Chapter 11

THREE-DIMENSIONAL PROJECTION DISPLAY SYSTEM

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Abstract: In this chapter, a current state of the art of 3D projection displays will be addressed. This begins with a review on conventional and three-dimensional projection display systems. And, some discussions on stereoscopic projection displays such as the polarization-based, the LC shutter-based and the ZScreen-based will be followed. Then, time-sequential multiview projection display and projection integral-imaging display will be discussed. Finally real 3D projection displays such as the Fresnel lens-based and the hologram-based will be reviewed.

Key words: 3D Display, Projection

1. INTRODUCTION

1.1 Overview of projection displays

In general, an electronic display is defined as a device or system that converts electronic signal information representing video, graphic or text to a viewable image of this information. Displays can be largely classified into direct-view or projection. Direct-view displays produce their images on the surface being viewed. On the other hand, the images from projection displays are formed on auxiliary surfaces, which are physically separated from the image-generating component. The direct-view technologies include cathode-ray tubes (CRTs) in televisions and computer monitors as well as plat-panel displays, such as liquid crystal displays (LCDs), plasma display
panels (PDPs), and organic light emitting diode displays (OLEDs) in various information terminals. All these displays have their own capabilities of high-resolution and satisfactory luminance. But, it is difficult and expensive to make a large-scale direct-view display enough to accommodate several viewers simultaneously.

Human visual system is known to have an angular resolution of approximately 1 minute of arc. In case an viewer would watch the HDTV (high-definition television) at a distance of 2 meters from the television as shown in Figure 11-1, the TV size must be as large as \(~70"\) in diagonal to fully resolve the TV video images with a resolution of high definition, which is shown in \(1920 \times 1080, \sim0.6\text{mm, full-color pixels}\) [1].

It is a surely expensive and challenging problem to implement a direct-view display of this size at present even though several prototypes of LCDs and PDPs of this size were being demonstrated very recently [2, 3].

Alternatives to the large-scale direct-view displays, Many types of projection displays have been devised [4]. Projection displays make use of an optical imaging system to magnify a small picture created either by conventional direct-view technologies, such as CRTs, or by modulating the light from an illumination system with a device called a panel. Projection displays produce larger images from electronic signals than is normally achieved by direct-view technologies. Figure 11-2 shows where projection displays are located in the display market with regard to resolution and screen size [1, 4].
Projection displays are commonly categorized as front-projection and rear-projection types depending on the optical path used as shown in Figure 11-3. In case of front-projection types, the image source and the viewer are on the same side of the projection screen and the image is viewed by reflection from the screen surface, whereas in rear-projection types the image source and the viewer are on the opposite side of the projection screen and the image is projected to the rear of the screen and observed through the translucent screen material. So far, projection display systems can offer an economical solution to large and high-resolution information displays.
There are two key technologies providing impetus for the development of advanced projection displays. The first technology is the personal computer, which can now provide portable information sources of high-quality electronic video signals, so that projector makers have developed transportable projectors for displaying these signals over the last 10 years. A second technology to make deep influence on the present development of projection displays is the digital HDTV. To implement direct-view displays for the purpose of HDTV is very difficult and expensive, because the present size range of direct-view displays cannot effectively display all the resolution contained in a HDTV signals as mentioned above. Accordingly various types of projection display systems will provide cost-effective displays for this need.

1.2 Projection display systems

The core part of all projectors is the light engine. The light engine is the subsystem within the projector, which converts incoming electrical signals into the intensity-modulated two-dimensional optical images. The key components required for the design of a light engine include image forming devices, lamps, optical components, and attributes of these components strongly influence the overall system performance. There are many kinds of projection display systems on market, the CRT-based, the LCD-based, the LCoS(liquid crystal on silicon)-based and the DMD(digital micromirror device)-based. These conventional projection display systems have been briefly reviewed here.

1.2.1 CRT-based projection display

So far the CRT-based is the most common projection display systems at the commercial market. In this type of projectors, separate image sources are typically used for generation of the three primary colors; red, green and blue, so that the light engine of these CRT projectors is composed either of the three-CRT/ three-lens or three-CRT/ one-lens configurations as shown in Figure 11-4[1].
Three monochrome tubes, each optimized for luminance and beam width of a specific primary color, are imaged onto the screen and combined to form a full color image. In case of three-lens CRT projectors, convergence of CRT projection systems is a most challenging problem. Because red and blue channels are in an off-axis arrangement in the three-lens CRT projection system as shown in Figure 11-4(a), a trapezoidal image known as keystone distortion can be generated from these off-axis tubes[5]. Even though single-lens CRT projectors shown in Figure 11-4(b) are free from this keystone distortion occurred in the three-lens system, they also suffer from some other sources degrading convergence of CRT projectors such as the long back focal length and the relatively high f-number, etc. [6]. Majority of conventional projection display systems are based on the three-lens architecture and these are made for both front- and rear-projection installations.

