Development of an Automultiscopic True 3D Display

Russell M. Kurtz, Ranjit D. Pradhan, Tin M. Aye, Kevin H. Yu, Albert O. Okorogu, Kang-Bin Chua, Nay Tun, Tin Win, and Axel Schindler

Physical Optics Corporation, Electro-Optics and Holography Division,
20600 Gramercy Blvd. Bldg. 100, Torrance, CA 90501

ABSTRACT

True 3D displays, whether generated by volume holography, merged stereopsis (requiring glasses), or autostereoscopic methods (stereopsis without the need for special glasses), are useful in a great number of applications, ranging from training through product visualization to computer gaming. Holography provides an excellent 3D image but cannot yet be produced in real time, merged stereopsis results in accommodation-convergence conflict (where distance cues generated by the 3D appearance of the image conflict with those obtained from the angular position of the eyes) and lacks parallax cues, and autostereoscopy produces a 3D image visible only from a small region of space. Physical Optics Corporation is developing the next step in real-time 3D displays, the automultiscopic system, which eliminates accommodation-convergence conflict, produces 3D imagery from any position around the display, and includes true image parallax. Theory of automultiscopic display systems is presented, together with results from our prototype display, which produces 3D video imagery with full parallax cues from any viewing direction.

Keywords: Stereo Vision, Automultiscopic Display, True 3D Display

1. INTRODUCTION

While 3D displays are quite useful, most present difficulties of various kinds. Volumetric holography, which produces the highest-quality, most realistic image, requires a significant amount of time to produce each image, and is most accurate when only a single color is used. Traditional holography includes many of the same advantages and disadvantages as volume holography. It produces an excellent 3D image, but in general is limited to a single color and demands a lengthy process to create – the holographic image must be recorded on photographic film, then developed, and playback normally requires laser illumination.

Stereopsis can show images in real time, as shown by 3D movies, such as *Jim, the Penman* (1915), *Bwana Devil* (1952 - the movie that kicked off the "3D craze"), and *Jaws 3D* (1983). Such films are of interest again in theme parks, started by *Captain EO* (Disneyland, 1986) and *Shrek 4D* (Universal, 2003), and in the popular IMAX 3D series. These stereoptic movies all require the use of special glasses to separate the right-eye and left-eye images. When the movies were filmed in black and white, the glasses could be quite inexpensive, with cardboard frames and red and blue plastic film for the lenses. As the audience began demanding color, this method no longer worked. The most common current method of separating the images is to use polarized glasses, with one eye's lens polarized horizontally and the other polarized vertically. These glasses are large, so they can fit over prescription lenses, and must be kept clean, or the movie will revert to a flat view.

Physical Optics Corporation (POC) has been a leader in autostereoscopic displays (steroptic 3D displays that do not require glasses). Such displays provide high-resolution, full-color 3D imagery for many uses, including science, communication, and gaming (Fig. 1). They overcome the problems associated with eyeglass-based stereoptic displays, but bring a new disadvantage – the 3D effect is seen only from a few viewing angles, and there is only a small viewing region that provides distortion-free 3D vision. Also, since steroptic displays—including autostereocopic displays—only present two specific images (right-eye and left-eye versions), they do not show motion (look-around) parallax, reducing their accuracy in presenting depth.

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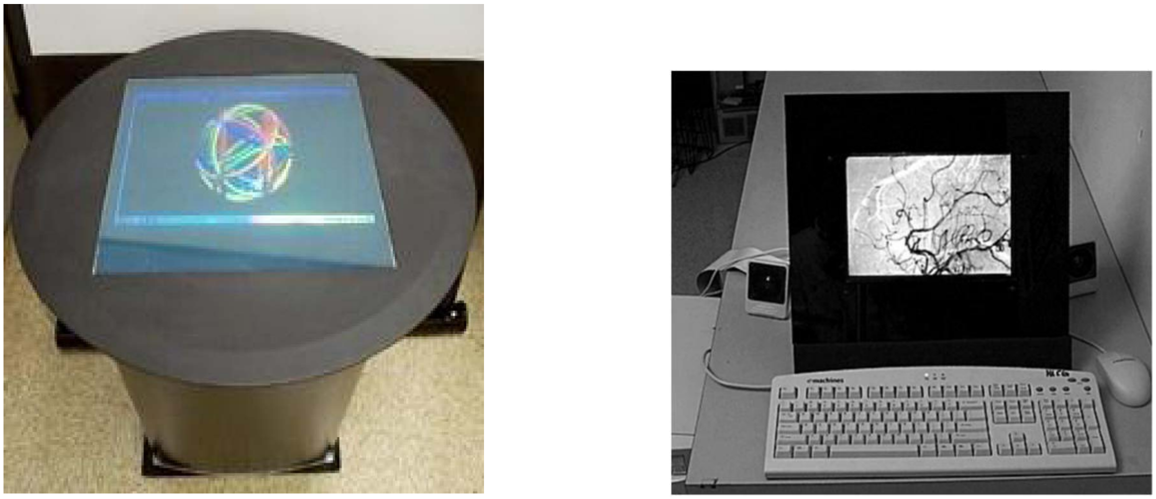


