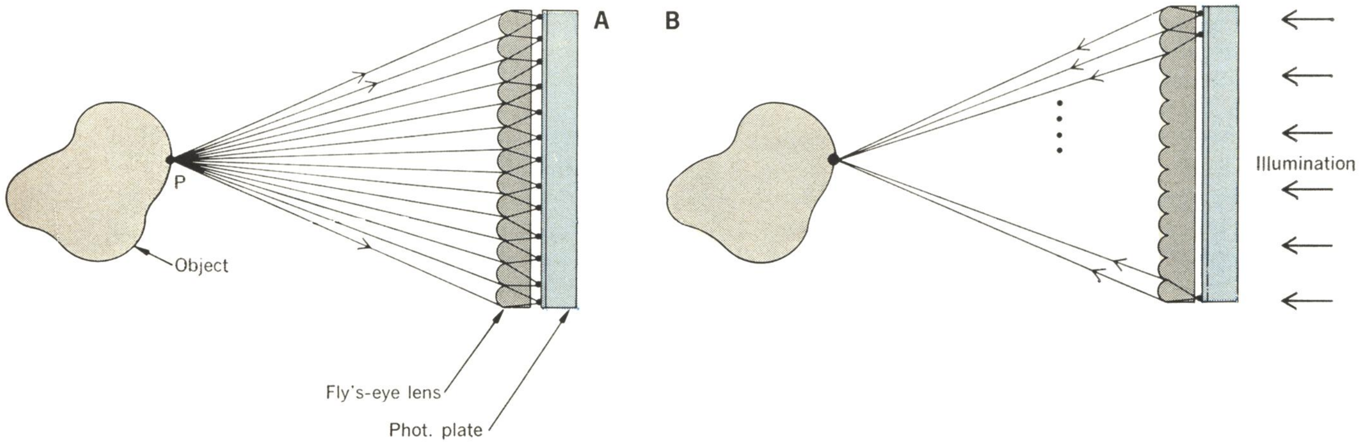


FIGURE 1. With stereo-pair viewing optics (A), two slightly different images are projected by two lens into the eyes that fuse the images at some point in space. Autostereoscopic display (B) allows viewers to see the reconstructed image from anywhere within the viewing "cone."

FIGURE 2. Integral photography. A—A fly's-eye lens forms multiple images on a photographic plate. The rays show the imaging of a point "P" on the object. B.—After the plate is reverse-processed, repositioned, and illuminated from behind, the light rays are refocused to point "P" and the image of the original object is reconstructed.



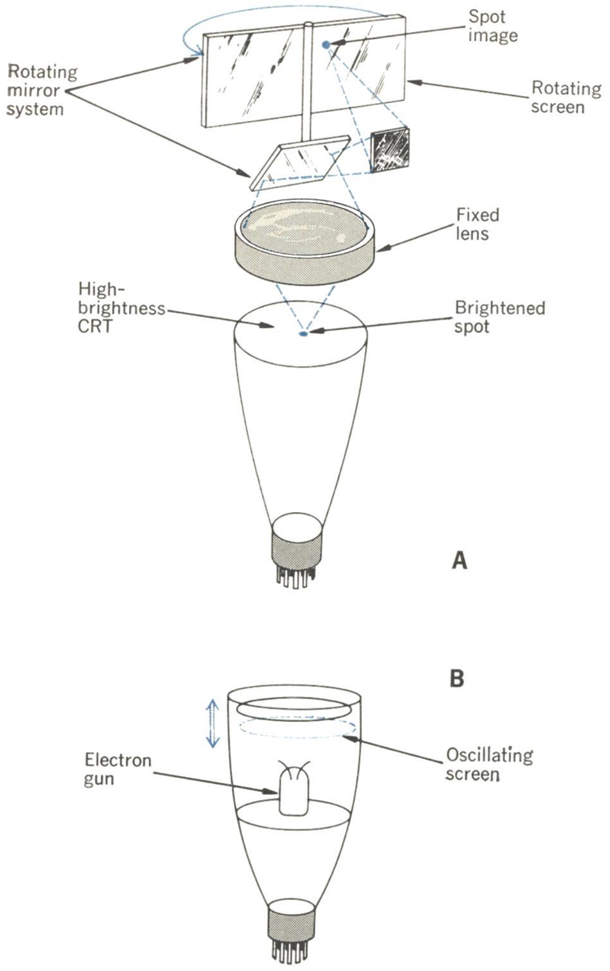


FIGURE 3. Autostereoscopic display system using a rotating screen (A),[12] and using an oscillating screen (B).[15]