1.2.2 Transmissive three-panel projection display

Most of front and rear transmissive projectors, which are commercially available now, incorporates high-temperature poly silicon(HTPS) panels in a standard three-panel, X-cube configuration[1]. Figure 11-5 shows a standard three-panel transmissive LC projection display system, which was first introduced commercially by Seiko-Epson in 1997[7]. In this projector, the incident white light is split into three primary colors by dichroic filters and each primary color passes through an LCD panel sandwiched between two sheet polarizers. Then, the output light is spatially modulated by the voltage applied to the pixels and the modulated three color beams are combined by a dichroic X-cube before the projection lens.
1.2.3 Reflective three-panel projection display

Commercial success of the standard transmissive three-panel projection system has driven down the cost of individual components. Accordingly a birth of the first three-panel LCoS projection architecture might be a derivative of the transmissive architecture, with each modulating subsystem (polarizer/panel/analyzer) being replaced by a PBS (polarization beam splitter) and LCoS panel. This architecture has been called ‘3xPBS/X-cube’ [8]. Figure 11-6 shows the reflective three-panel LCoS projection display based on three cube MacNeille PBSs surrounding an X-cube, which was first developed by IBM and Nikon [9]. As an alternative, an off-axis LCoS system was also developed [10, 11], in which the incident and reflective beams do not counter-propagate. Sheet polarizers can be used instead of PBSs to pre-polarize the incident beam and separately analyze the reflected light with off-axis designs. But, the panel convergence and projection lens design have been known to be difficult in this off-axis LCoS system.
More recently, three-panel LCoS architectures employing RSFs (retarder stack filters) with MacNeille PBSs, which combine the polarizing/analyzing of color, have been introduced[12]. This technology is capable of very compact color management systems. The ColorQuad™[12] shown in Figure 11-7 is one of LCOS projection architectures based on this approach.

1.2.4 DMD-based projection display

There is an optical semiconductor known as the DMD at the heart of every DLP projection system. This DMD chip, which was invented by Dr. Larry Hornbeck of Texas Instruments[13], might be regarded as the most sophisticated light switch in the world. It consists of a rectangular array of up to 1.3 million hinge-mounted microscopic mirrors. Each of these micromirrors is measured to be less than 10 μm in size and corresponds to
one pixel in a projected image. When a DMD chip is coordinated with a digital video signal, a light source and a projection lens, its mirrors can reflect an all-digital image onto a screen. The DMD and the sophisticated electronics that surround it are what we call DLP (digital light processing) technology. Figure 11-8 shows a photomicrograph of a DMD mirror array [14].

![Digital micromirror device (DMD)](image)

Figure 11-8. Digital micromirror device (DMD)

A DMD panel's micromirrors are mounted on tiny hinges that enable them to tilt either toward the light source in a DLP projection system or away from it, creating a light or dark pixel on the projection surface. The bit-streamed image code entering the semiconductor directs each mirror to switch on and off up to several thousand times per second. When a mirror is switched on more frequently than off, it reflects a light gray pixel; a mirror that's switched off more frequently reflects a darker gray pixel. In this way, the mirrors in a DLP projection system can reflect pixels in up to 1,024 shades of gray to convert the video or graphic signal entering the DMD into a highly detailed grayscale image.

### 1.3 Three-dimensional projection display

Human beings see the different viewpoint images of an object through two eyes, the right and left. Then, the human brain recognizes three-dimensional (3D) stereopsis of the object by synthesizing them with the binocular disparity of a stereo input image pair [15]. Most of the conventional 3D projection display systems have been implemented by
imitating this human visual system (HVS), so that these systems normally need a pair of cameras for capturing the left and right images of an object, and a pair of projectors for projecting the captured left and right images to the screen, and some special optical devices for separately inputting the projected left and right images to the corresponding eyes, contrary to the two-dimensional projection displays, in which only one camera, one projector is needed for capturing and projecting images of an object.

There are more than 50 kinds of 3D display systems developed up to now[15]. They can be largely categorized as stereoscopic and autostereoscopic 3D display systems depending on image separation methods as shown in Figure 11-9. In the stereoscopic 3D display system, the viewer is required to wear special glasses such as polarized or shutter glasses for separated reception of the left and right images on the eyes. But autostereoscopic 3D display systems can present 3D image to the viewer without a need for any special glasses, in which optical elements such as lenticular sheets or parallax barriers are attached on the display panels and they make the left and right images displayed on the panel to be collected on the corresponding eyes without any interference between them. In short, in the stereoscopic display systems the viewer takes on the polarized or shutter glasses, whereas the display panel is forced to take on special optical elements such as a lenticular sheet or a parallax barrier in the autostereoscopic display systems.