(a) (b)

Fig. 1. Autostereoscopic displays developed at POC include a tabletop version (a) for scientific use and a flat-panel version (b) for medical use.

The advantages of volumetric holography, then, are that it shows a complete 3D image that can be viewed from any angle, and that it demonstrates proper parallax. People can watch the image in a volumetric hologram without ever developing eyestrain from focus-convergence mismatch or from parallax disparity. The advantages of autostereoscopic displays are the capability of showing images in color and the capability of displaying these images in real time. Both types of display are viewed without the use of special glasses.

A better 3D display would be one in which the advantages of volume holography and austereoscopsis are combined, eliminating their disadvantages. In other words, it would be useful to have a 3D display that shows color images in near real time, and these images appear solid, can be seen from any angle and virtually any distance, and demonstrate accurate parallax. The automultiscopic display under development at POC meets all these requirements.

2. THEORY

2.1. Stereo Vision

The human brain merges separate 2D images from the two eyes and interprets the result as a 3D image in a process known as steropsis. The difference in viewing angle between the left and right eyes is interpreted as parallax, enabling the brain to determine distance to the object as well as its left-right and up-down (2D) position (Fig. 2).

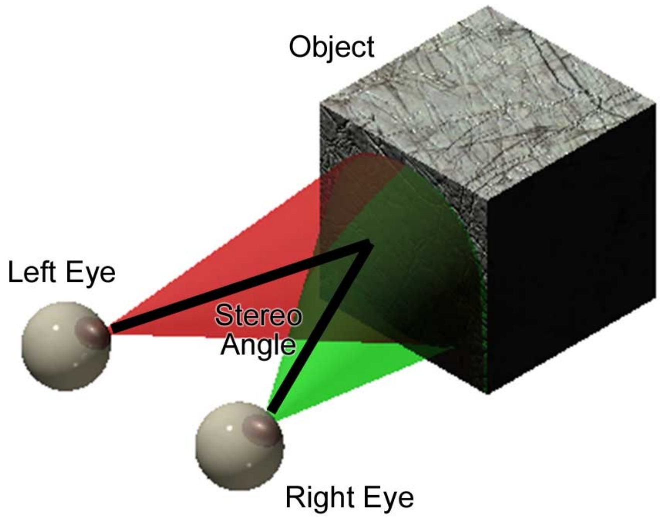


Fig. 2. The brain interprets the stereo angle between the left and right eyes as depth of a 3D object.

Stereopsis can be induced artificially by displaying different images to the right and left eyes. The easiest way to create these images is to set up two cameras with unit magnification the same distance apart as human eyes (typically 57-64 mm) so they have to see objects from the same angles as the two eyes. Each camera output can then be viewed by one eye. A head-up display (HUD), for example, can be used to show the separate images. As an alternative, two images can be broadcast simultaneously on a screen, one polarized vertically and the other horizontally (or any other method of ensuring the correct image reaches the intended eye). This requires the audience to wear special glasses and the 3D effect quality depends on the location of the observer, but the human brain is very good at converting the two images into a single 3D scene.

2.2. Autostereoscopic Display

An autostereoscopic display is one in which the stereoptic image is directed *by the display itself* to the individual eyes of the viewer. The first commercial implementation of this was in 1978, with a specially-designed television set that had a lenticular lens array on the front. The left eye image was directed to one side of each lens and the right eye image to the other side. The lenses would then deflect the images, and diverge the image rays, so that 3D imaging was available over a wide viewing angle and at a range of distance from the set. This was low resolution, but the 3D effect was very powerful at that time, and preceded the more popular 3D movies (Section 1), but it was not a commercial success. This technology is being revived and improved, however, by LightSpace Technologies[1].

