Ian Sexton and Phil Surman

Stereoscopic and Autostereoscopic Display Systems

An In-Depth Review of Past, Present, and Future Technologies

In this article, as in most discussions of 3D displays, we, unfortunately, need to define our terminology. Historically, authors may have used many definitions and descriptions ambiguously, often serving only to confuse the reader. For the purpose of this discussion, we will simply define a 3D display system as one which provides additional information to the observer as a consequence of the observer's being endowed with two eyes and stereoscopic vision (the former does not necessarily imply the latter, but this is an issue we prefer to sidestep).

In order for any technological advancement to gain widespread acceptance it should be capable of something new, previously unachievable, or else perform its task so much better than the existing alternative that it naturally supersedes it. As of this writing, no 3D display has been developed that could readily be described in this way. The advantages of stereoscopic viewing must outweigh any additional disadvantages, such as properties of the 3D viewing system that have been coincidentally introduced.

Stereoscopy can provide an interesting gimmick and, in this sense, has been ruthlessly exploited; Pulfrich and anaglyph television productions, children's toys, arcade games, and overzealous attempts in cinematography probably define the boundaries of common experience. Although these examples achieve their objectives in terms of sensationalism, enthusiasm soon pales as the observer becomes more aware of the sacrifices that have been made to achieve the effect. Thankfully there has always been a small, but growing number of niche application areas, where the true benefits of stereoscopy have been necessary. Advancement in the enabling technologies has led to the production of simpler stereo displays with fewer artifacts than have ever been achievable. While we might reasonably imagine that future 3D display systems will not be confined to highly specialized applications, it is conceivable that they will ultimately become commonplace in many applications from computer graphics to domestic television.

Television is the second largest consumer market after the car, yet a satisfactory implementation of 3D TV remains elusive due, in part, to the demands imposed by the viewing environment. In this article, the requirements for 3D television will be outlined, and the suitability of different display types will be considered. A brief description of our own approach is offered, which suggests that the first generation of 3D television will be a two-image system comprising a pair of images directed to the appropriate viewers' eyes. This will be achieved by means of steering optics controlled by a head-position tracker.

The Benefits of Stereoscopy

Our primary interest in stereoscopy involves its application to elicit depth and certain aspects of detail in what might otherwise be interpreted as a flat 2D image. We should note, however, that there are many other applications; the detection of counterfeit currency and documents, and the investigation of convergence disorders in ophthalmology are two diverse, but important examples. Sadly an examination of all aspects of stereoscopy is beyond the scope of this article.

At a very simplistic level, it seems only natural that we should utilize stereoscopy in the display of electronic im-

1053-5888/99/$10.00©1999IEEE

Leonardo da Vinci realized that to truly capture reality in a painting we should have two paintings, the views seen by each of the artist's eyes.

agery. We see the world stereoscopically and so, presumably, we should endeavor to recreate the visual experiences to which we are accustomed in other images. A similar argument may have been applied when color was introduced in electronic imagery, although we may recall that the widespread acceptance of color has not been achieved entirely without opposition. At its inception, color TV was considered by many as the height of extravagance with TVs being comparable in cost to a small family car. Nowadays, it is commonplace for households to possess several color TVs. Similarly, the color display has all but displaced the monochrome alternative in most computer displays. It is unlikely that we would succeed in applying this rationale to the introduction of 3D displays whose advantages, beyond being "more natural" (and possibly more sensational), can be quite subtle. Perhaps more significantly, each of the known implementations has many inherent disadvantages with which we must contend.

Seeing in Depth

Stereopsis, as an aid to depth perception, is simply one member of a set of properties commonly referred to as visual-depth cues. These properties are often classified as being either psychological or physiological although this discussion will not profit from such distinctions. Space prohibits a detailed analysis of these cues for which the reader is referred to the literature [16]. Very briefly, they include kinetic and static interposition, linear perspective, stereopsis, size constancy, accommodation, and aerial perspective. The meaning of each is fairly obvious, but a detailed study can be recommended, particularly for those involved in computer graphics, where the objectives may be clear, but computational expense dictates compromise.

Imparting an illusion of depth to an image could hardly be claimed to be a new idea. Artists have been familiar with many of the techniques for hundred of years, however some of the cues, particularly stereopsis, are rarely exploited to their fullest extent. Stereopsis has been employed in computer graphics, the graphic arts, and television systems with varying success—while the effect is reasonably well understood it can be fairly difficult to implement. There has been a fascinating diversity of approaches in the attempt to harness the power of these depth cues. The following section summarizes some of the prominent techniques.

3D Display Techniques—A Brief History

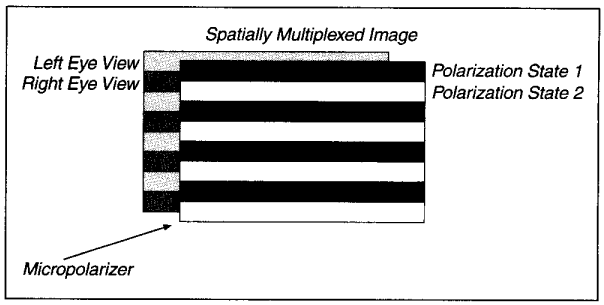
The desirability of stereoscopic imagery has been understood for many years; Leonardo da Vinci realized that to truly capture reality in a painting we should have two paintings, the views seen by each of the artist's eyes. Giovanni Battista della Porta practiced this technique in his stereoscopic drawings at the turn of the 17th century, but it was Euclid, the philosopher and father of classical geometry, who laid the foundations of stereoscopic "art" almost 2000 years earlier when he wrote, "To see in relief is to receive by means of each eye the simultaneous impression of two dissimilar images of the same object." [38]

It remains a mystery how della Porta and his contemporaries viewed their drawings because it was not until 1832 that Charles Wheatstone proposed what was probably the first practical stereoscopic display device, which he subsequently presented before the Royal Society. Wheatstone's stereoscope, somewhat refined, is still commonly used in photogrammetry. Unfortunately, his stereoscope was cumbersome and photography was still in its infancy; consequently, it was not particularly successful. The stereoscope was popularized by Brewster's introduction of a more compact device in 1849, which, following refinement by Oliver Wendell Holmes went on to become the ubiquitous Victorian "parlor stereoscope."

The essence of Wheatstone's original system, and most subsequent systems, is the presentation of disparate views to each eye. The variety of possible methods to achieve this is reflected in the diversity of the many techniques that have been developed since. Many of the techniques available to us today are derived from earlier photographic systems. Not all are readily compatible with electronic display devices, and of those that are, some are clearly best suited to particular applications.

Display Systems

It is useful at this point to draw a broad distinction between display types. Many display systems require the observer to wear some kind of headgear, usually in the form of special glasses. These systems are generally referred to as being *stereoscopic*. Displays that do not require such

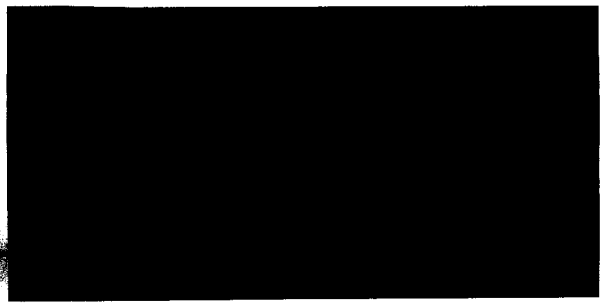


▲ *1. The Dimension Technologies approach.*

aids, and can be freely viewed, while still being stereoscopic are usually dubbed *autostereoscopic*.

Stereoscopic Techniques

The variety of stereoscopic displays is limited to only a handful of known implementations. Apart from variations on the stereoscope, the other techniques invariably require headgear, which ensure that the appropriate view is seen by each eye.



▲ 2. Chromostereopsis.

The Stereoscope

Probably the simplest form of stereoscopic display is merely an adaptation of the early stereoscopes, in which the photographic images are replaced by electronic ones. Although the optical systems in such displays are not necessarily trivial, the method of operation is conceptually fairly obvious. Modern head-mounted displays exemplify the state of the art using this approach.

Anaglyph Techniques

These displays employ color-separation techniques as the means of achieving stereopsis (the term "anaglyph" does not require this, but is commonly used imprecisely to describe such color-separation methods). Both components of the stereo pair are presented on a single display device in complementary, or near-complementary colors, typically red and green. The viewer's glasses, containing filters or lenses corresponding to the colors of the two images, direct the appropriate image to each eye. This approach was first demonstrated by D'Almeida in 1858, however the most significant demonstrations of the technique were by Lumiere in the 1920s. Lumiere produced the first effective stereoscopic cinema films [53].