![Figure 11-9. Types of conventional 3D projection display system](image)

Meanwhile a holographic display, which is totally different from the stereoscopic and autostereoscopic approaches, has been regarded as one of the most attractive approaches for creating the most authentic illusion of observing volumetric objects. It is because the holographic technology can supply high-quality images and accurate depth cues viewed by human eyes without any special observation devices [16].
2. STEREOSCOPIC PROJECTION DISPLAYS

With stereoscopic projection displays two different perspective views are generated simultaneously and then these left and right views of a scene are projected onto the screen and then distributed to the left and right eyes of the viewer independently. Often special viewing devices are required to direct the appropriate view to the correct eye and block the incorrect view to the opposite eye. This technology is called stereoscopic display. Several methods for stereoscopic projection display have been reviewed here.

2.1 Polarized stereoscopic projection display

2.1.1 Overview

There are many kinds of projector systems commercially available such as CRT, LCD and DLP projectors mentioned above[4]. All these projector systems are now being used for polarized stereoscopic projection display. Figure 11-10 shows a general geometry of polarized stereoscopic projection display systems, which consists of two video projectors, two external polarizers, screen and a pair of polarized glasses. Basically, polarized stereoscopic projection involves the polarization of the two (left and right) projected images in orthogonal directions[4, 17]. The general standard for linear polarized projection is $+45^\circ/-45^\circ$ from the vertical axis. But, vertical ($90^\circ$) and horizontal ($0^\circ$) polarization for the two views can be also used. For the case of circular polarization, the two views are clockwise and counterclockwise polarized.
Commercial video projectors have some different operational characteristics. Especially each projector has its unique polarization state of the output beam. Accordingly in order for these video projectors to be used with polarized stereoscopic projection, lots of attention must be given to the possible interaction between the polarization orientation of the projected output and the desired polarization direction for stereoscopic projection.

### 2.1.2 Configurations of projectors for polarized stereoscopic projection

In general, video projectors mostly used for polarized stereoscopic projection can be classified into three types depending on the polarization state of their outputs[17] The majority of commercial LCD projectors has the linear polarized output with two colors in one direction and the other color in an orthogonal direction, which are classified as the *Type-1* LCD projector here. Some other LCD projectors also have the linear polarized outputs with all colors in the same directions, which are classified as the *Type-2* LCD projector here. On the contrary to the LCD projectors, the CRT, DMD and DLP projectors have the unpolarized outputs, which are classified as the *Type-3* projector here.

Figure 11-11 shows the output polarization states of three types of projectors. *Type-1* LCD projectors have the linear polarized outputs with two colors of red and blue in the vertical direction and the other color of green in the horizontal direction. *Type-2* LCD projectors have the linear polarized outputs with all colors in the same directions and *Type-3* projectors have the unpolarized outputs.
For these three types of commercial projectors to be used for polarized stereoscopic projection, various configurations of optical polarizers must be employed to obtain correct polarization output and color balance with minimal light loss and color distortion.

Figure 11-12 shows an overall optical layout of the conventional polarized stereoscopic projection system, where RR, RB, RG and LR, LB, LG represent the red, blue and green color components for the right and left projectors, respectively[18-20]. As shown in Figure 11-12, this system consists of two projectors, two external linear polarizers, Fresnel screen and a pair of glasses with linear polarizers.

Basically, polarized stereoscopic projection involves the polarization of the two (left and right) projected views in the orthogonal direction. Accordingly, two external linear polarizers must be mounted at either $+45^\circ$ or $-45^\circ$ in front of the right and left projectors for achieving correct orthogonal polarization and color balance as shown in Figure 11-12. These left and right beams polarized in the orthogonal direction by two external linear polarizers are simultaneously projected onto the Fresnel screen. And then, observer can view the stereoscopic 3D image by putting on a pair of glasses polarized in the same directions with those of the external linear polarizers ($+45^\circ$ for the right eye, $-45^\circ$ for the left eye).
For the case of Type-1 LCD projectors having the polarization states of Figure 11-13(a), which are mostly consisted of three LCD panels, two external linear polarizers must be mounted at either $+45^\circ$ or $-45^\circ$ in front of the right and left projector for achieving the correct orthogonal polarization and color balance as shown in Figure 11-13(b). Here, two circular polarizers (one is clockwise, the other is counterclockwise) with their axis at $+/45^\circ$ could be also used instead of two external linear polarizers.

![Figure 11-13. Overall optical layout of the conventional polarized stereoscopic projection system](image)

For the case of Type-2 LCD projectors having the polarization states of Figure 11-14(a), which are consisted of single or three LCD panels, the vertically polarized output of the projectors are rotated into the $+45^\circ$ and $-45^\circ$ orientations using half-wave retarder and then, external linear polarizers are placed in front of the retarders at the desired directions of $+45^\circ$ and $-45^\circ$ as shown in Figure 11-14(b). Here, also two circular polarizers (one is clockwise, the other is counterclockwise) with their axis at $+/45^\circ$ can be also used instead of two external linear polarizers.
Figure 11-14. Method of linearly polarized stereoscopic projection with Type-2 LCD projectors (a) Polarized outputs of Type-2 LCD (b) Half-wave retarders and external linear polarizers.

