The Stereoscopic Cinema: From Film to Digital Projection

Lenny Lipton

By Lenny Lipton

A noteworthy improvement in the projection of stereoscopic moving images is taking place; the image is clear and easy to view. Moreover, the setup of projection is simplified, and requires no tweaking for continued performance at a high-quality level. The new system of projection relies on the Texas Instruments Digital Micromirror Device (DMD), and the basis for this paper is the Christie Digital Mirage 5000 projector and StereoGraphics selection devices, CrystalEyes and the ZScreen.

Stereoscopic cinema has not become an accepted part of the neighborhood theatrical experience because the technology hasn't been perfected to the point where it is satisfying for either the exhibitor or the viewer. However, the medium has become widely accepted in theme parks and location-based entertainment where some of the problems have been overcome. For the most part, the projection technology used in theme park theaters is identical to that first employed commercially in 1939: two projectors run in interlock with lenses projecting through sheet polarizer filters. Audience members wore polarizer analyzer eyewear for image selection (the means for getting the left eye image to be seen only by the left eye and vice versa).

It is expected that digital projection, which produces a clean ghost-free image and requires the use of only one projector, will undoubtedly usher in a new and superior version of the medium. First, let us take a historical detour in order to understand the problems of the past to better appreciate the virtues of the improvement described.

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Polarization Efforts

The first successful (and influential) commercial use of full-color stereoscopic movie projection in the U.S. was in 1940 (a similar film was projected in monochrome in 1939) at the World's Fair in New York. John A. Norling produced and photographed a film showing the assembly of a Chrysler automobile. The film was shot with a 35mm camera rig and projected with a pair of projectors in interlock. As mentioned, polarization was used for image selection.[1]

The film debuted some four decades after the suggestion was first made for using polarization as a method of image selection. This delay from idea to successful implementation is typical of technology in general, and the stereoscopic medium in particular, in which innovation has sometimes depended upon the arrival of new enabling technologies. In this case John Anderton[2] first suggested polarization for selection using the cumbersome piles-of-plates technique, but a viable implementation awaited the invention of commercial-quality sheet polarizers by Edwin Land, who applied the material to stereoscopic eyewear.[3]

The Norling approach became the model for the theatrical motion picture stereoscopic boom of the early 1950s. In those days theaters had two projectors in the booth for changeover from reel to reel, providing an opportunity to modify the setup to run interlocked left and right projectors (Fig. 1).

It may well be that problems in the projection booth bear the major share of responsibility for this short-lived effort. Polaroid researchers Jones and Shurcliff[4] described the artifacts related to projector synchronization and shutter phase. The same kind of dual-projector scheme is used in today's theme parks. The theme park theater is more manageable than a neighborhood theater, since more diligence can be devoted to making a touchy system work.

Single Projector Methods

The history of the cinema teaches that systems requiring multiple machines, for color, sound, or widescreen, will be displaced by single projector solutions. The same factors apply to the stereo-cinema. For example, in the early 1980s, attempts were made to commercialize single projector methods that placed left and right images above and below each other with Techniscope-style (two perf high) subframes.[5] Special dual optics that incorporated polarizing filters were required for projection.[6]