This approach is probably familiar to most of us, having been used many times in the cinema, TV, and in print. The quality of the spectators' glasses (in terms of how well they are matched to the display) are considered to be a vital element in the success of the anaglyph technique [32]. A major disadvantage of the technique is that the use of differently colored filters causes retinal rivalry. Furthermore, it is not possible to display color images, although methods have been devised to display the source material monoscopically in color [6]. The main advantages of this approach are that its relative simplicity makes it economical, several viewers can easily observe the same image, and this is one of the few approaches that lends itself readily to the production of hard copies.

Polarized Displays

The polarization method is probably the most familiar technique, having been used almost exclusively in recent 3D cinema productions (despite being over 100 years old!). Polarizing filters (plane or circular) that are placed in front of a viewer's eyes and oriented at right angles ("antagonistically" may be a better description in the case of circular polarizers) to one another provide an excellent means of maintaining separate channels of visual information [20]. Typically, the stereo pairs to be viewed are projected through polarizing filters oriented to conform with the "angles" of those worn by the viewer onto a non-depolarizing screen [42]. Stereo pairs may also be displayed on two CRTs by arranging them at right angles and by using a partially silvered mirror arranged at 45 between them. Polarizers are placed directly on the monitor screens and the filters are oriented at right angles to one another.

The plane-polarized display is somewhat compromised by the tendency for ghosting or crosstalk to occur if the viewer's head is not maintained in the correct position [2]. It also suffers from a loss of light intensity due to the polarizers. Circular polarizers can alleviate the problem of ghosting due to the viewer's head orientation, but tend to have an even higher transmission loss.

A technique that uses only one display screen together with a spatially multiplexed image was originally described by [8], but a practical realization of this proposal using *micropolarizers* is a fairly recent innovation [12]. The μPol™ optics technology consists of an array of microscopically small polarizers with a resolution of up to 1000 lines/cm. These are arranged in horizontal lines of alternate polarization and aligned with a spatially multiplexed image (Fig. 1); an image consisting of alternate strips of left and right eye views.

As with the other polarized displays, the image is viewed using passive polarized glasses. The vertical resolution of the images is halved using this approach.

Field/Frame Sequential Displays–Active Glasses

These displays incorporate shuttering glasses, a display, stereo image generator, and a system for synchronizing the components [40]. Typically the images are presented sequentially on the display using odd and even fields of the television interlace. The monitor is viewed using special glasses with PLZT or, more recently, liquid-crystal lenses that obscure the eyes alternately so that each eye only sees one of the images. This is not a new idea, but has only become practical because of developments in electro-optical technology. Also, many systems suffer from bad flicker due to the use of a low field rate. This problem is often overcome by using twice the normal vertical scan rate.

Field/Frame Sequential Displays–Passive Glasses

Most of the polarized displays described previously use separate sources for the left and right images in the form of CRTs, but it is possible to use a single CRT. The simplest way that this is achieved is by allocating separate areas of the screen to the left and right images, and using separate polarizing filters for each area. A better approach is to sequentially display left and right views (typically the odd and even fields in an interlaced system) with opposite polarization. This may be achieved by synchronizing an electro-optic device (invariably liquid crystal) with the vertical retrace of the display, the device being located close to the CRT face. This technique was originally devised to display successive fields as different colors in an effort to synthesize a color image from a monochrome source, the purpose being to eliminate the shadow mask in conventional color CRTs.

It is an interesting notion that a full-color stereoscopic image may be generated from a monochrome CRT mated with suitable electro-optic filters [21]. This feat is achieved in practice in the Cambridge Autostereoscopic Display described later, but it is perhaps, even more surprising that a mechanical implementation of this technique was demonstrated by J.L. Baird in 1941 [19].

Systems based on this technique are commercially available from Tektronix (π-cell) and Stereographics (Z-Screen). A potential advantage over shuttered spectacles (as claimed by Tektronix [4]) is the reduction of ghosting due to phosphor afterglow. This is achieved by dividing the liquid-crystal device into two horizontal strips. Rather than attempting to switch the entire device during the vertical retrace, the upper half is switched after the upper half of the raster has been drawn, and similarly with the lower half. Whether this is a design feature or a fortunate side effect of a technique devised principally to achieve the required switching speed is debatable, however the effect is excellent and is one of the best commercial stereoscopic systems available. Another, rarely cited advantage is a reduction of flicker. A system using shuttered glasses, even with the same refresh rate, will be more prone to flicker because ambient lighting can stimulate the viewer's peripheral vision through the shutters.

Chromostereopsis

It has been known for many years that appropriate use of color can impart an illusion of depth to an otherwise flat image. The use of super-chromatic prisms in Steenblick's system [45] exaggerates the natural effect and produces very impressive results with an appropriate source image. However, this technique should be seen as a tool for visualization rather than a general-purpose stereoscopic viewing system. That chromostereopsis could be considered to be autostereoscopic as headgear is not strictly necessary, however the effect is not reliable in its operation as Fig. 2 [25] suggests and possibly demonstrates.

Historically there have been two dominant techniques based upon parallax barriers and lenticular arrays, and variations on these themes remain popular today.

The Pulfrich Effect

If we observe a simple pendulum swinging to and fro in the frontal plane, and cover one eye with a darkened filter while doing so, the perceived motion of the pendulum is as though it is describing an ellipse and not its actual "linear" trajectory. Pulfrich [39] explains this phenomenon in terms of the response times of our eyes. In much the same way that a photographer uses a slower shutter speed in low light, it appears that our eyes take longer to integrate the light to form an image in such conditions. When the observed scene is stationary, this is of no consequence, but when motion is involved, the uncovered eye "sees" the pendulum in one position and the covered eye sees it where it was some time previously. This artificially induced disparity convinces the observer that the pendulum is swinging elliptically. This might seem to have very little to do with 3D TV, however, the effect is very simple to harness for use in video or TV, providing the simplest strategy for stereo television display that retains full color, no loss in resolution, and no additional bandwidth requirements.

If rather than observing an actual pendulum we observe an image of a pendulum on a TV display, the effect is preserved. In fact, any image that exhibits lateral movement will also exhibit the Pulfrich effect—a film of a parade marching past, for example (such a Pulfrich video was promoted in 1989 by the Coca Cola company in the U.S. [15], and this technique was used exclusively by the BBC in their 3D-TV week in 1994). The scene need not have natural movement, moving the camera has the same effect.

While this effect is very simple and quite dramatic, it obviously suffers severe limitations. The foremost objection being that it would be unacceptable (and impractical in many cases) to have a constant lateral movement in every TV image. A problem also occurs in obtaining a disparity of left and right images, which corresponds to a true stereo effect. To achieve this, we need to know the difference between the integration times of the eyes, if the camera platform is moved a distance equal to the inter-ocular distance in this time then the effect is guaranteed. Unfortunately, rather than use the integration times to produce the correct disparity, it turns out that the effect is traditionally used to compute this difference in latencies as a function of luminance [31]. Clearly the Pulfrich effect applied to TV is not acceptable for general viewing.

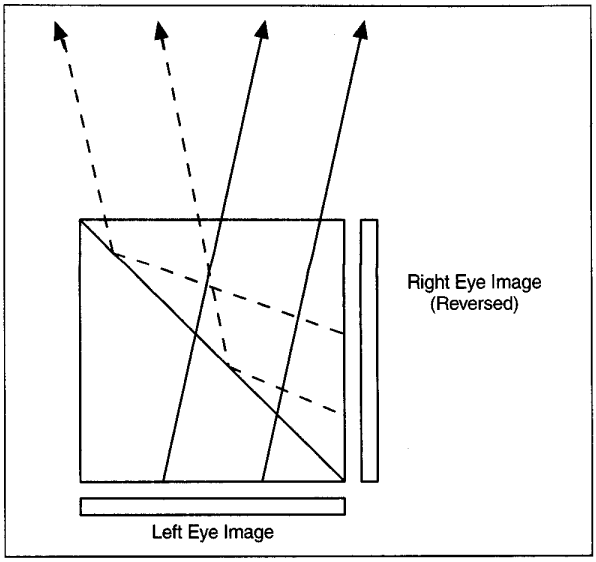
Autostereoscopic Techniques

Being barely over a century old, autostereoscopic displays are a relatively new concept! Historically there have been two dominant techniques based upon parallax barriers and lenticular arrays, and variations on these themes remain popular today. The electronic age has witnessed a resurgence of interest in 3D display techniques that has led to the development of many display systems that were previously unrealizable.