On the contrary to the Type-1, Type-2 LCD projectors the output of the Type-3 projector of Figure 11-15(a) is unpolarized, so that two external linear polarizers are simply needed for polarized stereoscopic projection. As shown in Figure 11-15(b), the external linear polarizers at the output of the projectors are oriented at +/- 45° from the vertical axis.

Figure 11-15. Method of linearly polarized stereoscopic projection with Type-3 projectors.

Configurations of polarized stereoscopic projection display by use of three types of commercial projectors in combination with external polarizers explained above are summarized in Figure 11-16. That is, the Type-1 LCD projector-based, Type-2 LCD projector-based, Type-3 projector-based polarized stereoscopic projection display systems are shown in Figure 11-16(a), (b) and (c), respectively.
2.2 LCD polarized stereoscopic projection display with improved light efficiency

2.2.1 Overview

Generally, it is well known that in the conventional projector configurations for polarized stereoscopic projection mentioned above, more than 50% of light energy might be inevitably lost in the process of polarizing the two projected views in the orthogonal directions. In particular light loss of these conventional polarized stereoscopic projection systems highly depends on the configuration of two projectors for polarized stereoscopic projection. A. Woods discussed various configurations of the commercial projectors for polarized stereoscopic projection and evaluated their performances in terms of light loss[17]. His experiments reveal that about 68%, 43%, 75% of light energy is measured to be lost for the cases of Type-1 LCD, Type-2 LCD and Type-3 projectors, respectively in the polarization process.

In case of Type-3 projectors, two polarizers must be placed in front of each projector for the two views to be polarized in the orthogonal directions, because the outputs of Type-3 projector are unpolarized, so that there can be no chance to get rid of the additional light loss caused by these polarizers in this system. On the other hand, in cases of Type-1 and Type-2 LCD projectors, their outputs are already polarized, so that a new type of LCD polarized stereoscopic projection display without using these additional polarizers can be devised by effectively taking advantage of the inherent polarization property of the conventional LCD projectors. Recently, S. C
Kim and E. S Kim[18] developed a new configuration of LCD polarized stereoscopic projection display with improved light efficiency, in which two external polarizers have been excluded and as a result, light loss could be dramatically reduced.

### 2.2.2 Type-1 LCD-based polarized stereoscopic projection display

Figure 11-17 shows a new configuration of the Type-1 LCD polarized stereoscopic projection display proposed by S. C Kim and E. S Kim[18, 21]. By comparing with Figure 11-12, this system also consists of two LCD projectors, Fresnel screen, and a pair of glasses with linear polarizers, but there are some differences. That is, two external polarizers employed in the conventional system are taken away, the right LCD projector is physically rotated by 90 degrees with respect to the left one and the green components of two projectors are mutually exchanged in this system.

![Overall optical layout of a new Type-1 LCD polarized stereoscopic projection system](image)

Figure 11-17. Overall optical layout of a new Type-1 LCD polarized stereoscopic projection system

Figure 11-18(a) shows the left projector and it has output polarization of the normal Type-1 LCD projector, in which red and blue components of the projector are vertically polarized, whereas green component is horizontally polarized[25]. If this right projector is physically rotated by 90° with respect to the left one then, the red and blue components, which are originally polarized at the vertical directions, are converted into horizontal polarization, whereas the green component, which is originally polarized at the horizontal direction, is transformed into the vertical polarization as shown in Figure 11-18(b).
Thus, red and blue components of the left projector and green component of the 90°-rotated right projector are vertically polarized. At the same time, red and blue components of the 90°-rotated right projector and green component of the left projector are horizontally polarized. Accordingly, by simultaneously exchanging the green color components between the left and 90°-rotated right projectors through the signal processing technique, two full linearly polarized color sets, which should meet the requirements of color balance and orthogonal polarization, can be obtained without a need of external polarizers as shown in Figure 11-19. That is, the left color set is vertically polarized, whereas the right one is horizontally polarized.

Figure 11-20 shows a flowchart of stereo image processing for the new Type-1 LCD projector-based polarized stereoscopic projection system. Firstly, the left and right video images captured by stereo camera are separated into three-color components of red, blue and green, respectively. Then, a new left image for the left projector, which is called a transformed left image here, is generated by mixing the red and blue components of the left image with the green component of the right image. At the same time, a
new right image for the 90°-rotated right projector is generated by mixing the red and blue components of the right image with the green component of the left image. But, because the right projector has been initially rotated by 90° with respect to the left one in the proposed scheme, the right image projected the right projector is also rotated by 90° with respective to the left one. Therefore, the new right image must be adjusted in its orientation and aspect ratio to match with those of the left one through some image processing techniques before it is loaded onto the 90°-rotated right projector, which is now called a transformed right image here. These newly transformed left and right images are sent to the corresponding left and 90°-rotated right projectors and the size of the projected stereo image pair is matched on the screen by using a 3D reform function of the projector. Then, by using a pair of glasses with linear polarizers oriented at the horizontal(right eye) and vertical(left eye) directions, the newly transformed stereoscopic images can be finally viewed.