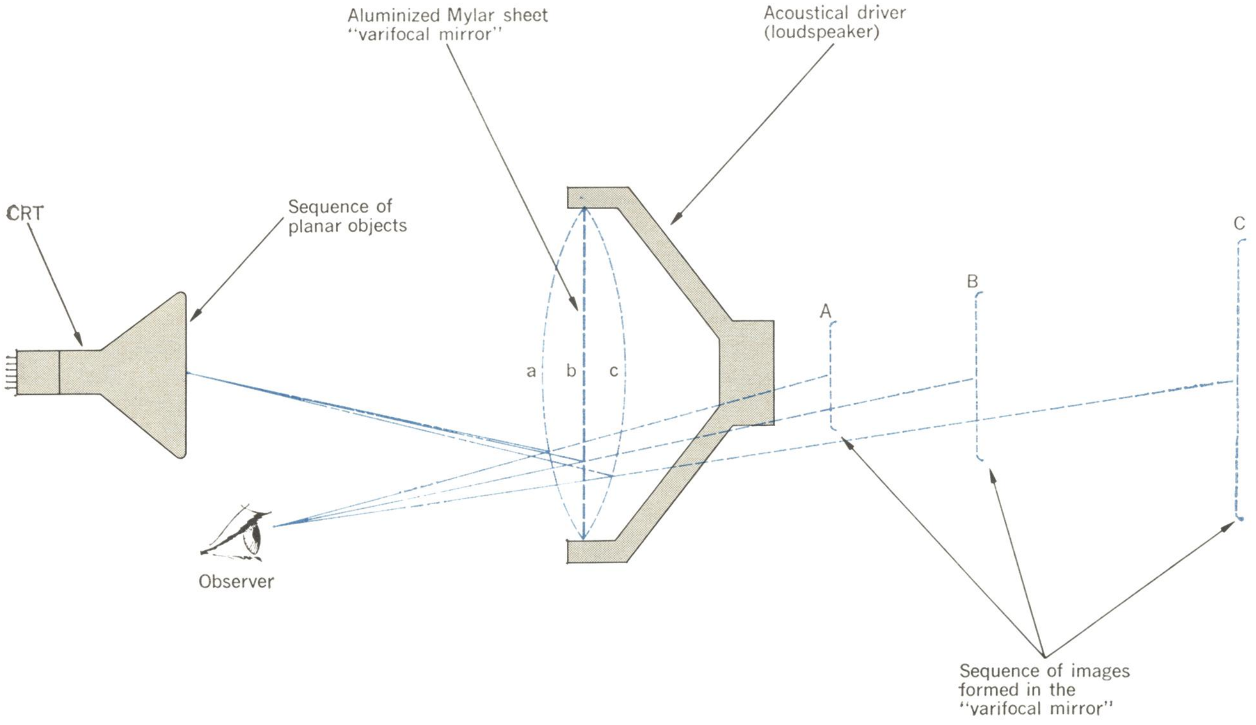
mirror for autostereoscopic imaging.[1] The essentials of the method are illustrated in Fig. 4. The thin aluminized Mylar film is stretched taut and driven sinusoidally by a 15- to 60-Hz tone from a loudspeaker. If the Mylar mirror is taut enough and the amplitude of the oscillation not too large, the mirror's surface is essentially a sphere of continuously changing curvature. Thus, when an observer views an object (such as the face of a CRT) by reflection in the mirror, the changes in curvature cause a corresponding change in the position of the reflected image. In a typical operation a rapid sequence of perhaps 20 or 30 two-dimensional images appears on the object screen. During this time the loudspeaker causes the aluminized Mylar mirror to change curvature smoothly from one extreme (a) to the other (c). As a result the image position sweeps from A to C and the sequence of images is spread out more or less evenly between the two extremes. This display sequence is repeated cyclically at a frequency of 15 Hz or higher. Due to persistence-of-vision effects, the result is an autostereoscopic image that is essentially a transparent stack of two-dimensional images viewed in the varifocal mirror.