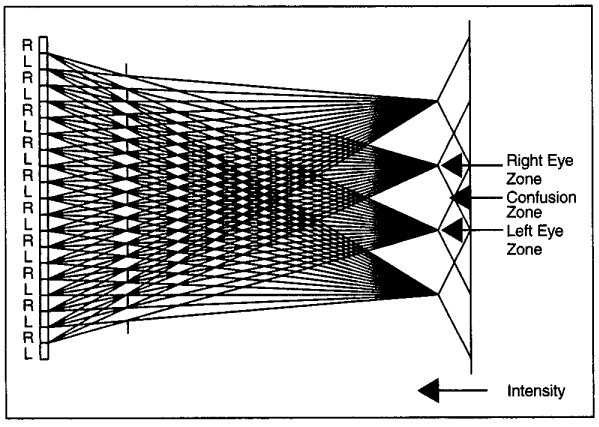
The three basic autostereoscopic display types are *holographic*, where the image is formed by wavefront reconstruction, *volumetric* where the image is formed within a volume of space without the use of light interference, and *multiple image* where different two-dimensional images are seen across the viewing field.

Swan's Cube

The earliest known autostereoscopic imaging device was demonstrated by H. Swan in 1862. The cube is constructed from two triangular prisms (Fig. 3). Light from one of the images is seen directly through both prisms by one eye, whereas light from the other image undergoes total internal reflection at the interface and is directed to the other eye. The original images produced by this technique were extremely small, but Swan's technique was (briefly) revisited by The Bright and Morning Star Company in California who assessed its potential for autostereoscopic television [28]. Their system used two matched TV monitors arranged at right angles with a diffractive optical element placed at 45 between them.



▲ *3. Swan's cube.*



▲ *4. The parallax barrier.*

Parallax Barrier Systems

The parallax barrier method of 3D display is probably the oldest-known autostereoscopic technique that is capable of preserving horizontal parallax. The original proposal made by F.E. Ives [22], [23] at the turn of the century, consisted of a fine vertical slit plate or grid superimposed upon a specially prepared photograph comprising fine alternate vertical strips of left and right eye views (Fig. 4). The principal of operation is very simple: assuming that the geometry is correct, each eye sees only one set of image stripes and is prevented from seeing the other by virtue of the barrier effect of the grid.

A major limitation of Ives parallax stereogram was its restricted viewing position. Kanolt [26] overcame this limitation with the "parallax panoramagram" (Fig. 5). A simple extension to Ives approach, Kanolt's method was to reduce the width/pitch ratio of the grid, facilitating a much wider viewing angle and preserved horizontal parallax. Apart from some experimental work by H.E. Ives [24], there was little development of this approach for many years.

Integral and Lenticular Techniques

Parallel with the development of parallax barrier techniques was the development of integral photography. These systems have much in common, like a lens and a pinhole have many similar properties. Pioneered by M.G. Lipmann [30], the original proposal for integral photography comprised a "fly's-eye" lens sheet and photographic plate. Interestingly, the first practical realization of integral photography, which is attributed to Sokolov in 1911 [53] actually used a pinhole sheet due to difficulties in producing lens sheets.

Integral photography preserves both horizontal and vertical parallax. It was argued that because our eyes are horizontally disposed, it should be possible to dispense with the vertical parallax information, just as the parallax stereogram and panoramagram do. This led to the development in the late 1930s of what has come to be known as lenticular sheet photography (Fig. 6).

A very simple, and effective 3D display system can be produced using lenticular screens, and most of us are probably familiar, perhaps without realizing it, with such autostereoscopic images. With the exception of a hologram, any 3D postcard or photograph that does not re-

3D TV should supply stereo to several viewers who are reasonably free to move throughout the room. Most contemporary autostereoscopic displays constrain viewers to a fairly rigid viewing position.

quire special glasses or viewing devices probably uses this technique. It is characterized by a convoluted plastic screen on the surface of the image that directs slightly different images to each eye. This technique is commonly used as a gimmick, although in recent years the American Nimslo [29] system attempted to introduce the effect into "serious" photography.

Holography

Holographic images provide the viewer with a richness of depth cues associated with true 3D viewing that most autostereoscopic displays lack, namely binocular convergence, accommodation, motion parallax, and occlusion. This is achieved by recording the fringe pattern caused by interference between illumination of an object and a reference beam from a coherent light source [13]. The resulting hologram is, therefore, not simply a pixel-by-pixel representation of the illumination of a scene, but a record of the phase and amplitude of the illumination of the scene.

Although holography has enjoyed widespread exposure, its success as a general 3D display medium has been limited. Moreover, the generation of holograms by electronic means presents a significant challenge.

The Requirements of 3D TV

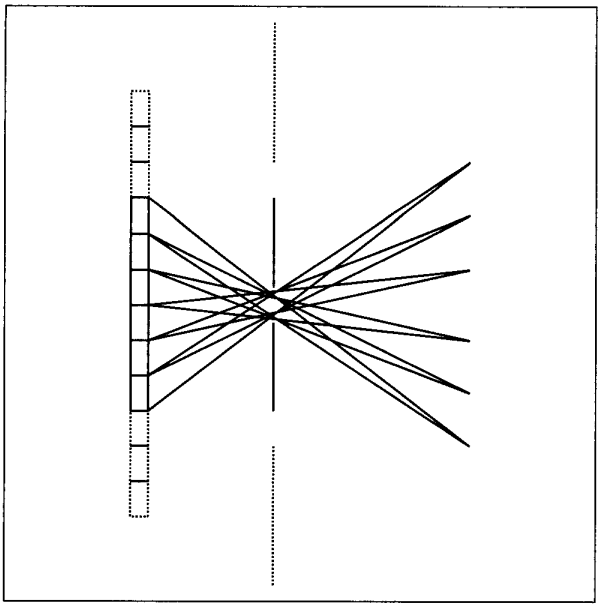
Cost should be an important consideration as there is little doubt that 3D television displays will be significantly more expensive than current monoscopic sets. However, when color television was introduced, the cost of a color set was around five times that of black and white, yet this did not deter consumers from buying them.

It is a widely held belief that 3D television should be autostereoscopic. Although the continuous wearing of glasses might be acceptable for cinema where viewing is uninterrupted, television tends to be more casually viewed.

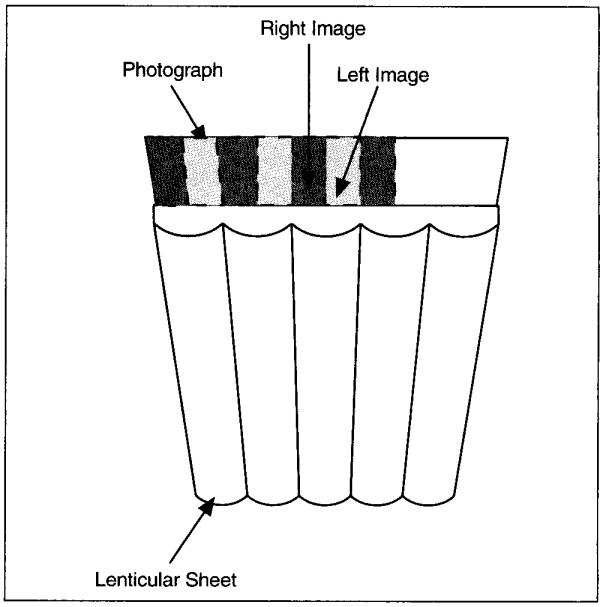
The typical viewing requirement for television will be the presentation of stereo to several viewers who occupy a typical living room. This is in contrast to computer monitors and arcade games where one viewer may be positioned over a relatively small area, or cinema where there may be hundreds of viewers located in fixed positions throughout an auditorium. 3D TV should supply stereo to several viewers who are reasonably free to move throughout the room. Most contemporary autostereoscopic displays constrain viewers to a fairly rigid viewing position.

The overall size of the set should not be too large. Some systems where moving projectors are used [50], or where two images are produced by two separate screens [11] would require a housing size that would probably be unacceptable in a domestic setting.

Finally, if 3D television is to be realized in the foreseeable future, it must use a technology that is available. There is little point in proposing a system that requires say, many millions of pixels or hundreds of Hertz video rate, if suitable devices are unlikely to be available.



▲ *5. The parallax panoramagram.*



▲ *6. Lenticular photograph.*

Even if it were practical, the use of 96 separate frames per displayed image might prove problematical in terms of bandwidth!

The Television Age

The advent of electronic displays in the form of cathode ray tubes sparked a revival of interest in many of the techniques outlined previously. In some instances, it has been possible to simply replace a photographic image with an electronic one, but advances in the enabling technologies has also facilitated the development of many displays that were previously unrealizable.

Volumetric Displays

Sometimes described as "space filling," these display types tend not to rely upon flat displays, but generate an image that occupies a volume.

Moving Screens

These are 3D displays that create the illusion of depth by presenting a sequence of 2D cross-sections of a 3D volume in rapid succession [43], [56]. As the cross-sections are presented intermittently, they are positioned appropriately with respect to the observer. This can be accomplished by using either translating or rotating screens and/or mirrors. These multiplanar techniques represent an important part of 3D imaging in scientific applications. Since, in some cases, conceptualizing the 3D structure represented in 2D cross-sections can be difficult without a suitable display to combine the multiple planes into a 3D image.