Figure 11-20. Flowchart of stereo image processing for the proposed Type-1 LCD projector-based stereoscopic display

It is certain that output beam intensities of the new Type-1 LCD-based polarized stereoscopic projection system are increased two times than those of the conventional system, which means 50% of light energy might be inevitably lost in the conventional system because the external polarizers are employed. Moreover the external polarizers mentioned above are assumed to be ideal for theoretical analysis, but in case the commercial polarizers are used more than 50% of light loss might be expected. According to the experimental results of A. Woods[17], 68% of light loss is measured in the
practical Type-1 LCD-based polarized stereoscopic projection system. From some experimental results with NEC MT 1060R projectors belonging to the Type-1 LCD projector[21, 22], S. C. Kim and E. S. Kim[18, 21] show that light efficiency of the new system could be maximized and the stereoscopic video image projected from the new system can be made to be 213%, 75% and 300% brighter than those projected from the conventional Type-1 LCD projector-based, Type-2 LCD projector-based and Type-3 projector-based systems, respectively. Figure 11-21 shows experimental results for stereoscopic video images of 'Korean traditional wedding' projected on the screen from the conventional and new Type-1 LCD polarized stereoscopic projection systems, respectively. These figures visually conform that output light beam projected from the new system is much brighter than that of the conventional system.

![Experimental results of the Type-1 LCD-based polarized stereoscopic projection system](image)

*Figure 11-21. Experimental results of the Type-1 LCD-based polarized stereoscopic projection system*

### 2.2.3 Type-2 LCD-based polarized stereoscopic projection display

A new configuration of Type-2 LCD polarized stereoscopic projection system is shown in Figure 11-22[23, 24]. By comparing with Figure 11-12, this system also consists of two LCD projectors, Fresnel screen, and a pair of glasses with linear polarizers, but two external polarizers are eliminated and the right LCD projector is physically rotated by 90 degrees.
Figure 11-22. Overall optical layout of a new Type-2 LCD polarized stereoscopic projection system.

Figure 11-23(a) shows the left projector and it has output polarization of the normal Type-2 LCD projector, in which all color components of LCD projector are vertically polarized. If the right projector is physically rotated by 90° with respect to the left one, then, all color components of the projected right image, which are originally polarized at the vertical direction, are converted into the horizontal polarization as shown in Figure 11-23(b). Thus, all color components of the left and the 90°-rotated right projectors are vertically and horizontally polarized, respectively. Accordingly, on the contrary to the case of Type-1 LCD projectors, a process of color separation and exchange between two stereo images are not needed any more in case of Type-2 LCD projectors, because two full linearly polarized color sets, which should meet the requirements for correct color balance and orthogonal polarization are already obtained just by rotating the right projector by 90° with respect to the left one as shown in Figure 11-23. Here the left color set has vertical polarization, whereas the right one has horizontal polarization.

Figure 11-23. Output polarization of the left and 90°-rotated right projectors for the case of Type-2 LCD

Figure 11-24 shows a flowchart of stereo image processing for the new Type-2 LCD projector-based polarized stereoscopic projection system. In
case of Type-2 LCD projector, because the polarization directions of all color components are equal, a process of color separation and exchange is not required. But, because the right projector has been initially rotated by 90° with respect to the left one, the right image projected from it is also rotated by 90° with respective to the left one, so that the new right image must be reformed in its orientation and aspect ratio to match with those of the left one through some image processing techniques before it is input to the 90°-rotated right projector just like the case of the Type-1 LCD projector.

![Figure 11-24. Flowchart of stereo image processing for the case of Type-2 LCD projector](image)

The original left image and the newly transformed right image are sent to the left and 90°-rotated right projectors, respectively and the size of the projected stereo image pair is also matched on the screen by using a 3D reform function of the projector. Then, by taking on same glasses used for the case of Type-1 LCD projector, we can observe the newly transformed stereoscopic images on the screen with a good quality.

It is certain that output beam intensities of the new Type-2 LCD-based polarized stereoscopic projection system must be improved by comparing with those of the conventional system. In case of the conventional Type-2 LCD-based polarized stereoscopic projection system, half-wave retarders and polarizers must be employed, so that these optical devices inevitably cause lots of light loss and image distortion. According to the experimental results of A. Woods[17], 43% of light loss is measured in the conventional
Type-2 LCD-based polarized stereoscopic projection system. Moreover, it is also reported that light losses of the JVC’s Type-2 LCD projectors of Model M1500 and G150CL caused by the half-wave retarders and polarizers are tested to be 49% and 39%, respectively[26].