The nature of the imaging process is governed by the spherical mirror equation,[17] which says that the amplitude of the image position motion, AC, is typically 15 to 30 times larger than the corresponding mirror oscillation amplitude, ac. By increasing the ratio of the object distance to the mirror diameter, or by increasing the mirror oscillation amplitude, the distance to the farthest image plane C can be easily increased to infinity. This allows wide flexibility in the image depth range.

Two laboratory applications

Traub demonstrated his discovery in a variety of configurations, one of the most interesting of which was a real-time display of a computer-generated autostereoscopic image.[1] A computer-controlled CRT display con-

FIGURE 4. Principle of varifocal mirror autostereoscopy.



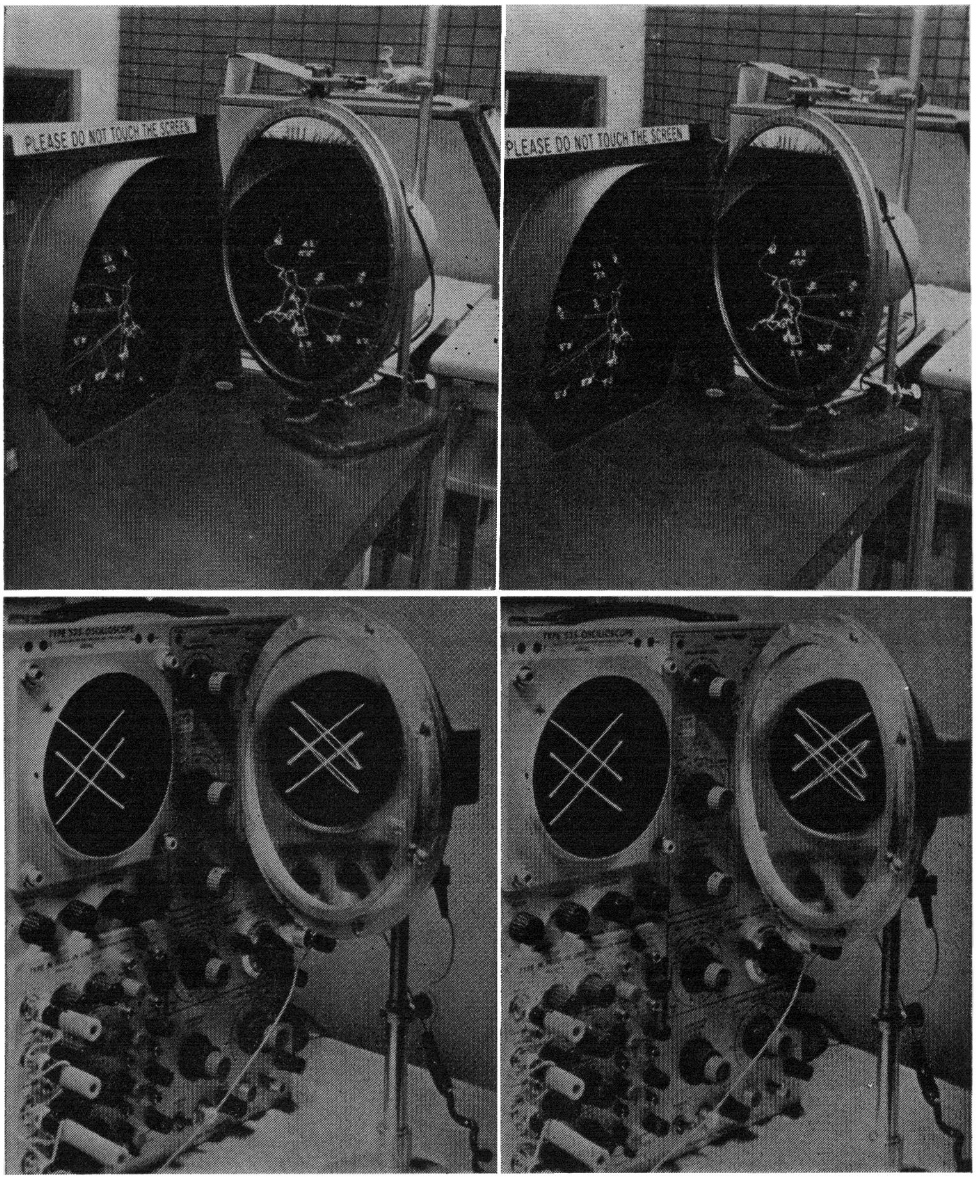


FIGURE 5. Stereo pairs (top) showing varifocal mirror displays of Traub's computer simulation of a 3-D radar display, and (bottom) a 3-D Lissajous figure. The stereo pairs can be viewed by hand holding a pair of lenses (of 10- to 30-cm focal lengths) in front of each eye.

sole was used to generate the required sequence of two-dimensional source images. This system was used to simulate an air traffic controller's three-dimensional radar console, in which the altitudes as well as the positions of aircraft were easily perceivable. Figure 5(A) shows a stereo pair of the radar display; also shown is a stereo pair of a three-dimensional Lissajous figure [Fig. 5(B)].