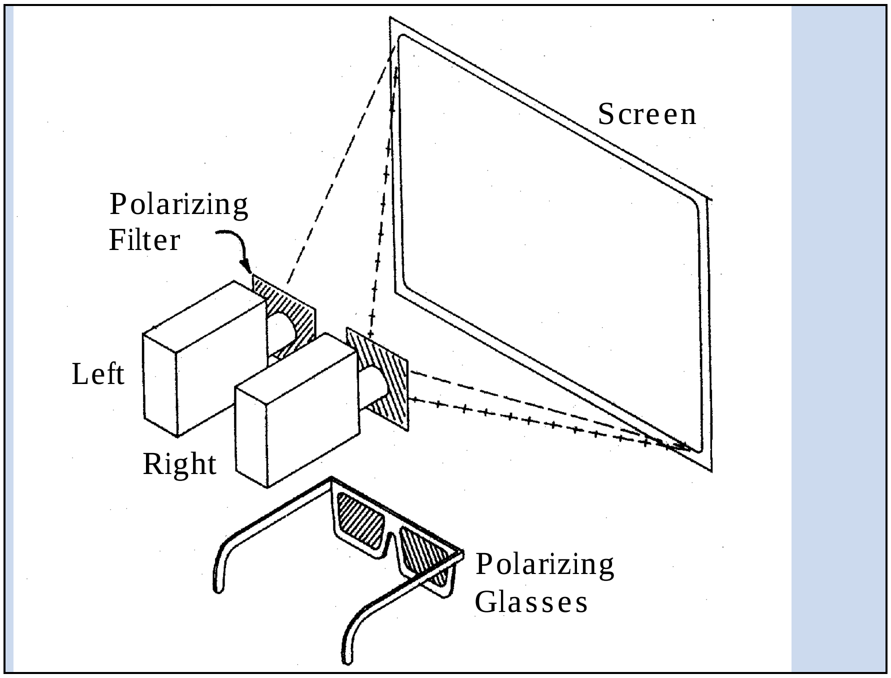

Figure 1. Polarization image selection. Sheet polarizers are used over the projection lenses and as analyzers in eyewear. Projection screen must conserve polarization.

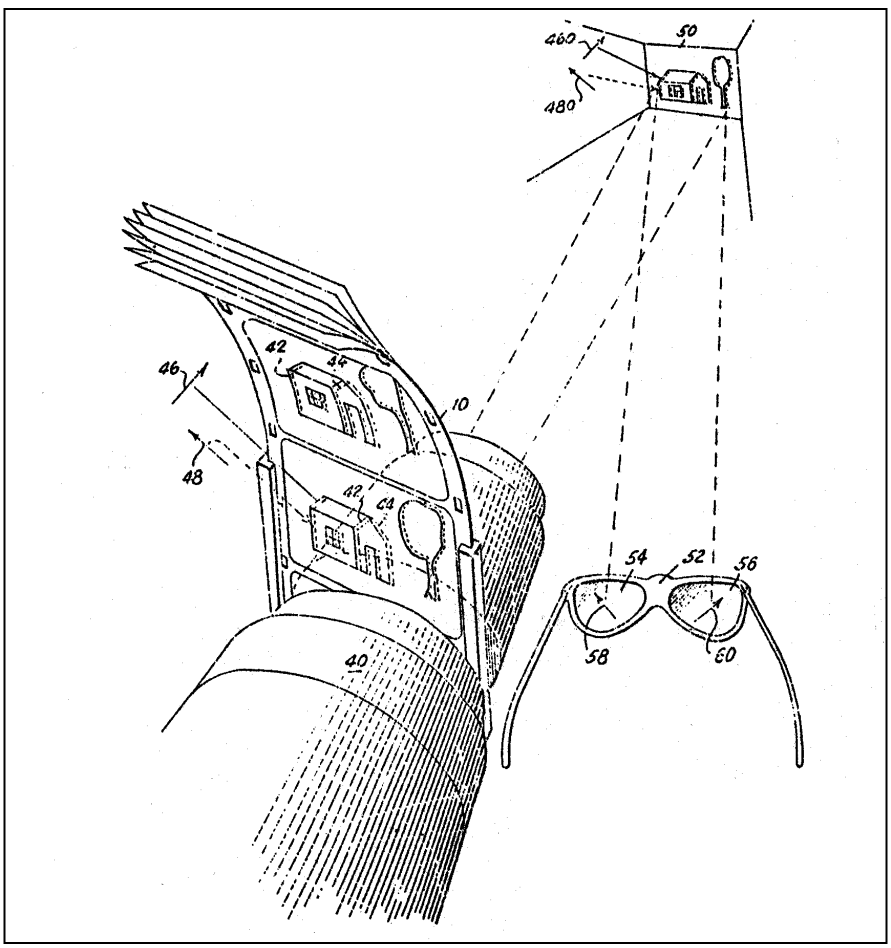

Figure 2. Vectograph projection. A single film contains both left and right images with each having the ability to polarize light. This drawing is from a 1942 patent by Land.

In the early 1980s a few films were shot and released using this approach. Unfortunately, one set of difficulties had been replaced with another: this subframe method is considerably less bright than the dual-projector method. It was introduced at a time when screen sizes were larger than ever and more brightness was needed. In addition, while synchronization of two projectors was not an issue, it was too easy for the projectionist to splice reels together at the subframe line rather than at the frame line. The result is the projection of a pseudo-stereoscopic image.

The viewing of a left perspective view with the right eye and vice versa does not happen in the visual world; people have a hard time articulating the nature of the problem. The result of this mistake is the destruction of the raison d'être of the medium causing audience discomfort. This subframe technique has more or less fallen by the wayside, not having been able to live up to its promise.