Varifocal Displays

Another means of displaying multiplanar information is the varifocal mirror display [48]. Early systems used a membrane mirror driven by an audio loudspeaker. When the speaker produces a tone, the mirror alternates between convex and concave extremes. If a CRT is reflected in the mirror, the image on the monitor will appear to advance and retreat as the mirror is deformed. The CRT, therefore, presents a sequence of cross-sections of an image in depth. The display of these cross-sections is synchronized with the vibrating mirror so that, when viewed by reflection, each cross-section appears to be located at its appropriate depth. A peculiarity of this optical arrangement is that as a reflected image appears to retreat in the vibrating mirror, it is also magnified. To counteract this effect, the more distant images displayed on the monitor must be appropriately reduced in size. Viewers are able to move their heads freely to see over and around the foreground detail. Generally, these displays have a limited display volume and are mainly used in computer graphics, although attempts have been made to apply this technique to 3D TV [27].

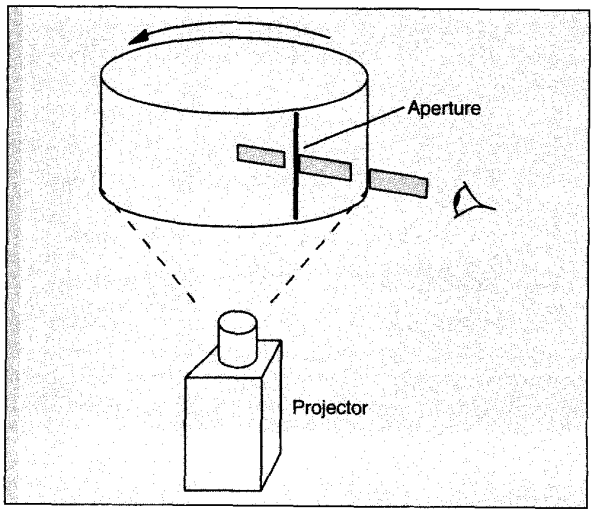
Resonant Absorption Displays

A conventional monoscopic CRT has two essential components: a steerable electron beam and a phosphor. When the beam impinges upon the phosphor, it fluoresces. If it were possible to produce a phosphor that occupied a volume rather than a flat surface, and then, if it were possible to address areas within this volume, a volumetric, and potentially 3D, display would result. Although this is a very simplistic explanation, a display system that operates in an analogous fashion has recently been described and demonstrated by Downing et al [9]. The operation of their device is explained very succinctly in their article:

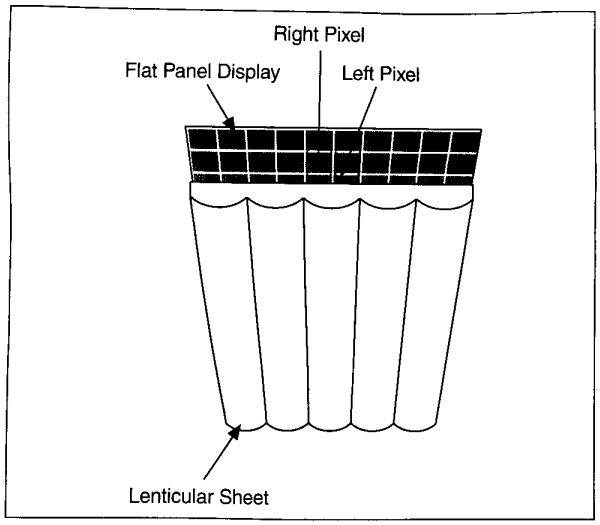
> The device uses infrared laser beams that intersect inside a transparent volume of active optical material to address red, green, and blue voxels by sequential two-step resonant absorption. Three-dimensional wire-frame images, surface areas, and solids are drawn by scanning the point of intersection of the lasers around inside of the material. The prototype device is driven with laser diodes, uses conventional focusing optics and mechanical scanners, and is bright enough to be seen in ambient room lighting conditions.

It is thought that this type of display is very costly to produce, and the mechanical nature of the scanners is undesirable, however, these would probably be easier to eliminate than the mechanical attributes of many other volumetric display systems. Tilton also describes a conceptually similar system [47].

A characteristic of multiplanar displays is that the 3D image is transparent. That is, background information



▲ *7. Collender's stereoptiplexer.*



▲ *8. Lenticular display.*

can be seen through foreground information. While this "unrealistic" effect can be a benefit in analytical work, it can, of course, be a disadvantage in applications such as TV, where such an image would cause confusion.

Parallax Barrier Techniques

In 1932, V.K. Zworykin [58] proposed a TV system with vertical scanlines—alternate scanlines being keyed to left and right images. This was, in fact, no more than a repetition of F.E. Ives original parallax stereogram proposal, and in 1953, G. Bradshaw made a similar proposal [5] which appears to be based upon Kanolt's parallax panoramagram.

A recent innovation in this area involves an "inversion" of the parallax barrier arrangement. Carefully structured backlighting of a transmissive (LCD) display panel forces each eye to see different sections of the display device [10].

The Stereoptiplexer

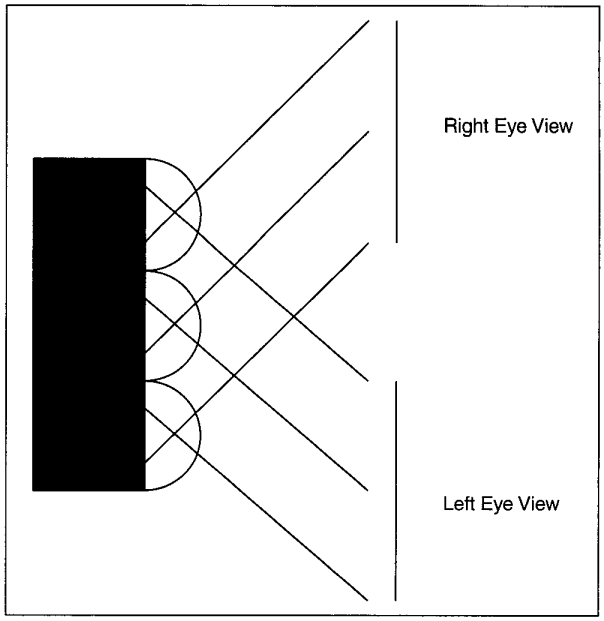
In 1967, R. Collender published details [7] of a display system that used a different type of parallax barrier. Instead of using a grid, he used a single, rapidly moving vertical slit (a slot cut in a cylindrical drum). This system could not use a composite image as in the aforementioned stereogram and panoramagram because the scanning slit could not step discreetly to the relevant grid positions. Instead, many separate photographs (96 in total) are taken from different horizontal angles and subsequently processed to form a continuous loop of cine film. The film is then projected into the drum. By virtue of the rapidly changing images and the moving slit, a 3D reconstruction is seen within the drum (Fig. 7). Being an entirely mechanical system, the stereoptiplexer has serious limitations. It is best suited to displaying still images, and the use of film as the image medium is not compatible with television or computer graphic applications. Even if it were practical, the use of 96 separate frames per displayed image might prove problematical in terms of bandwidth! Despite its limitations, the stereoptiplexer represented a fascinating and diverse approach to the problem. It would be churlish to deny Collender the credit for this invention although it does bear a remarkable similarity to the zoetrope. First described by the English mathematician William George Horner in 1834, the zoetrope is also based upon a rotating drum with vertical slits encircling a sequence of photographic images, however, the purpose was to display moving pictures rather than 3D ones.

The Parallactiscope

In 1968, inspired by Collender's work, H.B. Tilton set about producing a 3D display that used an electronic display rather than photographic images. Tilton's approach was to use a cathode ray oscilloscope (CRO) [46]. While still unsuitable for TV applications, this may be thought of as a step in the right direction. The use of a CRO heralded other departures from Collender's work; the stereoptiplexer allows the viewer complete 360° horizontal freedom of movement around the display volume (the slotted drum). Without elaborate optics, this would not be possible with a CRO, and so a different arrangement is used for the scanning slit, this comprises a narrow vertical strip of half-wave retarder that moves from side to side between crossed linear polarizers.

In some respects, the parallactiscope is the ultimate scanning slit parallax barrier system. It is an analog instrument in every sense—neither the image nor the scanning slit change discreetly, but continuously so that within the display envelope, the horizontal parallax is truly continuous and not some discrete approximation.