Another application of varifocal mirrors, a computer-generated autostereoscopic movie projection system,[3] was made in the author's laboratory. Figure 6 shows the system schematically. A special, high-speed, 16-mm movie projector casts a sequence of 15 movie frames onto a rear projection screen, during which time the image plane advances toward the observer. This is followed by 15 opaque frames (during which time the image plane retreats to its starting point). Thus, a single three-dimensional image volume is assembled from a spatially distributed sequence of 15 planar images. To accomplish this, the projector runs at 450 frames per second.

The 16-mm movie film was generated using a Stromberg-Carlson 4020 microfilm recorder under the control of a GE 645 computer. In order to synchronize the mirror oscillations to the free-running movie film, the computer was programmed to draw sync marks (small transparent areas) in the corners of appropriate movie frames. During projection, the resulting light pulses are photoelectrically detected and used to generate the sine wave required to drive the loudspeaker.

Figure 7 illustrates the autostereoscopic nature of the movie image. This movie consists of a line drawing of a three-dimensional house with a front yard and two front doors, through which a boy and a girl move back and forth. The top two photographs are oblique views of the image from different directions within the solid angle, and the third is a single frame that is included to assist in interpreting the first two. The blurring in these pictures

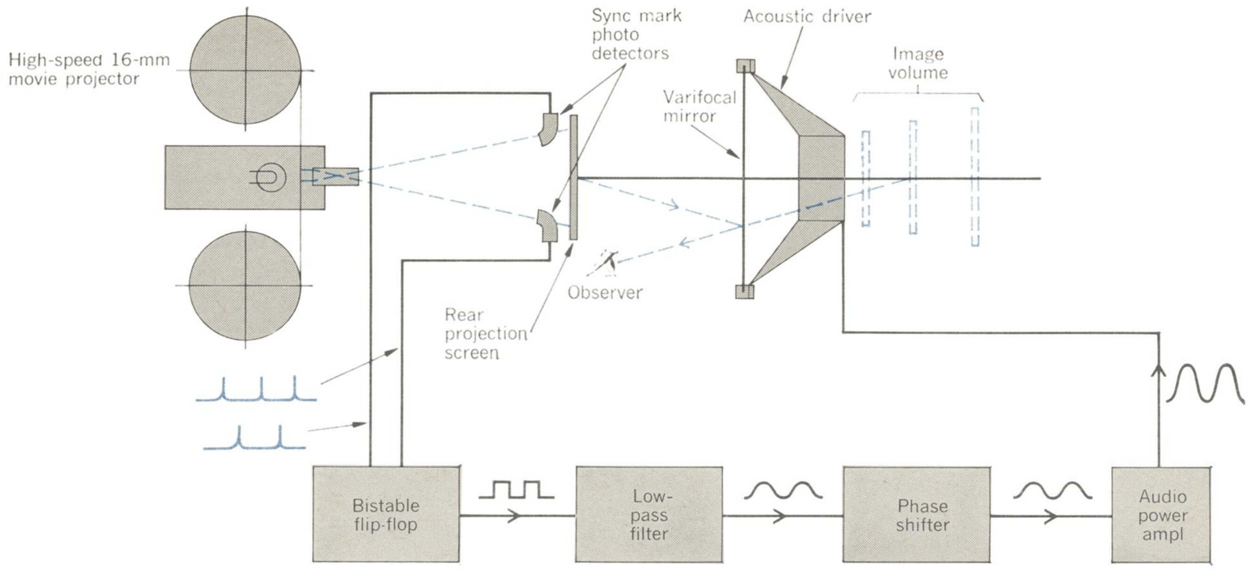


FIGURE 6. Schematic diagram of a 3-D computer-generated movie projection system. Photodetectors are used to detect sync marks and generate the mirror driving voltage.