Anaglyph and Vectograph

In addition to the polarization method, two other technologies have been considered for theatrical stereoscopic projection, both of which offer a single projector solution. One, the anaglyph, employing complementary colored images, with selection eyewear using similar complementary colored filters, has a long history of on-again/off-again use since the early days of the motion picture industry. Although it requires only one projector, a monochrome image and eye fatigue have precluded its acceptance.

The Vectograph, a trade name of the Polaroid Corp., was another contender, and it has interesting similarities to the anaglyph, except that it allows for full color (Fig. 2). At a special session of Siggraph about a decade ago, a test reel produced by Polaroid in conjunction with Technicolor was shown in a Manhattan screening room. The image was extremely bright and sharp with excellent stereoscopic effects.

The Vectograph process imbibes polarizing dyes onto two reels of specially prepared film that are then cemented together.[7] This duplitized process was never used commercially for motion picture projection.

Eclipse Technique

Another approach worthy of attention, because it is the basis for the improvement in technology described here, is the eclipse or occlusion method. It has a great deal in common with the polarization projection technique since both use dual interlocked projectors. It was first proposed in 1855 for the projection of slides,[8] requiring the images for the left and right eyes to be alternately blocked and passed. The projector shutters are out of phase with each other, and the shutters used in the selection devices open and close in synchrony with the projector shutters.

Laurens Hammond[9] invented the first commercial motion picture eclipse system, Teleview, used in the screening of the movie *MARS*, at the Selwyn Theater on Broadway in New York City in 1923. Mounted on the back of every seat in the theater was an adjustable gooseneck, and mounted on the gooseneck was a spinning mechanical shutter in electrical synchronization with the projector's shutters. When the pie-shaped shutter's movement uncovered the right eye, the right projector shutter was also open. At that moment the viewer's left eye was blocked, so was the left projector lens. As the viewer shutters continued to rotate, the left view was unblocked and so on and so forth. If the repetition rate is high enough the result is a flicker-free stereoscopic moving image (Fig. 3).

It's not surprising that this method works, because it is an extension of basic motion picture technology. The interrupting projector shutter occludes the film as it is transported, to prevent travel ghost, and also interrupts the projected frame when it is at rest, to increase the repetition rate of the projected fame in order to satisfy the critical flicker frequency condition. The result is that half the time the viewer is observing "nothing" on the screen, since the image is blocked. The stereoscopic occlusion technique fills in the periods of nothing with image.

Until IMAX's revival of the process for dome projection, Teleview was the only commercial use of this motion picture process for over 60 years. IMAX's addition was the use