Despite its many virtues, the parallactiscope is not without limitations. Its purpose is to apply 3D imaging techniques to oscillography, i.e., to display 3D wave-

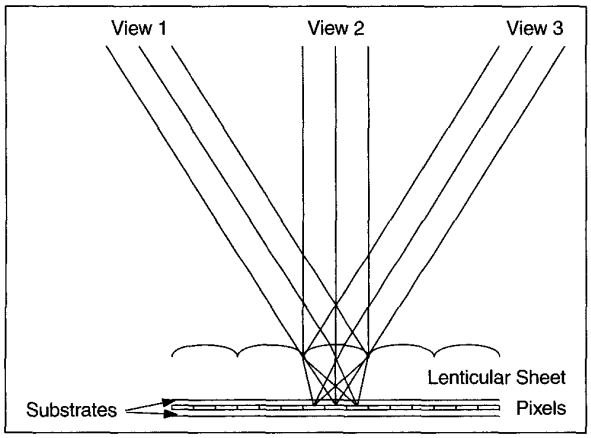


▲ *9. Using sub-pixel addressing.*

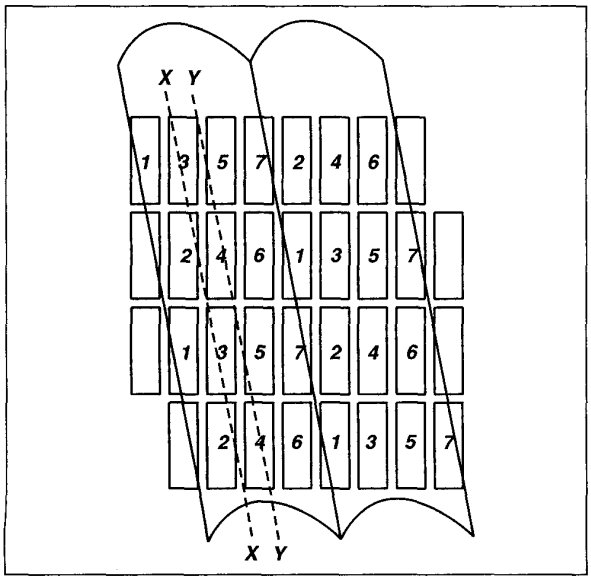
forms (or "spaceforms," as Tilton calls them). This device cannot display images of the type we would expect to see on television or computer displays, nor does the technology used lend itself readily to such applications. Recent research in this area involves the use of advanced ferroelectric, liquid-crystal devices to implement the scanning slit in the hope of applying this technique to television and computer-generated imagery [41].

Lenticular Systems

A practical difficulty in producing such images is the alignment of the lenticular screen with the source image(s). Close lamination satisfies this criteria in a photograph, but unfortunately, it is not as simple with a CRT. In that case, it would require a truly rock-steady picture, probably with a special CRT such as a beam-indexed tube, compounded with the problem of CRT's curved face. A number of proposals have been made that use CRTs [55], [1], [14], but the authors are not aware of



▲ *10. Three-view lenticular display.*



▲ *11. Philips' slanted lenticular.*

A particular frustration for the would-be display developer is the arrangement of the RGB triplet in readily available flat-panel displays. Typically, these have a 4:3 aspect ratio with the RGB sub-pixels arranged horizontally in a line.

any practical implementations apart from projection systems. The future may hold the answers to these problems; LCDs are just one of the emerging flat-screen display technologies and they are beginning to compete realistically with CRTs.

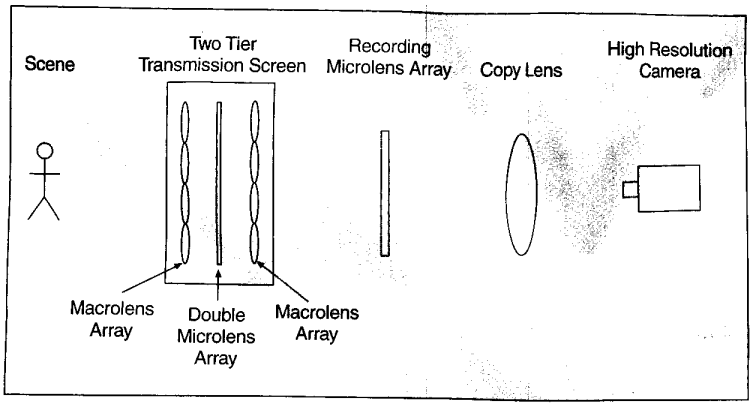
This technique can be implemented very simply using a LCD and a lenticular sheet, with its lenses running vertically. The principle of operation is shown in Fig. 8. The liquid-crystal layer lies in the focal plane of the lenses, and the lens pitch is slightly less than the horizontal pitch of the pixels in order to give viewing zones at the chosen optimum distance from the screen.

A particular frustration for the would-be display developer is the arrangement of the RGB triplet in readily available flat-panel displays. Typically, these have a 4:3 aspect ratio with the RGB sub pixels arranged horizontally in a line. Consequently, it is necessary to operate a "simple" lenticular display [3] in portrait mode, thereby halving the resolution of the display in the (now horizontal) worst direction. Sub-pixel addressing can counter this effect to some extent, in which case, the RGB triplet of the monoscopic, off-the-shelf, flat panel does not constitute a pixel in the stereoscopic adaptation [37] (Fig. 9).

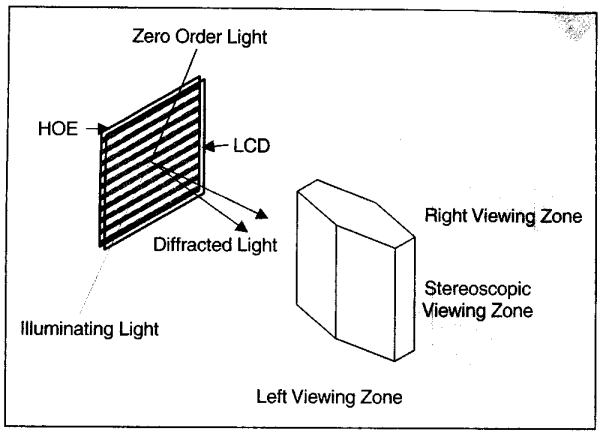
Multiview Lenticular Systems

A multiview stereoscopic display is one where a series of discrete views is presented across the viewing field. One eye will lie in a region where one perspective is seen, and the other eye in a position where the adjacent perspective can be seen. Previously, without recourse to multiple projections, this approach was unrealistic due to the loss of resolution involved, but has become practicable as high-resolution flat-panel displays have become available. In Fig. 10, three columns of pixels contribute to three viewing zones. The implementation is much the same as that of the "two-view" system in Fig. 8. In essence, the number of pixel columns covered by a lenticule determines the number of views.

A simple multiview display with this construction suffers from two quite serious drawbacks. Firstly, the black mask between the columns of pixels in the LCD gives rise to the appearance of vertical banding on the image, commonly referred to as a "picket-fence" effect. Secondly, when a viewer's eye traverses the region between two viewing zones, the image appears to flip between views.



▲ *12. Single-step integral image capture.*



▲ *13. Using a HOE.*

These problems have been addressed by Philips Research Laboratories in the U.K. [54], by the simple expedient of setting the lenticular sheet at an angle in relation to the LCD. As an observer moves sideways in front of the display, he or she always sees a constant amount of black mask, therefore rendering it invisible, and eliminating the appearance of the picket-fence effect. The transition between adjacent views is also softened so that the appearance to the viewer is closer to the continuous parallax of natural images rather than a succession of flipping views.

Fig. 11 shows the relationship between the pixels and the slanted lenticular sheet for a seven-view display. Because the LCD is located in the focal plane of the lenticular sheet, the horizontal position on the LCD corresponds to the viewing angle. As a result, all points on the line XX directly view 3 in a given direction and all points on line YY direct view 4 in another direction. The way in which the flipping effect is reduced is evident by examining line XX where view 3 predominates, but has some contribution from view 2. Similarly, for the angle corresponding to line YY, view 4 with some contribution from view 5, is seen. As the observer moves laterally, he or she sees a mixture of views that changes gradually rather than abruptly.

Although, by their very nature, multiview displays are limited, owing to the size of the usable viewing region, the actual appearance of the Philips display is remarkably good, especially bearing in mind its simplicity. However, it is unlikely to form the basis of a television system.

Integral Imaging

Research at De Montfort University (UK) involves the use of integral imaging to produce an electronic autostereoscopic display with full-motion parallax [37]. If a photographic emulsion is located in the focal plane of an array of small lenses, parallax information is recorded. If this information is used to reconstruct an image after being developed, the image produced will be pseudoscopic, that is, it will be stereoscopically inverted. In traditional photographic systems, the image would be restored to its original orthoscopic form by means of a second capture stage.

The implementation of the display is shown in the schematic diagram in Fig. 12. The optical transfer required to produce images *could* be achieved by using a semi-silvered mirror and a retro-reflecting screen. The disadvantages of this arrangement being light loss at the semi-silvered mirror, and the relatively low-modulation transfer function of the retro-reflecting screen. For these reasons, a two-tier transmission screen has been adopted for the first stage of the capture system.