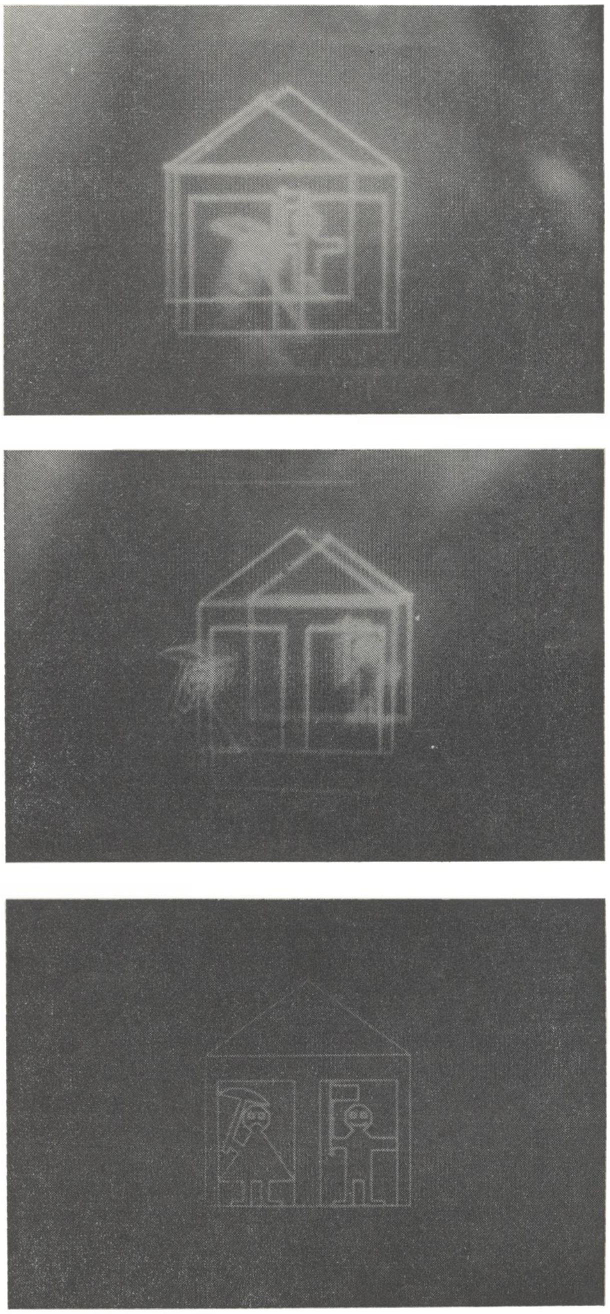


FIGURE 7. The top two photographs show two oblique views of the 3-D computer-generated movie. Blurring is due to figure movement and image jitter during exposure. The bottom photo is a single frame to assist in the visual interpretation of the top two photos.

is considerably greater than that noticed in direct viewing, and is due to the problem of photographing a low-brightness moving image.

Peculiarities of varifocal mirror systems

It is apparent that this technique has its own peculiar limitations and shortcomings. First, it generates a transparent or "phantom" image. That is, the important depth cue of interposition—the obscuring of farther portions of a scene by nearer portions—is missing. This suggests that varifocal mirror displays may find their most successful applications where symbolic data (such as three-dimensional position coordinates) rather than realistic images (such as scenes or people) are being displayed.

Another peculiarity of the varifocal process is that, as the image moves along the depth axis toward the observer, the image size diminishes. This is shown by Fig. 8(A). Traub has called this effect "anomalous perspective,"[1] since objects of equal size are imaged in such a way that distant images subtend larger angles at the observer's eye than do near images. Figure 8(B) suggests a simple cure for anomalous perspective. The scale of the object pictures is modulated so that the size of the object is inversely proportional to the instantaneous magnification. The result is a constant lateral scale throughout the image volume.