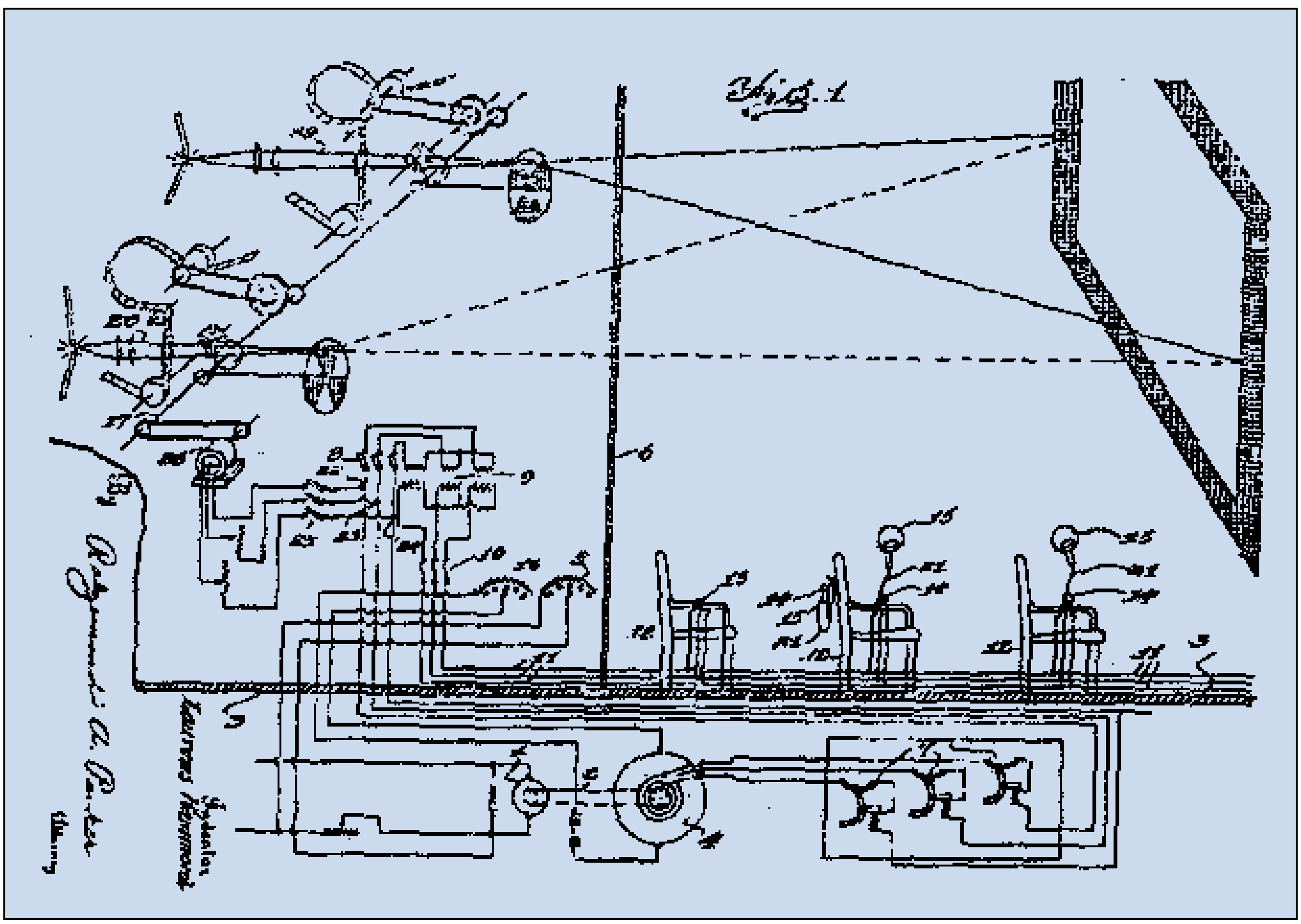

Figure 3. Teleview theater setup. Spinning shutters cover projector lenses and the viewers' eyes. The drawing is from the 1924 patent by Hammond.

of liquid crystal shutters for the selection eyewear, an approach that had been used for some years for stereoscopic computer graphics.

Ghosting

The cross-talk artifact of polarization image selection is one of the art's most serious technical problems. The term ghosting is sometimes used in place of cross-talk to describe the visual result, an effect that is similar in appearance to a double exposed image. Despite the fact that good linear polarizer sheet filters are available, they are imperfect devices and will pass a small amount of unwanted light in their crossed or occluded state. The problem is exacerbated because of the Law of Malus,[10] which, applied to the case at hand, teaches that even a few degrees of head tipping will produce a substantial increase in cross-talk.

The dynamic range of the projection filters' polarized light in combination with the eyewear analyzers is a measure of the ratio of light transmitted with the filters' axes parallel to that measured with the filters' axes crossed. Measured on an optical bench, sheet polarizers can have a dynamic range of several thousand to one. After reflection from a metallic coated screen, the dynamic range can be reduced, especially for corner seating.

Cross-talk is dependent on the filters' characteristics and the properties of the screen. The screen is an imperfect device with respect to its conservation of polarization characteristics. Having said this it should be noted that there are some stereoscopic projection screens that do a reasonably good job of conserving polarization.

Linear polarization selection is the accepted standard for stereoscopic projection, but if care isn't taken, ghost images can result that are noticeable for high-parallax (object coming off the screen) and high-contrast images. As mentioned, even a slightly tipped head can produce a ghost image.

Binocular Symmetries

In addition to the ghosting issue, there are other factors that determine the visual experience one will have at a stereoscopic movie. These factors need to be understood to grasp the extent of the improvement resulting from the digital projection technique described here. One set of concerns has to do with the correlation of the left and right images, or what has been termed binocular symmetries.[11] The left and right images must be substantially identical in all ways except for the entity of parallax. That means, within specifiable tolerances, the left and right images must have identical magnification, color balance, and illumination, and they must be aligned in the vertical so that a horizontal line can pass through corresponding points.

In this regard the Vectograph and field-sequential electro-stereoscopically projected images are beneficial in that both use the same optical system for both perspective views. Since they are treated identically, the condition of binocular symmetries will be fulfilled. As described by Spottiswoode et al.,[12] when such a condition is fulfilled we have a neutral stereoscopic transmission system.