The POC autostereoscopic display (Fig. 3) provides an excellent 3D image without glasses, with high resolution. This technology is based on an idea originally proposed by Dennis Gabor[2] in the late 1960s, and fully realized in 1995 at POC[3]. Two independently-controlled images are provided, one each for the left and right eyes. Each image is directed to its selected eye by diffraction through a special holographic optical element (HOE). The resolution is extremely high, color fidelity is excellent, and the 3D effect is optimal, but these advantages only occur for an observer in a small viewing region. Moving outside this region eliminates the 3D effect and can also reduce the color fidelity. Within the region, however, a simple transformation of data in standard 3D formats into stereo image pairs enables real-time 3D imagery from standard computer files.

Fig. 3. The POC 3D video game screen permits the user to play computer games in full autostereoscopic 3D vision.

2.3. Automultiscopic Display

The autostereoscopic display can function either by directing two simultaneous images to the two eyes or by sending the two images sequentially. The eye response time can be as long as 1/20 s in a dark environment, allowing movies to change their frames at 24 Hz, or as short as 1/45 s in a brighter environment, permitting the 50 Hz field rate of European television. This technique can be extended to multiple images being displayed rapidly. If the image rate is sufficiently rapid, a very large number of views can be sent at slightly different angles. For example, if images are sent at a rate of 21.6 kHz, each image can be from a viewpoint only 1° different from the one next to it. If the viewing region is also 1° wide, the image appears continuous. From any position around the image, the image is viewed as if the display were only sent to that position and the object were filmed from that position. Since the images are directed at individual angles by the HOE, the display provides true motion parallax for both forward-backward and side-to-side observer motion.

There are even more advantages to this sort of display. Since the spacing between adult human eyes averages between 57 and 64 mm, as long as the 1° image box is <57 mm wide (at a distance of 320 cm from the display), the two eyes viewing the display will receive different images. Then the image will be 3D, using the autostereoscopic effect. Moreover, the closer the viewer comes to the display, the farther apart (in angle) the two images are that form the 3D image. Thus, parallax is maintained by the automultiscopic display. By comparison, this parallax is reversed in a typical stereoscopic display[4]. A properly designed automultiscopic display meets all the requirements delineated in Section 1 for the best 3D display.

The timing of an automultiscopic display can be optimized through the use of six parameters:

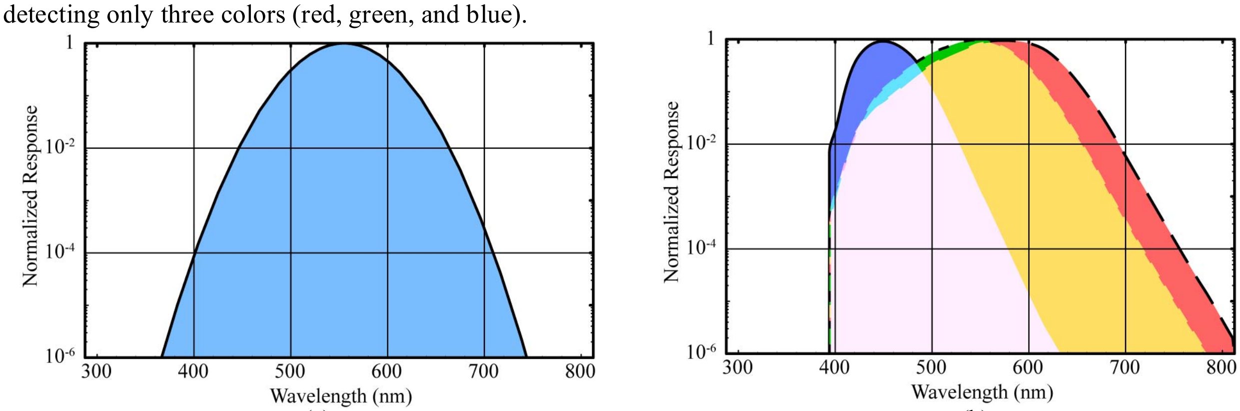
- Image rate – the rate at which images are displayed at all angles combined
- Frame rate – the rate at which images are displayed at a single viewing angle
- Color depth – the number of images required to generate the viewed image (generally either 3, for RGB color, or 1, for grayscale)
- Distance from the display to the observer – the maximum distance (including viewing angle) from the observer's eyes to the center of the display for 3D imaging
- Size of the viewing region – the width of the viewing region for a single image

- Walkaround viewing angle – the angular distance around the display for which the 3D image shows a true representation of the object.