This screen consists of three stages. The first stage is an input macro lens array that produces a series of real images. Within the volume of these images lie two, back-to-back microlens arrays that have a common focal plane. Light leaving these arrays is focused by an output macro lens array into a single pseudoscopic image. The recording microlens array is situated within the volume of this pseudoscopic image. It is the image on the focal plane of this array that is transmitted to the display, which is simple, consisting merely of a high-resolution TFT LCD and a microlens array.

The resolution required is higher than that necessary for 2D imaging, but the team working on the project anticipates that an increase in the information content by a small factor will enable the transmission of full parallax images.

Holographic Optical Systems

The optical properties of the lens sheet tend to limit the performance of conventional lenticular and integral systems. However, a stereoscopic display where left and right viewing zones are produced in front of the screen can be implemented by using holographic optical elements (HOEs) to form the zones. The HOE is an off-axis transmission hologram that produces a real image of a diffuse object. This image can be of any required shape and have even brightness across its surface. This enables the formation of regions where either a left or a right image is seen when the HOE is used to direct the backlight of an LCD.

Owing to the manipulation of light required, a transmission display as opposed to an emissive one must be used—an LCD. As a left image has to be seen in one zone and a right image in the other, the screen must display two images. This can be achieved in three ways. Twin LCDs whose images are combined by a semi-silvered mirror can be used to provide a full-resolution image [11], but the resulting display is bulky and expensive. The left and right images *could* be presented sequentially on one display if a sufficiently fast device were available, and this would give no loss of vertical resolution. The third option is to employ spatial multiplexing where the left and right images are presented on either alternate rows or columns of pixels.

The HOE display of RealityVision uses alternate rows for the image pairs [52]. This enables the use of available LCDs contained within a moderate housing size. As shown in Fig. 13, an HOE that is aligned with the rows on an LCD can form separate viewing zones for each of the images. This is a very neat solution to the problem as it combines both image multiplexing and viewing zone formation in one operation.

Electroholography

Obviously it would desirable for a stereoscopic display to produce, in real time, images that exhibit all the characteristics of the original scene. This would require the reconstructed wavefront to be identical to that of the original scene, and could only be achieved using holographic techniques. The difficulties of this approach are the huge amounts of computation necessary to calculate the fringe pattern, and the high resolution of the display that has to be of the order of a wavelength of light. Approximately 10 million discretized samples per square millimeter are required to match the resolution of an optically produced hologram.

An electroholographic display was first demonstrated by the Spatial Imaging Group at MIT in 1989. They created an image the size of a golf ball by using an acousto-optic modulator (AOM) and moving mirrors [33], [34]. Computation of the fringe pattern took several minutes using traditional methods. The speed of this was limited by the large number of samples in the discretized fringe pattern, and by the complexity of the physical simulation of the light propagation used to calculate each sample value.

Another strategy employed to reduce the information content in the fringe pattern was to dispense with vertical parallax. This reduced the spatial resolution required in the vertical direction from around 1000 lines/mm to approximately 10 lines/mm, therefore giving a reduction factor of roughly 100 in the information content. A horizontal-parallax-only hologram can be considered as being an array of one-dimensional holograms known as hololines. Each of these hololines diffracts light into a single horizontal slice of the image.

The future of electroholography depends on more computing power, higher-bandwidth optical modulation, and improvements in holographic information processing.

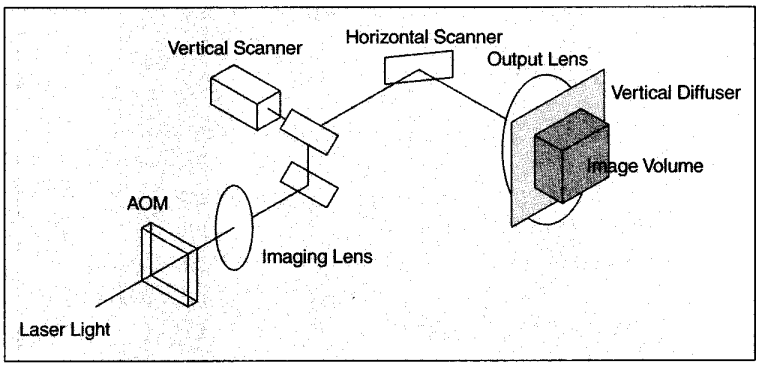
The use of a time-multiplexed AOM makes the display configuration similar to the Scophony television system of the 1930s. The AOMs are crossfired (run alternately in each direction) to provide a bidirectional Scophony geometry that utilizes the mirror scan in both directions.

The hardware of the display is very large in relation to the size of the image (150 x 75 x 150 mm). The most recently published work by MIT describes a large he-ne laser, an 18 channel AOM, a vertical scanning mirror, a beamsplitter, six tiled galvonometric horizontal scanners, a screen-sized output lens, and a vertical diffuser. This is shown in the simplified schematic diagram in Fig. 14.

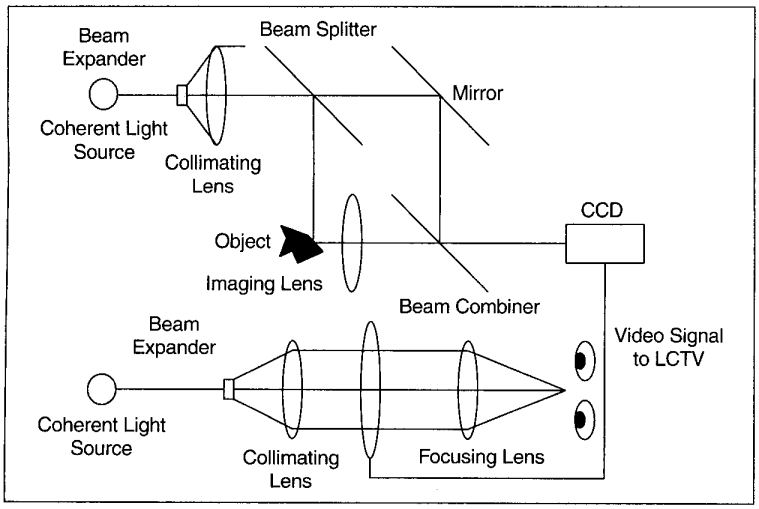
Moving parts can be eliminated by replacing the AOM with an LCD. One of the projects within a five-year initiative by the Telecommunications Advancement Organization of Japan (TAO) utilizes a 15-million-pixel LCD that consists of five separate LCD panels [35]. This produces an image that is 50 mm wide, 150 mm high, and 50 mm deep. The viewing zone is 65 mm wide at around 1 m distance. As in the MIT display, vertical parallax is abandoned.

A pulsed laser light source can be used to eliminate the galvonometer mirrors or rotating polygon mirrors that are generally used to "freeze" the motion of the acoustic waves on the AOM. A combined Korean/Russian team is working on a system that gives a 74 x 50 x 50 mm image with a 60 Hz frame rate [44].

A holographic display using a CCD camera to record fringe patterns, and an active-matrix LCD has been described [18]. As shown in Fig. 15, a he-ne laser is used to generate the hologram. The beam is split by a semi-silvered mirror into the object beam and the refer-



▲ *14. MIT's electroholographic display.*



▲ *15. Hashimoto's electroholographic display.*

ence beam. The light diffracted by the object interferes with the reference beam at the CCD where the image is recorded. This hologram is transmitted to the LCD, which is illuminated by a second he-ne laser to produce the image.

The future of electro-holography depends on more computing power, higher bandwidth optical modulation, and improvements in holographic information processing. Computing power is likely to increase sufficiently quickly to support electro-holography within the next few years. Possible candidates for the optical modulators could be the digital micromirror device (DMD) and active-matrix LCDs constructed directly on a semiconductor chip.

The Cambridge Autostereoscopic Display

This display presents stereo to a viewer by providing a series of discrete views across the viewing field. Unlike the multiview lenticular system described previously, which uses spatial multiplexing, the Cambridge display uses temporal multiplexing, where the series of images is presented in sequence [51].

The operation of the display can be best understood by imagining a transmission LCD (Fig. 16). If a large Fresnel lens is located adjacent to the LCD, a vertical illumination source behind the lens will form a real image in the viewing field. This image is the exit pupil for the view being displayed on the LCD at that particular time. The illumination will be even over the complete area of the LCD, and the view will only be visible over the area of the exit pupil.

If the adjacent view is next displayed on the LCD, the illumination source moves laterally to form an exit pupil in a position next to the previous one. This process is repeated until the complete series of views is presented across the viewing field. Operation in this mode would require the LCD to be running at N times the normal video rate where N is the number of views.

Because a sufficiently fast LCD is not currently available, the display is implemented using a CRT that can operate at the necessarily high frame rate. Instead of a view being displayed on an LCD, it is projected onto the Fresnel lens by a second lens located where the illumination sources were, and the illumination sources are replaced by a ferroelectric liquid-crystal shutter.