2.3 Time-sequential stereoscopic projection display

2.3.1 LC shutter-based active eyewear system

As an another approach for stereoscopic projection displays, a time-sequential stereoscopic projection with a pair of LC shutters has been suggested, in which the two left and right views are alternatively projected on the screen and these two views are separated by using a pair of LC shutters synchronized with alternating video signals as shown in Figure 11-25[27].

![A schematic of LC shutter-based stereoscopic projection display](image)

(a) Left images are displayed  
(b) Right images are displayed

*Figure 11-25. A schematic of LC shutter-based stereoscopic projection display*

A pair of LC shutters is mostly employed as an active eyewear system. In this approach wireless battery-powered eyewear with LC shutters, which are running in synchrony with the video field rate, is employed. Synchronization information between the alternating video signals and a pair of LC shutters can be communicated by means of an infrared 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[27]. The eyewear incorporates an IR detection diode which sees the emitter’s signal and tells the eyewear shutters when to make on and off. 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.
2.3.2  **ZScreen-based passive eyewear system**

An alternative to the active eyewear system is the ZScreen, which is a special kind of LC polarization modulator[28]. It is placed in front of the projection lens just like a sheet-polarizing filter, and this changes the characteristic of polarized light and switches between left and right-handed circularly polarized light at the video field rate. Viewers are forced to wear circular polarizing analyzing eyewear in this stereoscopic projection system as shown in Figure 11-26. Although most of theaters putting stereo films on the screen uses 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.

![ZScreen-based stereoscopic projection display system](image)

**Figure 11-26.** ZScreen-based stereoscopic projection display system

The ZScreen uses two liquid crystal cells (called pi-cells) in optical series with their optical axes orthogonal. 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.

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, tipping is possible. The combination of ZScreen and polarizing eyewear forms a shutter, although one could make a case for classifying it as a polarization selection method.
3. TIME-SEQUENTIAL MULTIVIEW PROJECTION DISPLAYS

Depending on the development stages of the 3D display technologies, various degrees of resolution and spatial perception are now offered[29]. In stereoscopic projection displays discussed above, they require viewers to wear special glasses such as a pair of polarized or shuttered glasses to feel the depth, which has been regarded as a main shortcoming in practical applications. Therefore, many kinds of autostereoscopic projection displays have been developed, because autostereoscopic displays could present 3D image to viewers without a need for any special glasses. Here a time-sequential projection multiview display system developed in Cambridge University has been discussed.

3.1 Concept of time-sequential multiview projection display

The time-sequential multiview projection display, which has been developed in the rainbow group in Cambridge university, consists of a high-speed liquid crystal display, a Fresnel lens and a series of abutting bar shaped light sources as shown in Figure 11-27(a)[30]. The light sources are positioned just beyond the focal plane of the Fresnel lens so that an image of the light bars is projected into the user's view space (they called this image of the light bars the 'eye box'). Each light bar is illuminated in turn and, in synchronization with this, successive laterally adjacent views of an object are displayed on the high-speed liquid crystal display. The effect of the lens is that each view is visible in a different window in front of the display. Provided the multiviews are repeatedly illuminated sufficiently rapidly, the user can perceive a three-dimensional image with both stereo and horizontal movement parallax, as long as both of the eyes are within the eye box. Of course the best position from which to view autostereoscopic images is at the eye box, but a good 3D effect can be obtained over a large range of distances, from 50 cm to several meters[31].
For the practical implementation of this time-sequential multiview projection display, a very fast liquid crystal display panel should be required. That is, in case 8-view images of an object might be displayed at a 60Hz refresh rate, it requires a liquid crystal display with a field rate of 480 Hz (8×60 Hz). Moreover, for the case of 32-view images, it would require a field rate of almost 2 kHz(32×60 Hz). So far these high field rate cannot be feasible with present nematic liquid crystals, but it may be attainable with ferroelectric liquid crystal displays(FLCD) if image data can be transferred to the ferroelectric liquid crystal arrays sufficiently quickly[32].

3.2  Practical implementation

A practicable monochrome 16-view version of a Cambridge display has been developed by use of a high speed CRT, an ‘image transfer’ lens and a ferroelectric LC shutter element in 1992 as shown in Figure 11-28 [33-35]. The implemented system is capable of 16-view at 320×240 resolution or 8-view at 640×480(both interlaced) on a 10-inch diagonal screen. This requires horizontal and vertical scan rates of 150 kHz and between 400 and 1000 Hz, to give individual view direction refresh rates of 50–60 Hz, and an eye box of about 250 mm width at a viewing distance of 1 meter.
Figure 11-28. A practicable monochrome 16-view version of a Cambridge display

Figure 11-29 shows an optical schematic of the 50 inch Cambridge full-color projection display system[36]. All Cambridge projection displays built before 1995 were monochrome. Color was achieved in late 1995 using a color sequential solution, since shadow-mask based color CRTs are not capable of the required luminance.