In addition, there are temporal considerations. Although moving stereoscopic images must be captured simultaneously, they can be successfully projected out of phase to within a specifiable tolerance.[4] If dual motion picture cameras are used, their shutters must be adjusted to run in phase and video cameras must be genlocked. For computer generated imaging, it should be a given that action in left and right image views will be "captured" at the same moment.

Field or frame-sequential electrostereoscopic displays cannot project left and right images simultaneously; rather, they present left and right images in sequence. However, because the field rate is high enough, usually 100 per sec or higher, a temporal artifact is never seen.

Accommodation and Convergence (A/C)

There is another phenomenon peculiar to the display of plano-stereoscopic images (a stereo image made up of planar left and right perspective views) that may detract from the enjoyment of the image. It is the breakdown of accommodation (the muscle controlled change of shape of the eyes' lenses to accomplish focusing) and convergence (the muscle-controlled movement of the eyes that allows them to rotate as a coordinated pair to accomplish fusion).

The A/C breakdown occurs when viewing a stereoscopic image, and does not take place in the visual world. We are accustomed from birth to having our eyes focus and converge on the object we are looking at. For a projected stereoscopic display the habituated A/C response breaks down, since the eyes are focused on the plane of the screen but convergence is determined by parallax.

The muscles and neurological pathways that control A/C are separate, but we become habituated to their working together. Viewing a projected stereoscopic image derails this learned response, and for some people makes it difficult to enjoy a stereoscopic image. Interestingly, when looking at images from some considerable distance, in a theater setting for example, the breakdown is less troublesome, because the eyes are focused at (or nearly at) infinity.

Most of the author's work has been in designing systems for viewing images on workstation monitors, which are typically 20 in. or so diagonal and viewed from only a few feet. This is the most demanding situation for viewing a (rear) projected stereo image, since the eyes must accommodate for the close distance. These displays, based on CRT monitors, have afterglow characteristics that contribute to cross-talk or ghost images. Working with a digital projector, which contributes no ghosting artifact, proves that the presence of even a faint ghost image may be as important as the A/C breakdown.

When viewing images in a Brewster lenticular stereoscope,[13] like the familiar ViewMaster, there is no cross-talk, because there are two separate viewing channels. In addition, the stereoscope uses accommodating lenses that help the eyes focus. Both of these factors make looking through a stereoscope the most pleasant stereoscopic viewing experience. The Brewster stereoscope is an excellent neutral transmission component and remains the gold standard for viewing stereo images.

Electronic vs. Film Projection

A review of the prior art continues with a brief discussion of cathode ray tube (CRT)-based projection. For the past decade or so electro-stereoscopic images have been projected by CRT devices, usually using three tubes and associated lenses. Today they are most frequently used for industrial virtual reality (VR) or simulation applications. The technique is related to that used for viewing stereo images on desktop workstations (often for applications like molecular modeling and aerial mapping). This is a variant of the eclipse or occlusion system described above in which significant improvements have been made: electro-optical shutters have replaced mechanical shutters and one projector replaces two.

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Electronic projection does not have to deal with the limitations of film transport and the mechanical pull-down of a frame of film. A quarter of the motion picture projection cycle, or about 0.01 sec, is required for the pull-down of a frame of film. For CRT projection the analogous entity, vertical blanking, is a tenth of that in duration, and for digital projection the vertical blanking is even less.

A major attraction of the single projector approach is that two projectors do not have to be calibrated to work in concert. In addition, since a single optical path is used for both left and right images binocular asymmetrical artifacts are eliminated.

In electronic projection two selection methods are used, one employing shuttering (active) eyewear, and the other using a polarization modulator and polarizing (passive) eyewear. As will be described, these techniques can be applied to digital projection with great success.

Active Eyewear

The active eyewear approach uses wireless battery-powered eyewear with liquid crystal shutters that are run in synchrony with the video field rate. Synchronization information is communicated to the eyewear by means of an infrared (IR) emitter. The emitter looks at the computer's video signal and seeing the vertical blanking synchronization pulse broadcasts coded IR pulses to signify when the left eye and the right eye images are being displayed.[14] The eyewear incorporates an IR detection diode that sees the emitter's signal and tells the eyewear shutters when to occlude and transmit.