Various versions of the display have been built with up to 16 views and with color and monochrome images, in which color is obtained by using sequential liquid-crystal shutters. Recent work involves the use of a display with a 25-in. diagonal screen with 15 full-color 400 x 300 pixel views.

Head-Tracked Binocular Displays

Currently, bandwidth limitations of both the transmission channel and the display device itself hamper the viability of systems that use multiple views, or attempt to display a 3D continuum. Fixed-view binocular displays are unlikely to be acceptable for television applications as viewers are denied freedom of movement. One way of enabling freedom of movement for the viewer, but without the need to transmit and display large amounts of information, is to track the position of the viewer's eyes and ensure that the appropriate images are directed to those eyes.

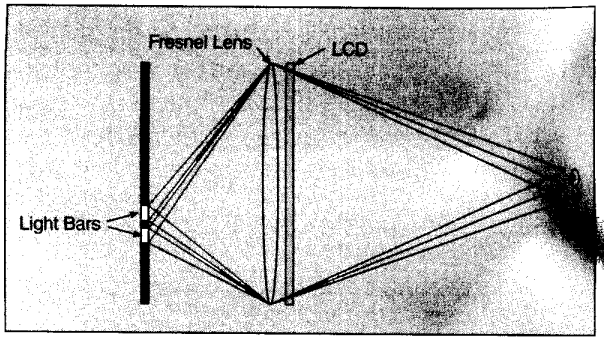
It is difficult to imagine how the light from an emissive display could be manipulated to produce multiple, steerable exit pupils, which is unfortunate as emissive technology is advancing quickly. Consequently, the options for binocular displays lie with projection, or with transmission displays utilizing either field-sequential or single-screen spatial multiplexing.

There have been several proposals for projection displays that use projector pairs moving around behind a double lenticular screen [49], [50]. If the front and back lenticulars have the same pitch and focal length, exit pupils at "mirror-image" positions are produced in front of the screen. Problems with this approach are that a projector pair is required for each viewer, and the projectors need to move over an area as large as the viewing field in order to give viewers freedom of movement. Variants of this method using a retro-reflecting screen and a semi-silvered mirror to produce an equivalent configuration still suffer from the same disadvantages.

By manipulating the pitch and/or focal length of the lenticulars it is possible to obtain angular magnification. Moderate magnification factors would allow the projectors to move over a smaller area, but the problem of having a separate projector pair for each viewer remains.

Sharp Laboratories System

Sharp Laboratories of Europe have developed several different displays that employ head-tracking schemes.



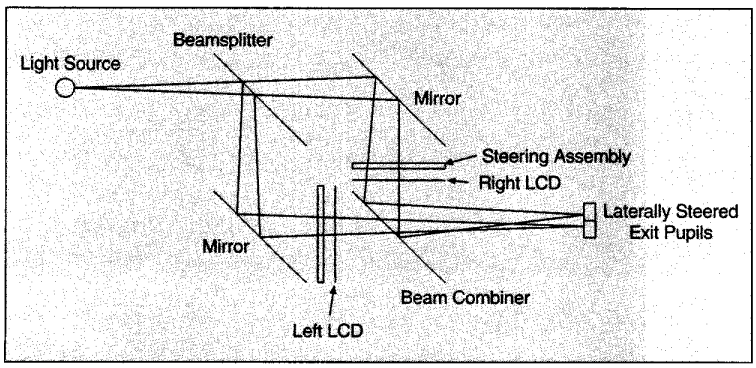
▲ *16. Underlying principle of Cambridge autostereoscopic display.*

The earliest involved the use of two separate LCD screens and a semi-silvered mirror to provide the left and right images. Fig. 17 is a schematic diagram of this setup. The use of two screens provided full resolution images, but also required a very large housing size in relation to the image size.

The overall size was reduced in a later version by using arrays of slits and lenses in what Sharp terms the Micro-Optic Twin-LCD display. This still used two LCDs as its name implies, and required moving parts. Head tracking on earlier displays was achieved by attaching an infrared retro-reflector to the viewer's forehead. Although this obviously would not be suitable for a production display, it served to demonstrate the proof of principle. Work is currently being carried out on a machine-vision tracking system that is not intrusive to the viewer.

Sharp has also produced a stereo display that uses a single LCD panel. In order to eliminate problems caused by the LCD mask, a novel pixel configuration called PIXCON has been developed. This enables access of the addressing lines to the thin-film transistors (TFTs) whilst effectively eliminating the vertical mask components. The use of a PIXCON TFT-LCD in a mechanically tracked system has produced a display free of the artifacts associated with conventional LCDs, and which has the same dynamic performance and lateral viewing freedom as the Micro-Optic Twin-LCD display.

The latest PIXCON display has no moving parts and operates by swapping the images on three separate windows in accordance with the viewer's head position. Moving images with full look-around have been demonstrated on this display [56].



▲ *17. Sharp Labs' head-tracked display.*

A New Approach

The object of our own research is to produce a display that will be suitable for television use, and will be available within the foreseeable future. Although holography may ultimately provide the solution, we do not consider that it will be practicable for the next generation of television.

Our research addresses the particular requirements of television, the most important of which are to provide stereo images to multiple viewers and to allow those viewers to perceive stereo over a large area. As any stereo system will be limited by the available display and transmission technology, we feel that initially, the delivery of only two images will suffice. The provision of motion parallax, that is, where the image continuously changes with viewer position, will require the presentation of large amounts of information that is beyond the capability of most current displays.

Our method presents the same image pair to every viewer, as in current systems that require special glasses, but without the need for these glasses. This is achieved by tracking the viewers' eye positions in a manner similar to the previously mentioned Sharp display. A head tracker is used to determine viewers' head positions. A basic right image field is provided in front of the screen, and when a head is detected, a left exit pupil is formed where the left eye is located. An exit pupil is defined as that region where a left image is seen across the complete width of the screen.

The exit pupils are formed by passing light through an LCD from novel optics that replace the conventional backlight. These optics are controlled by the output of the head tracker, and have the advantage that several exit pupils can be formed simultaneously and at any distance from the screen. The majority of current stereo displays require the viewer to be located close to an optimum viewing plane. The advantage of our optics is that they provide 2D control of the exit pupil positions, not just lateral control.

In order to display the left and right image on one screen, they are presented on alternate rows of pixels as in the HOE display of RealityVision. The light forming the exit pupils passes through the "left" rows only, and the remainder of the light passes through the "right" rows. The images are spatially multiplexed. Although the optics would be simplified by using a fast LCD operating in the field-sequential mode, it is unlikely that such a fast display will be available in the near future.

Presenting each image on alternate rows halves the vertical resolution, however, multiplexing by rows, as opposed to columns, does not increase the coarsening of depth quantization. This can occur, for example, in some lenticular stereo displays.

Conclusions

Despite the existence of many 3D display systems, their popularity remains very limited. Perhaps this is due to the many different display techniques, each of which has its own unique set of virtues and vices whereby each technique is well suited only to quite specific application areas. The emergence of a dominant technique may help to popularize 3D technology. This, in turn, might be facilitated by advances in display and electro-optic technology.

Undoubtedly, the "killer application" for 3D displays is domestic television and the prize for the successful implementation of a viable 3D-TV system is significant. It is perhaps no surprise then that many of the consumer electronics giants have fairly significant investment programs in this area, and those who do not are undoubtedly following the current research trends with interest.

Ian Sexton received a B.S. in Electrical and Electronic Engineering from Leeds University in 1982. He worked in the telecommunications industry prior to becoming a lecturer in Computer Science at De Montfort University where he completed his Ph.D. His current areas of teaching encompass computer architecture, computer graphics, and image processing, while his research interests primarily concern 3D display systems. Sexton is also an active member of SID and sits on the U.K. and Ireland Chapter Committee. *Phil Surman* received his B.S. in Electrical and Electronic Engineering from Heriot-Watt University in Edinburgh in 1971. He has been conducting independent research for several years into 3D television. This work is being continued as the subject of a Ph.D. project at DeMontfort University, Leicester.

References

[1] A. Abramson, "Stereoscopic color television system," U.S. Patent 2,931,855, April 5, 1960.

[2] K. Balasubramonian, S. Gunasekeran, N. Nithiyanandam, and K.P. Rajappan, "On the merits of bicircular polarization for stereo color TV," *IEEE Trans. Consumer Electron.*, vol CE-28, no. 4, Nov. 1982.

[3] T.N. Bardsley, "The design and evaluation of an autostereoscopic computer graphics display," Ph.D. thesis, De Montfort University, Leicester, U.K., 1995

[4] P. Bos, T. Haven, and L. Virgin, "High-performance 3D viewing systems using passive glasses," *SID'88 Digest of Technical Papers*, 1988, pp. 450-453.