In the prior system, a color sequential shutter is used, which gave no color convergence problems, but the system required a factor of three increase in the CRT frame rate to produce the three color fields needed in each cycle. As a result this prototype used four CRT's abutted together horizontally had shown three faint seams in the field of view. And in the posterior system, three-CRTs are used to represent the color image as shown in Figure 11-29. The different color fields in the chosen RGB system must
be combined at some point in the optical train to be co-axial. Green CRT phosphors are much more efficient than red and blue phosphors, so a neutral 60/40 dielectric beam-splitting surface is used to fold in the green, wasting 60% of that CRT light. And a single dichroic surface is used, which efficiently transmits red and reflects blue light, to combine these two colors with very little loss. This is because, with no green light at this point in the optical train, we can design the dielectric-coating stack to have a broad transition region in the green part of the spectrum.

4. PROJECTION INTEGRAL IMAGING DISPLAYS

Integral imaging (II) or real-time integral photography has been studied for optical display and visualization of true three-dimensional images in space with incoherent light[37]. In II, three-dimensional images are formed by crossing the rays coming from two-dimensional elemental images using a lenslet array. Although II can provide observers with true 3D images with full parallax and continuous viewing points as in holography, it has some drawbacks also. For example, the viewing angle, depth-of-focus and resolution of 3D images are limited because lenslet arrays are employed. In addition, 3D images produced in direct-pickup II are pseudoscopic (depth-reversed) images. To overcome those limitations, projection-type of II systems with either a lenslet array or a micro-convex-mirror array has been developed[38].

4.1 Projection types of integral imaging system

There are two kinds of projection types of II system, the lenslet array-based and the micro-convex-mirror array-based. A projection II using a lenslet array can be implemented as shown in Figure 11-30(a). The projector casts entire elemental images onto the corresponding lenslet array. Of course the diverging angle $\theta$ of the projection beam should be close to 0. In this projection II scheme using a lenslet array, however, the Pseudoscopic/Orthoscopic (P/O) conversion is required and the viewing angle is narrow as in the conventional scheme.

Figure 11-30(b) shows a 3D projection II scheme using a micro-convex-mirror array. In this case, orthoscopic virtual images are automatically reconstructed, when the elemental images obtained from direct camera pickup. This is because each micro-convex mirror does not rotate the corresponding elemental image around its own center optic axis in the 3D image reconstruction process. Therefore, the display of raw elemental images using a micro-convex mirror is exactly equivalent to the display of
P/O-converted elemental images using either a lenslet array or a micro-
concave-mirror array. Each convex mirror element could have an f/# smaller
than 1. For example, if $f/# = 0.5$, the viewing angle $\psi$ becomes 90 degrees,
which is acceptable for many practical applications.

Note that optical barriers are not required in projection schemes, if 1) the
focal length of micro-convex mirrors is shorter than the depth-of-focus of the
relay optics, and 2) the diverging angle $\theta$ of the projection beam is small.
These conditions are easily satisfied in projection II systems. Then, each
elemental image is projected onto its own micro-convex mirror, i.e.,
elemental images are not displayed through their neighboring micro-convex
mirrors. Therefore, as observers' viewing direction deviates from the optical
axis that is normal to the display lenslet array, they do not experience
flipping of the reconstructed 3D image.

![Diagram](image)

*Figure 11-30. Projection II (a) with a lenslet array, (b) with a micro-convex-mirror array*

### 4.2 Experiments on projection integral imaging

A feasibility of projection II using a micro-convex-mirror array could be
demonstrated through a simple optical setup, which is composed of a micro-
convex-mirror array, imaging lens and projector[38]. Figure 11-31(a) shows
the 3D object to be imaged in the projection II experiments. A pickup lenslet
array with $53 \times 53$ plano-convex lenslets and a color LCD projector with three
panels were employed in the experiments. For the micro-convex-mirror
array, the pickup lenslet array itself was used. This is possible, because some light energy could be reflected for normally incident light at the surface of the lenslet array. Therefore, to produce the micro-convex-mirror array, the lenslet array is positioned so that the convex surfaces of lenslets face the 2D image projector. Then, the reflected light from the surface of the lenslet array can be observed. If the lenslet array is flipped so that the opposite side faces the 2D image projector, the effect of a micro-concave-mirror array can be obtained.

The raw elemental images obtained from direct camera pickup are shown in Figure 11-31(b) and they are projected onto the micro-convex-mirror array for reconstruction of a 3D orthoscopic virtual image. The left, upper, and right views of the reconstructed 3D image are finally shown in Figure 11-32, in which viewing directions for the three images were deviated from the optical axis by ~30 degrees, respectively. In case the lenslet array is used as a micro-concave-mirror array by facing its plano side to the viewer, the reconstructed image became a pseudoscopic real image, as we expected.