Other peculiarities of varifocal mirror systems come to light when one considers what is the best distribution of image planes along the depth axis. Figure 9 illustrates two such image distributions: the first (A) involves an even spacing of planes along the depth axis; and the second (B) is an uneven distribution in which each plane subtends an equal angular increment at the observer. This latter distribution is suitable for displays requiring infinite or near-infinite depth ranges.

In order to achieve an even distribution of images along the depth axis, a linear time sweep of the depth axis is often desirable. This is true because the patterns usually appear on the object screen at a constant rate (generally, the fastest possible rate). Therefore, to minimize the retrace time, a sawtooth-like motion of the image plane along the depth axis is desirable. It is here that two more peculiarities appear. The first is that the image position is not a linear function of the mirror displacement.[3] Thus the sawtooth image motion requires a more complex mirror motion and loudspeaker driving voltage waveform. The second peculiarity is that the speaker–mirror combination will usually have a highly nonlinear frequency response, as illustrated in Fig. 10. In this figure, salt granules collect along nodal lines and show the nature of the mode of oscillation. It can be

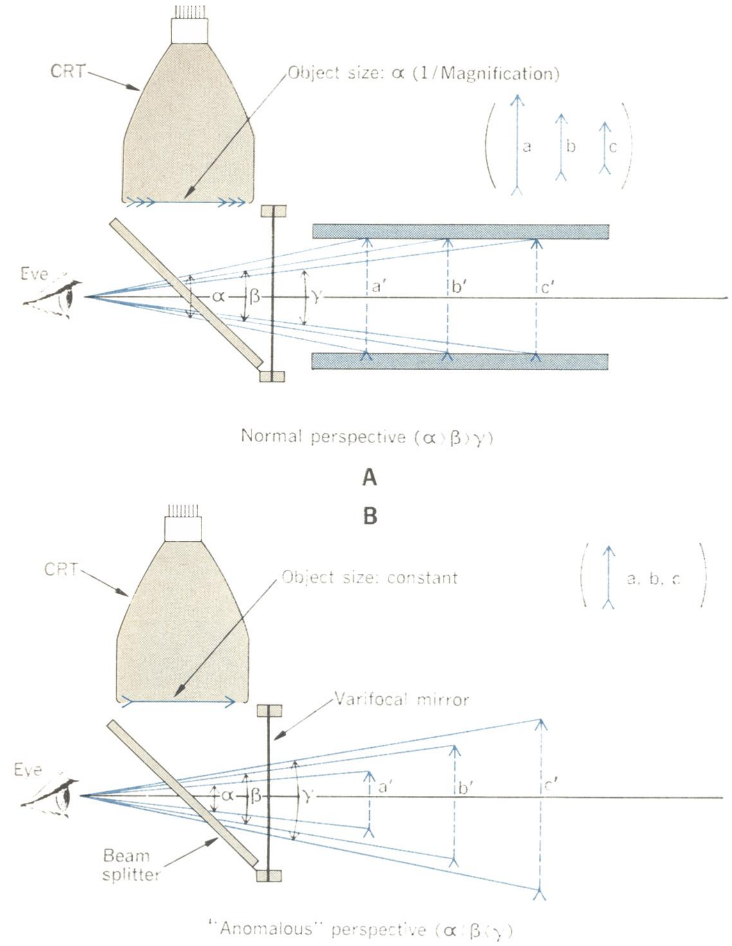


Figure 8. "Anomalous" perspective (A) in which the angle subtended at the observers eye of normally equal sized subjects increase with distance. If the object varies inversely as the magnification (B), the subtended angle decreases normally with distance.