An active eyewear product, like CrystalEyes by StereoGraphics, has shutters with a dynamic range better than 1500:1, which is about an order of magnitude better than the polarized light method of selection (considering the total optical system inclusive of the screen). It uses a type of super-twisted nematic liquid crystal (LC) shutters to produce both fast switching speed and high dynamic range, as described by Tilton et al.[15]

The shutter is a sandwich made of two linear sheet polarizers (whose axes are orthogonal) on either side of the liquid crystal cell. The cell itself is made up of a thin film of LC material contained between two parallel sheets of glass. The inside of each glass sheet is coated with a transparent conductor, indium tin oxide. The conductors have a voltage applied to them and in this way an electric field can be set up within the gap of LC material.

When a field is induced, the LC material becomes isotropic and the crossed polarizers block light. Without a field having been applied the axis of incoming polarized light is toggled through 90°, by means of the phenomenon of optical activity; in this mode the shutter transmits light.

CrystalEyes, in conjunction with CRT projectors, is commonly used in industrial VR applications such as the CAVE.[16] Also, simulators with screens from 10 to 30 ft across (often with projectors set up in a triptych arrangement like that employed by Cinerama) are used. The principal contribution of cross-talk comes from the CRT display's phosphor afterglow and not from the eyewear shutters. The stereoscopic effect is achieved by projection of a succession of left and right images, but CRT projector tubes, even when optimized for the stereoscopic task, have phosphors that continue to glow into the adjacent field.

My team and I became interested in the problem many years ago, and did an experiment to understand the nature of ghosting. Placing spinning mechanical shutters in front of the twin lenses of a stereoscopic slide projector, we then coupled a CrystalEyes emitter to the action of the shutters and studied a series of projected images. When viewing the images through active eyewear with high dynamic range shutters, we could see virtually no cross-talk, no matter how high the parallax values. Since the mechanical shutter had no phosphor afterglow this experiment established that the CRT-based display devices, and not the selection device, contributed to ghosting.

Passive Eyewear

An alternative to active eyewear is the ZScreen, which is a special kind of LC polarization modulator. It is placed in front of the projection lens(es) like a sheet-polarizing filter. The device changes the characteristic of polarized light and switches between left and right-handed circularly polarized light at field rate. Audience members wear circular polarizing analyzing eyewear. Although the great majority of theaters showing stereo movies use linearly polarized light for image selection, circular polarized light has the advantage of allowing a great deal of head tipping before the stereoscopic effect is lost.[17]

The ZScreen uses two liquid crystal cells (called pi-cells or surface mode devices) in optical series with their optical axes orthogonal. Unlike the twisted nematic cells used in CrystalEyes, which depend upon optical activity, the ZScreen uses phase shifting of linearly polarized light to achieve its electro-optical effect. A linear polarizer, at the surface of one of the cells (closest to the projection lens), has its axis oriented to bisect the pi-cells' orthogonal axes. The pi-cells are driven to quarter-wave retardation but with their electric potential out of phase. A low-voltage bias must be applied to the cells in order to tune their birefringence so that the vector sum of the cells' phase shift achieves a quarter-wave retardation.[18]

Figure 4. ZScreen mounted on a Mirage projector.

The projector's light is first linearly polarized which is next subjected to phase shifts based on the voltages applied to the cells. In combination the cells function as a variable retarder so that left and right-handed circularly polarized light is output in synchrony with the video field rate.

The dynamic range of the ZScreen is on the order of 150:1 (when measured in combination with typical analyzers found in off-the-shelf-eyewear). The transition between left and right circularly polarized states is fast, 0.5 ms, or about half the usual CRT display vertical-blanking interval. Compared with CrystalEyes shutters the dynamic range is lower, but the ZScreen has its virtues. Its image quality is on a par with what people have come to expect from stereoscopic movies but with the virtue that head tipping is possible. In addition, there are venues in which it is more appropriate to use cardboard or plastic-framed eyewear than more costly active eyewear.

The combination of ZScreen and polarizing eyewear forms a shutter, although one could make a case for classifying it as a polarization selection method.

Digital Projection

This paper presents a brief history of the technology of motion picture and electronic stereoscopic projection, with an emphasis on understanding the artifacts that can detract from the enjoyment of the medium. In this way the stage has been set for the reader to understand the improvements that are made possible with digital projection.