[5] G. Bradshaw, "We can have 3-D television," *Picture Post*, July 25, 1953, pp. 36-37.

[6] D. Burder, "Full color 3D photos in a magazine," *Amateur Photographer*, pp. 37-40, Aug. 25, 1984.

[7] R.B. Collender, "The stereoptiplexer," *Information Display*, Nov/Dec 1967, pp. 27-31.

[8] C.W. Carnahan, "Stereoscopic method and apparatus," U.S. Patent 2,301,254, Nov. 10, 1942.

[9] E. Downing, et al, "A three-color, solid-state, three-dimensional display," *Science*, vol. 273, no. 5279, p. 1185-1189, Aug. 30, 1996.

[10] J.B. Eichenlaub, "Stereo display without glasses," *Advanced Imaging*, May 1990, pp. 52-54.

[11] D. Ezra, G.J. Woodgate, B.A. Omar, N.S. Holliman, J. Harrold, and L.S. Shapiro, "New autostereoscopic display system," *Proc. SPIE, Stereoscopic Displays and Virtual Reality Systems II*, vol.2409, 1995, pp. 31-40.

[12] S.M. Faris, "Novel 3D stereoscopic imaging technology," *Stereoscopic Displays and Virtual Reality Systems, SPIE*, vol. 2177, 1994, pp. 180-195.

[13] D. Gabor, "A new microscopic principle," *Nature*, no. 161, 1948, pp. 777-779.

[14] C.W. Geer, "Three-dimensional display apparatus," U.S. Patent 3,184,630, May 18, 1965.

[15] W. Glenn (1989) "An interview with William and Karen Glenn," OE Reports, No.64, April 1989

[16] C.H. Graham, "Visual space perception," in *Vision and Visual Perception*, C.H. Graham, Ed., New York: Wiley, 1965.

[17] N. Hashimoto, and S. Morokawa, "Motion-picture holography using liquid crystal television spatial light modulators," *SID'95 Digest*, pp. 847-850.

[18] T. Hattori, "Stereoscopic display employing head-position tracking using large format lenses," *Proc. SPIE Sstereoscopic Displays and Applications IV*, vol. 1915, 1993, pp. 2-5.

[19] R. Herbert, "Television in depth," *IEE Review*, Nov./Dec. 1991.

[20] C.E. Huffman, "Television viewing device," U.S. Patent 2,845,618, Jan. 11, 1954.

[21] "Frame-sequential Electronic Color Display Filters," *IBM Technical Disclosure Bulletin*, vol. 28, No. 6, Nov. 1985.

[22] F.E. Ives, (1901), U.S. Patent, 666,424682.

[23] F.E. Ives, (1903), U.S. Patent, 725,567682.

[24] H.E. Ives, "A camera for making parallax panoramagrams," *J. Opt. Soc. Amer.*, vol. 17, pp. 435-439, 1928.

[25] R. Jackson, L. MacDonald, K. Freeman, *Computer-Generated Color*, New York: Wiley, 1994.

[26] C.W. Kanolt, (1918), U.S. Patent, 1,260,682.

[27] M.C. King and D.H. Berry, "Varifocal mirror technique for video transmission of three-dimensional images," *Appl. Opt.*, vol. 9, no. 9, Sept. 1970.

[28] C. Laron, "What's new in 3DTV," *Radio Electronics*, vol. 55, pp. 57-60, 1984.

[29] A.K.W. Lo, and J.C. Nims, U.S. Patent 3,953,869, April 27, 1976.

[30] M.G. Lippmann, "Epreuves reversibles donnant la sensation du relief," *J. Phys.*, 4th series, pp. 821-825.

[31] A. Lit, "The magnitude of the pulfrich stereo-phenomenon as a function of binocular differences of intensity at various levels of illumination," *Amer. J. Psychol.*, vol. 62, 1949.

[32] R.J. Littlefield, "Stereo and motion in the display of 3-D scattergrams," *Proc. 8th Annual Conf. Equip. Display*, 1982, pp. 13-17.

[33] M. Lucente, and T.A. Galyean, "Rendering interactive holographic images," *Computer Graphics Proceedings*, Annual Conference Series, ACM SIGGRAPH 1995, pp. 387-393.

[34] M. Lucente, "Interactive three-dimensional displays; seeing the future in depth," ACM SIGGRAPH 1995, "Computer Graphics—Current, New, and Emerging Display Systems."

[35] K. Maeno, N. Fukaya, O. Nishikawa, K. Sato, and T. Honda, "Electro-holographic display using 15-megapixel LCD" *SPIE Proceedings*,"Practical Holography X," 1996, vol. 2652, pp. 15-23.

[36] M. McCormick, N. Davies, and E.G. Chowanietz, "Restricted parallax images for 3D TV," *IEE Colloquium* "Stereoscopic Television," 1992, pp. 3/1-3/4.

[37] A. Miyazawa, K. Shimizu, and K. Sugimoto, "Interactive stereoscopic display system for personal computers," *Stereoscopic Displays and Virtual Reality Systems, SPIE*, 1994, vol. 2177, pp. 26-30.

[38] J.A. Norling, "The stereoscopic art—a reprint," *J. SMPTE*, vol. 60, 1953, pp. 268-308.

[39] E. Pulfrich, "Die Stereoskopie im Dienste der isochromen und heterochromen Photometrie," *Naturwissenschaften* vol. 10, 1922.

[40] J.A. Roese and A.S. Khalafalla, "Stereoscopic viewing with PLZT ceramics," *Ferroelectrics*, vol. 10, 1976, pp. 47-51.

[41] I. Sexton, D.I. Crawford, "Parallax barrier 3DTV," *Three Dimensional Visualization and Display Technologies, SPIE*, 1989, vol. 1083, pp. 84-94.

[42] W.A. Shurcliff, "Screens for 3D and their effects on Polarization," *Journal of the SMPTE*, vol. 62, Feb. 1954.

[43] W. Simon and T. Walters, "A spinning mirror autostereoscopic display," *Three-Dimensional Imaging, SPIE*, 1977, vol 120.

[44] J.Y. Son, S.A. Shestak, S.K. Lee, and H.W. Jeon, "Pulsed laser holographic video," *Proc. SPIE, Practical Holography X*, vol. 2652, 1996, pp. 24-28.

[45] R.A. Steenblick, "A novel single image stereoscopic process," *True 3D Imaging Techniques and Display Technologies, SPIE*, 1987, vol. 761, pp. 27-34.

[46] H.B. Tilton, "An autostereoscopic CRT display," *Three Dimensional Imaging, SPIE*, 1977, vol. 120.

[47] H.B. Tilton, *The 3-D oscilloscope: a practical manual and guide*, Englewood Cliffs, NJ: Prentice Hall, 1987, pp. 28-29.

[48] A.C. Traub, "Stereoscopic display using rapid varifocal mirror oscillations," *Appl. Opt.*, vol. 6, no. 6, June 1967.

[49] N. Tetsutani, S. Ichinose, and M. Ishibashi, "3D-TV projection display system with head tracking," *Japan Display '89*, pp. 56-59.

[50] N. Testsutani, K. Omura, and F. Kishino, "A study on a stereoscopic display system employing eye-position tracking for multi-viewers," *SPIE Proceedings on Stereoscopic Displays and Virtual Reality Systems*, vol. 2177, 1994, pp. 135-142.

[51] A.R.L. Travis, "Autostereoscopic 3-D display," *Applied Optics*, vol. 29, pp. 4341-4342, 1990.

[52] D. Trayner and E. Orr, "Autostereoscopic display using holographic optical elements," *Proc. SPIE Stereoscopic Displays and Applications VII*, vol. 2653, 1996, pp. 65-74.

[53] N.A. Valyus, "Stereoscopic cinematography and television," in *Stereoscopy*, 1st ed., Berg W.F., Ed., New York: Focal Press, 1966, p.209.

[54] C. Van Berkel and J.A. Clarke, "Characterization and optimization of 3D-LCD module design," *Proc. SPIE* vol. 3012, 1997, pp. 179-186.

[55] J.J. Vanderhooft, "Stereoscopic television means," U.S. Patent 2,783,406, Feb. 26, 1957.

[56] R.D. Williams and F. Garcia, "A real-time autostereoscopic multiplanar 3D display system," *SID'88 Digest*, 1988, pp. 91-94.

[57] G.J. Woodgate, D. Ezra, B.A. Omar, J. Harrold, N.S. Holliman, G.R. Jones, and R.R. Moseley, "Observer tracking Autostereoscopic 3D display systems," *Proc. SPIE*, vol. 3012, 1997, pp. 187-198.

[58] V.K. Zworykin, "Television system," U.S. Patent 2,107,464 Aug. 5, 1932.