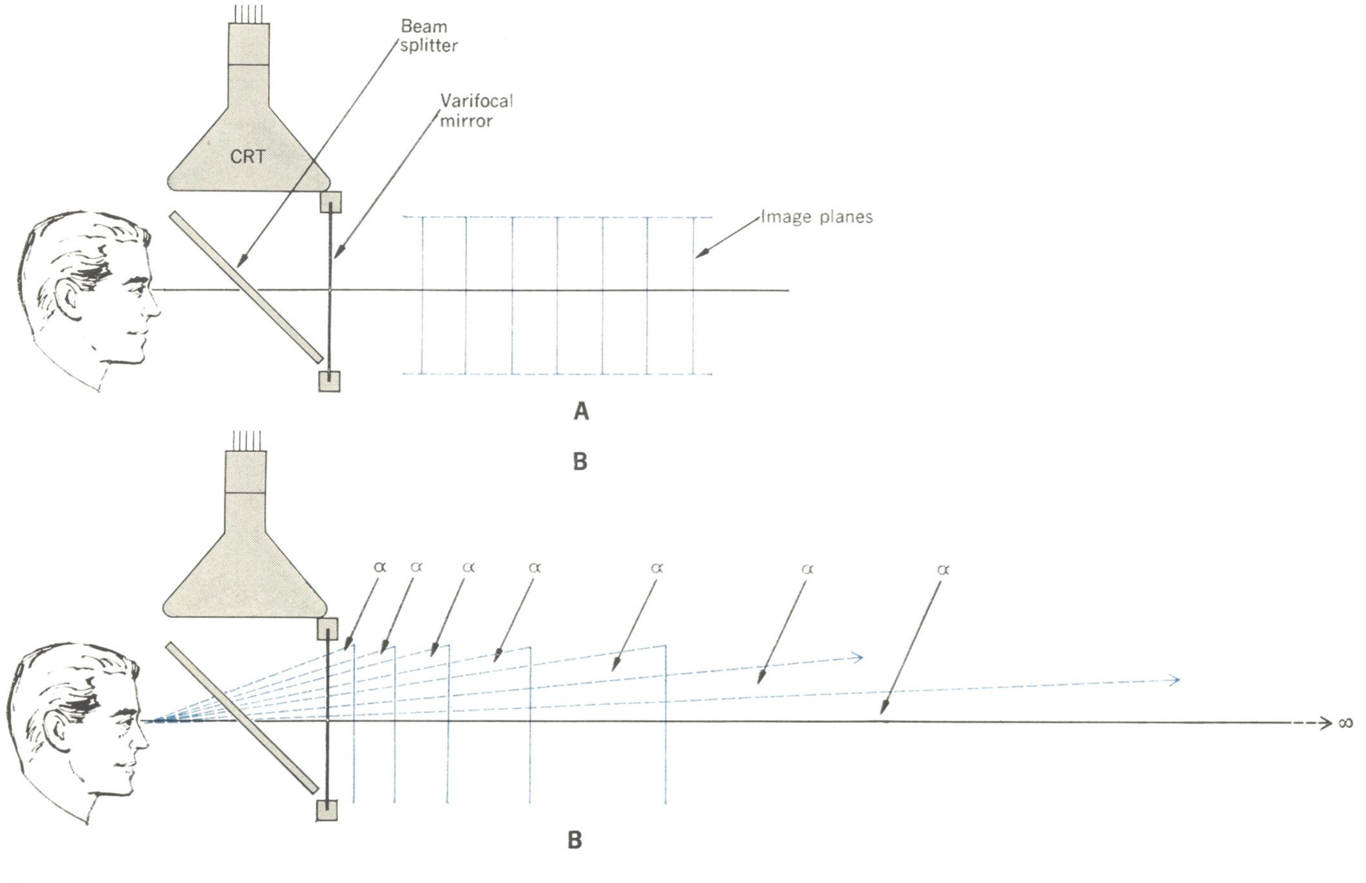


FIGURE 9. Optimum distribution of images along the depth axis depends upon the application. A—A linear distribution is suitable for displaying 3-D functions in a rectilinear coordinate system. B—The nonlinear system is suitable for "scenic" displays spanning great depth ranges.

seen that the desired zero-order mode of oscillation is attained only at frequencies up to about 150 Hz with this particular 20-cm-diameter varifocal mirror. At higher frequencies, higher-order modes of oscillation appear. It is apparent that a waveform such as a sawtooth wave, which is rich in high-frequency harmonics, will excite these undesired higher-order modes of oscillation in the Mylar. However, a filtered sawtooth wave in which the harmonic components above about 150 Hz are strongly attenuated has been successfully used to drive the mirrors in a quasi-sawtooth manner, achieving a scanning duty cycle of about 90 percent.[3]