The paper is the result of a working relationship between Christie Digital and StereoGraphics Corp. in an attempt to create a stereoscopic digital projector solution. The author and a team of engineers at StereoGraphics have been working with the Mirage 5000 (5000 L) to gain an understanding of its characteristics to create a fully integrated stereoscopic solution. We have been adapting our CrystalEyes and ZScreen devices to digital projection (Fig. 4). In addition, we have been working to interface the projectors with Windows operating system video accelerator boards. The projector can run as high as 108 fields/sec at a resolution of 1280 by 1024 per field.

There are two contributions to stereoscopy that DMD projectors make: they greatly increase image brightness and substantially reduce cross-talk. DMD projectors are able to do this because the DMD device is a light modulator, or reflector, rather than a generator of light itself, as is CRT projector. The DMD device has no image afterglow to create a residual left image which will leak into a right field (and vice versa), as do the phosphors used in CRT devices; hence, they do not contribute to cross-talk. In addition, like current CRT-based stereo projectors, they use the field-sequential approach treating both left and right images by means of a single optical path. The digital projector is a neutral stereoscopic transmitter, doing no harm to the image.

DMD Projection

The basis for the Mirage projector's imaging is the Texas Instruments DMD chip. This is a micro-electro-mechanical (MEMS) microchip made up of minute tiled mirrors. TI uses the term DMD to refer to the MEMS microchip itself, and another term, Digital Light Processing (DLP) to refer to the image forming engine including optics.

DMD devices form a Cartesian array of pixels (mirrors)[19]. The mirrors can be tilted on hinged structures and move through a rotation of +/-10°. The mirrors can be actuated 1000 times/sec and can be addressed individually.

In the case of the Mirage projectors, three DMD devices are illuminated by a single light source through an optical path that is divided into three primary color components and then reflected off of the surface of the DMDs. The light reflected by the three DMDs is recombined and imaged through a single projection lens. The DMD device has an active area or fill factor of about 90%, an improvement over a comparable LC device.

Since the DMD is intrinsically a monochromatic device, the three DMDs must be used to produce a color image that is made up of color-filtered gray scales contributed by each device. The speed with which the mirror can be tilted has lead to a pulse-width modulation scheme wherein the mirrors are turned on and off so that, integrated over time, a single pixel will have the desired density.

It is the speed of the mirrors that makes them so interesting for stereoscopic displays. Unlike LC devices, which are slow to switch, the DMD is fast enough to be used for field-sequential stereoscopic application. Unlike CRT-based imaging, the DMD does not leak unwanted image into adjacent fields. The titling mirrors are, essentially, either on or off with an extremely short duration devoted to the intermediate position.

Other configurations of the DMD chip exist, especially for the Road Warrior class of projectors. In this case, the speed of the DMD is taken advantage of to produce field-sequential color using the light reflected by a single chip through a rotating color wheel. Combining colorplexing and stereoplexing would be demanding of a single chip, so the three-chip design is used for our application.

Until the Mirage series of projectors three-chip DMD projectors could not be driven at a high enough field rate for stereo applications. One problem was the scaling chip employed to homogenize video signals of different resolutions. The scaling chip would take video of whatever field rate and turn it into a 60-Hz signal to be displayed by the DMD. This approach is incompatible with the needs of field-sequential stereo, which requires a high field rate.

Light Loss

The amount of light loss associated with stereo digital projection is the same as that associated with CRT projection, but ultimately it's less of a problem since the digital projectors can be so much brighter. In the stereo mode the digital projector is running at about twice the usual field or picture rate. Half the light is now used for each perspective view so compared to the planar mode the light is cut in half. In addition, both the ZScreen with passive eyewear or CrystalEyes (both depend upon light absorbing sheet polarizers for their electro-optical effect) transmit about 30% of the light. Combined with the duty cycle loss this diminishes the projector's light output to 15% of what it would have been. In effect this reduces the output of the Mirage 5000 from 5000 to 750 lumens. Front projection high gain screens, which also conserve polarization (required for the ZScreen), can boost the light output by a factor of four (more or less depending upon the screen), restoring the Mirage to an effective 3000 lumens.

Theatrical Applications

Stereo digital projection will be a boon for industrial VR users, but there is a future use of immense importance. I began this article by stating that the stereoscopic medium has not become accepted as part of the theatrical cinema. Other technologies like sound, color, and wide screen, have become products in daily use in theaters around the world, but the projection of stereoscopic movies is an event restricted almost entirely to theme park venues.

Most of the public is now aware that a purely electronic or digital cinema is being contemplated as a replacement for the present film-based technology. It may well take years for the transition to take place. In this context there are a number of technical issues to address, such as the nature of the format to be used for distribution. This is a good time for projector manufacturers and others in the industry to plan for adding stereoscopic capability.