Size of the viewing region increases with increasing frame rate, walkaround viewing angle, color depth, and viewing distance, but decreases with increasing image rate. For example, decreasing the walkaround viewing angle from 360° to 180° reduces the required image box region by a factor of 2, while changing from grayscale to color without increasing the size of the image box requires increasing the image rate a factor of 3. More precisely, if the walkaround viewing angle is 180°, the frame rate is 45 Hz, the display is operated in full color, the image rate is 6 kHz, and the image box is to be no more than 50 mm, the viewer must be within 140 cm of the display to get a smooth, distortion-free 3D effect. Likewise, if the frame rate stays at 45 Hz with a color image and a 50 mm image box, for the viewer to be as far as 70cm from the display and the walkaround angle to be 360°, the image rate must be at least 6 kHz.

2.4. Light Source for Full Color System

Since images are rapidly scanned in creating the automultiscopic 3D views it is important to consider eye response to the illuminating light sources, especially with respect to a full-color system. The eye has an overall response to brightness with its peak at 556 nm and a specific response to intensity in the color regions roughly corresponding to red, green, and blue (Fig. 4). While the "real world" is illuminated by a near continuum of light, color vision is achieved by detecting only three colors (red, green, and blue).



(a) (b)

Fig. 4. (a) The overall spectral response of the eye is modeled as a Gaussian centered at 556 nm. (b) The spectral response of blue cones (solid line) peaks at 445 nm, while green sensitivity (short dashed line) is maximum at 535 nm and red (long dashed line) at 575 nm[5].

It is interesting to note that the photoreceptor cones in the eye responsible for red vision have their peak response in the yellow-green. At the center of the red spectrum, 701 nm, the response of these cones is only 0.55% of its peak response, but that is 16 times greater than the response of the green cones. Additionally, if the red and green response curves are scaled by the eye's sensitivity to each, the transmission spectrum of the eye lens is removed, and these two response curves are added, the resulting curve matches the overall response of the eye shown in Fig. 2(a). Three narrow-spectrum light sources for red, green, and blue, with proper power ratios, can be used to generate the required color response. Since a wavelength multiplexed HOE is used to project dispersion-free-images, these sources should be narrowband, for example, red, green, and blue lasers. The blue source would need to be centered between 400 nm and 460 nm, the green between 510 nm and 540 nm, and the red could be centered at any wavelength longer than 620 nm (as long as it was still visible). Three-color laser systems typically exploit these values by using the 457.1 nm blue line of the Ar^+ laser, the green 532 nm line of frequency-doubled Nd:YVO_4, and the red line of the Kr^+ laser at 647.1 nm. The colors of the visible spectrum, and the response of the eye at the center of each color, appear in Table 1.

Table 1. Relationship Between Color and Wavelength.

Color	Wavelength Range (nm)	Center Wavelength (nm)	Overall Response	R	G	B
Violet	390-455	422	0.1%	2.0%	2.5%	60%
Blue	455-492	474	7.8%	11%	20%	54%
Green	492-577	534	84%	81%	96%	0.89%

Yellow	577-597	587	68%	95%	54%	0%
Orange	597-622	610	31%	71%	21%	0%
Red	622-780	701	0.03%	0.55%	0.034%	0%

3. EXPERIMENT

To see the automultiscopic "volumetric" 3D images, we constructed an experiment using a string of perspective images of a tank. This was designed for viewing from any angle around the display (walkaround viewing angle = 360°). We can calculate the other parameters defining the performance of this display, such as viewing distance 50 cm and viewing region 65 mm. To achieve a reasonable frame rate (40 Hz in this case), we were limited to a single color by the 1-kHz maximum image rate of the scene generator. The images are projected into their individual viewing regions (Fig. 5) to create a virtual volumetric display.