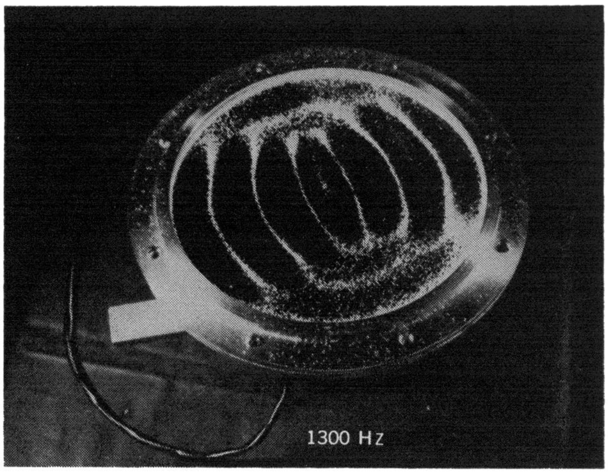
Varifocal mirrors in light sculpture

As an interesting sidelight, vibrating varifocal mirrors have recently been used in light sculptures by New York artist Robert Whitman, working in collaboration with the author and under the auspices of Experiments in Art and Technology, a nonprofit organization whose aim is to encourage the collaboration of artists and engineers. In these works, several large varifocal mirrors, some of them 1.2 meters in diameter and others 1.2 meters square, are each acoustically driven by four, 38-cm-diameter loudspeakers. The mirrors are driven for a random time interval ranging from 1 to 30 seconds with one of five randomly selected waveforms (sine waves and sawtooth waves of various frequencies); then the mirror is quiescent for a random time interval ranging from 1 to 30 seconds. The cycle then begins again with the random selection of another waveform. Certain waveforms on the mirrors are accompanied by stroboscopic illumination of the observers in the vicinity of the mirror. The strobe light frequency is adjusted to within about 1 Hz of the fundamental mirror frequency, resulting in the observer's reflected image moving back and forth along the depth axis at the difference frequency, about 1 Hz. Due to the large size of the mirrors, many high-order vibrational modes are excited, resulting in complex undulations of the reflected images.

Conclusion

Do vibrating varifocal mirrors provide the much needed autostereoscopic display device discussed earlier? In many respects they do. The hardware is simple, inexpensive, and reliable. However, a cost increase does appear in the form of additional system bandwidth requirements as compared with its two-dimensional equivalent. Ideally one should have almost as many stacked z-axis images as one has resolved spots along the x- and y-axes of the corresponding two-dimensional image. This suggests bandwidth increases of 100 to 1000 times. On the other hand, visually acceptable systems have been demonstrated using as few as 15 resolved depth planes. For specialized display systems, the cost of additional bandwidth may not be prohibitive. Furthermore, when used to display data in which most of each image plane is dark, it may be preferable to draw only the bright portions of each frame rather than raster-scan the frame completely, thus achieving a saving in bandwidth. But despite the bandwidth requirements and their other limitations, vibrating varifocal mirrors may provide an important new display technique.

FIGURE 10. Oscillation modes of the Mylar film are indicated by salt granules collected along nodal lines.



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Eric G. Rawson received the B.A. and M.M.A. degrees in physics from the University of Saskatchewan in 1959 and 1960, and the Ph.D. degree in physics from the University of Toronto, Canada, in 1966. At the University of Saskatchewan, he was active in nuclear spectroscopy and in upper atmospheric physics. At Toronto he carried out spectroscopic studies of Brillouin scattering of light by gases, studies of relaxation phenomena in gases, and the measurement of ultrasonic velocities in gases. In the course of this work, he discovered the phenomenon of the propulsion and orientation stabilization of certain dust particles through air within a laser cavity, which became known as the "runners and bouncers" phenomenon. Since 1966 he has been with Bell Telephone Laboratories, Murray Hill, N.J., where he has been working on optical information processing techniques. These include optical memories, autostereoscopic displays involving integral photography and vibrating varifocal mirrors, and the computer-automated design of complex lenses. For the past three years he has been active within "Experiments in Art and Technology," collaborating with artists on a variety of projects. He is a member of the Optical Society of America.