The deterrents to the widespread acceptance of the stereoscopic theatrical medium have, in principle, been solved by digital projection. The same projector can be used for showing planar content as well as stereo content with the flip of a switch. Digital projectors can project images that are free of eyestrain or discomfort producing components, assuring the enjoyment of stereoscopic films. The future of the stereoscopic digital cinema is up to us and will depend on the strength of our determination.

Conclusion

There have been many solutions offered for solving the riddle of stereoscopic projection. Some of them have fallen by the wayside and some are with us to this day. The field-sequential system, using occlusion for image selection, combined with digital projection, has produced, in the author's view, the most promising solution. The image is free from binocular asymmetries and cross-talk. The result is a perfectly beautiful stereoscopic moving image. Equally important, the result has been achieved not only in laboratory experiments but also in a real-world product.

Acknowledgements

I would like to thank my colleagues at StereoGraphics R&D for their contributions in engineering an integrated digital projection solution. They include Jeff Halnon, Bill McKee, Bruce Dorworth, and Jeff Wuopio. Without the persistence of our Director of Marketing Ian Matthews, the project might never have taken root. I would also like to thank our colleagues Bill Speer and Wayne Bickley at Christie Digital for their cooperation.

References

1. John A, Norling, "Three-Dimensional Motion Pictures," *J. SMPTE, 33*:612-634, Dec. 1939.
2. John Anderton, "Method by which pictures projected upon screens by magic lanterns are seen in relief," Pat. no. 542,321, July 9, 1895, (July 7, 1891 in England).
3. Edwin H. Land, *Stereoscopic Motion Pictures: A Special Report to the Directors of the Polaroid Corp.*, Polaroid Corp., Cambridge, MA, 1935.
4. R. Clark Jones and William A. Shurcliff, "Equipment to Measure and Control Synchronization Errors in 3-D Projection," *J. SMPTE, 62:*134-41, Feb. 1954.
5. Lenny Lipton, "A Plea for Technical Standards in 3-D," *Amer. Cinemat.*, July 1983.
6. Chris J. Condon, "Film projection lens system for 3-D movies," Pat. no. 4,235,503, Nov. 25, 1980.
7. Land, E. H., "Light-polarizing image full color," Pat. no. 2,289,714, July 14, 1942.
8. Arthur J. Judge, *Stereoscopic Photography: Its Application to Science, Industry and Education*, Chapman and Hall: London, 1950.
9. Lauraens Hammond, "Stereo-scopic motion picture device." Pat. no. 1,506,524, Aug. 26, 1924.
10. Francis A. Jenkins and Harvey E. White, *Fundamentals of Optics (Fourth Ed.)*, McGraw-Hill: New York, 1976.
11. Lenny Lipton, *Foundations of the Stereoscopic Cinema*, Van Nostrand-Reinhold: New York, 1982.
12. Raymond Spottiswoode and Nigel L. Spottiswoode, *The Theory of Stereoscopic Transmission and its Application to the Motion Picture*, Univ. of California Press: Berkeley, 1953.
13. David Brewster, *The Stereoscope: Its History, Theory and Construction, 1856, Reprinted 1971*. New York: Morgan and Morgan.
14. Lenny Lipton and Marvin Ackerman, "Liquid crystal shutter system for stereoscopic and other applications." Pat. no. 4,967,268, Oct. 30, 1990.
15. Mary Tilton and Lenny Lipton, "Fast switching 270 degree twisted nematic liquid crystal device and eyewear incorporating the device," Pat. no. 5,327,269, July 5, 1994.
16. www.aec.at/center/proj/cavee.
17. Vivian Walworth, "Three-Dimensional Projection with Circular Polarizers." *SPIE Vol. 462, Optics in Entertainment II,* 1984.
18. Lenny Lipton, Arthur Berman, Lawrence D. Meyer, and James L. Fergasen, "Method and system employing a push-pull liquid crystal modulator," Pat. no. 4,792,850; Dec. 20, 1988.
19. www.dlp.com/dlp/resources/white papers/overview.

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Lipton was the first person to produce a flicker-free field-sequential stereoscopic display and holds 20 patents in the field. He received an award from the Smithsonian for his invention of CrystalEyes. His films are collected in the Pacific Film Archive, and as a filmmaker he has traveled to South America as a cultural liaison for the Department of State.

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