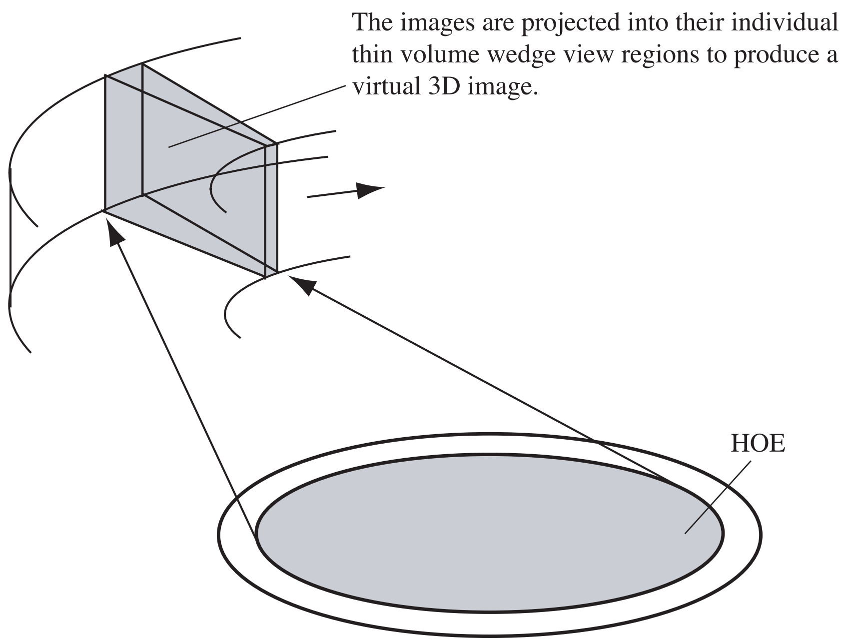


Fig. 5. The HOE/scene generator combination results in an indivdual image box.

The image of the tank behaved exactly as predicted. Horizontal look-around parallax was fully correct and the images looked solid and volumetric (Fig. 6). We then repeated the experiment with some changes. By increasing the image rate to 2 kHz we were able to reduce the image width to 24.5 mm, resulting in better 3D imagery and a smooth volumetric display at the cost of reducing the overall frame rate to 30 Hz.

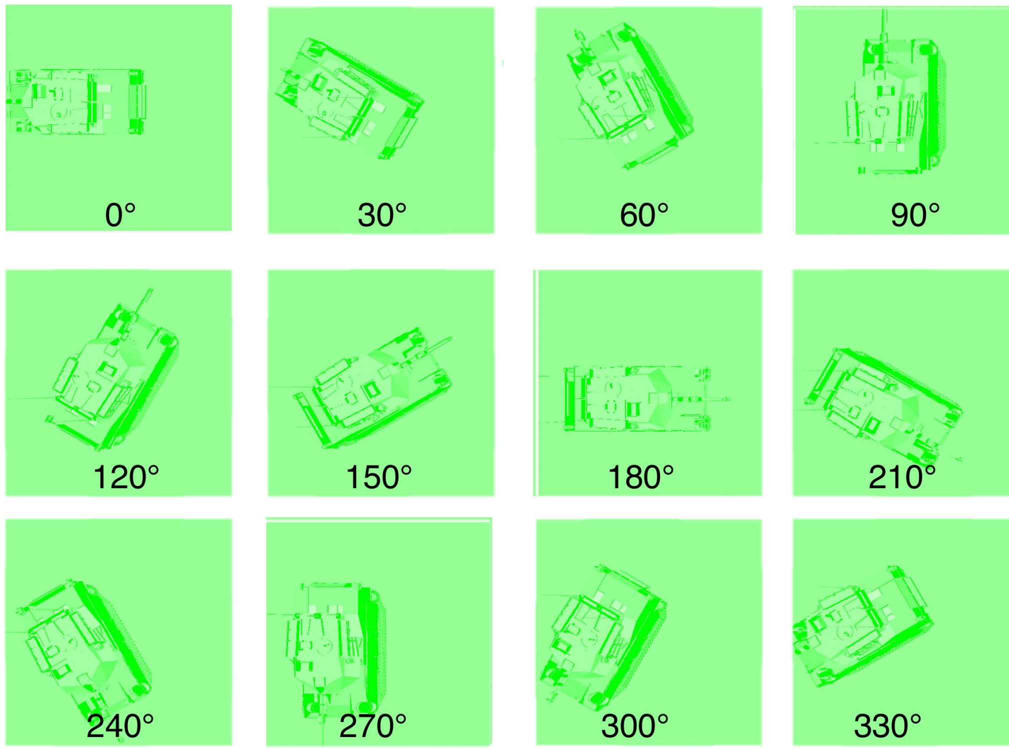


Fig. 6. The 3D tank image was volumetric, as shown by these photos from 12 angles around the display.

4. CONCLUSIONS

POC has developed the first version of a new automultiscopic display, one that overcomes the limitations of many other 3D displays while meeting the requirements of a “good” display. The automultiscopic display is volumetric, showing a 3D image that occupies space and can be viewed from any position around the display. It demonstrates the correct relationship between parallax and position, so the image appears closer in every respect when the viewer moves closer to it. This allows a group of viewers to see simultaneously a common 3D display object from perspectives appropriate to their positions, without special eyeglasses and without head tracking. We developed a tradeoff equation to analyze the performance of the system, and showed that this type of display can provide this smooth volumetric 3D imagery over any volume, limited by the speed of the image generator. Future development of the automultiscopic display will include both the increased image rate and addition of full-color images.

ACKNOWLEDGMENTS

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