![3D object and its elemental images](image1)

*Figure 11-31. 3D object and its elemental images*

![Reconstructed orthoscopic virtual 3D images](image2)

*Figure 11-32. Reconstructed orthoscopic virtual 3D images*
5. FRESNEL LENS-BASED PROJECTION DISPLAYS

5.1 Concept of image floating

Image floating is a simple 3D display method in which the feel of depth is emphasized using a floating lens. Figure 11-33(a) shows a schematic concept of the floating display[39]. The floating image, however, can be located in front of or behind the floating lens, and the position of the floating image is determined by the lens equation related with the focal length of the floating lens and the position of the object. A system in which the distance between the object and the floating lens is always a greater distance than the focal length is amenable for use in the floating system. Consequently, the floating system, the floating image of which is located in front of the floating lens, is mostly employed in the practical applications. As shown in Figure 11-33(a), the floating image is rotated by 180° because of the imaging phenomenon of the floating lens.

![Floating display](image1)

**Figure 11-33. Concept of image floating**

The floating display system cannot make a 3D image from a plane image but can only change the position of the image, which means that a 3D image cannot be generated by a floating display system in which an ordinary 2D display device replaces a real object. Therefore, the electro-floating display
system which does not use a real object requires a 3D display component which is capable of providing the volumetric 3D images in order to represent 3D moving pictures. Figure 11-33(b) shows the concept of the electro-floating display. In this case, the inversion of the floating image can be easily corrected through rotating the object image, as shown in Figure 11-33(b). The floating lens shown in Figure 11-32 can also be changed into a concave mirror because the concave mirror is similar to the convex lens from the viewpoint of optics. The floating image can be observed through the floating lens. As a result, the viewing area of the floating system is restricted by the aperture of the floating lens. This restriction becomes severe when the distance between the floating lens and the floating image, referred to as the floating distance, is longer, which is determined by the lens equation with the focal length of the floating lens and the distance between the floating lens and the object, referred to as the object distance.

5.2 Doublet Fresnel lens (DFL) system

In the floating display systems, which can provide a floating 3D image with real depth in the air, Fresnel lens is mostly employed as a floating lens[40-43]. Fresnel lens is regarded as a very useful and attractive optical device in case a large-size lens might be required in the optical system, because it can be made to be very thin and flat contrary to the conventional optical concave and convex lenses [44, 45]. In particular, a doublet Fresnel lens (DFL) can be effectively used for projecting a 2D image into the front focal length of it as a form of the floating image with some depth. Operating in conjunction with the display system such as a CRT or the like, the DFL is found to achieve a substantial image improvement in terms of image contrast, signal-to-noise ratio and field of view by comparing with those of the single Fresnel lens. A pair of Fresnel lenses acts as a single optical element, in which each of Fresnel lenses exhibits the same focal length. However, acting as a pair of Fresnel lens, the focal length will change to one-half that of the individual Fresnel lenses. Figure 11-34 shows a schematic diagram for the DFL system.
Figure 11-34. Schematic diagram of a DFL system

Figure 11-34 illustrates the operation principle of a DFL system. Generally, a single Fresnel lens system shows considerable chromatic aberrations, so that it causes some distortions in the floated images. To reduce this aberration of a single Fresnel lens, a DFL system might be preferred, in which the chromatic aberration and the focal point caused by refraction can be reduced. The DFL system shown in Figure 11-34 is composed of two Fresnel lenses having a positive focal length. The first lens acts as a collimator to direct light rays from points on a source image to the second lens and by using the second lens the light rays transmitted by the first lens are collected and focused in the front of the second lens. Thus, the DFL serves to direct and cause light rays from the source image to converge at locations in front of the second lens, so that a real image appears in front of the second lens.

In Figure 11-34, a source image is appeared as a line having two end points represented by A and B, and its projection along a common optical path is represented by the dotted line. A curved bold line A-B in conjunction with projection lines can represent the substantially transmitted focal plane. As the floated image size is related to the spacing between two Fresnel lenses, $d_2$, its size can be changed in proportion to the distance of the spacing $d_2$. The distance of the spacing $d_2$ should be also selected as large enough to avoid the moiré fringe effects at the projected image.

The back focal length of the lens, $d_1$, is related to the distance of floating image in front of the second lens, $d_s$. That is, variation of the distance $d_1$ leads the changes of displayed image size and the floating distance $d_s$ in front of the screen. An increase of distance $d_1$ results in the decrease of the image size at the distance $d_s$, whereas a decrease of the distance $d_1$ leads to the magnification of virtual images in front of screen.

At the distance $d_3$, floating image creates a dynamic movement when an observer shifts its perspective. For all cases, the size of the aperture should
be at least as great as the corresponding dimension of the source image at screen.

When a flat image derived from the LCD or PDP display system is projected to such a curved focal plane, a form of object parallax is evoked wherein the viewer observes portions of the originally flat image at either side of the curved focal plane. In the projection system employing a schematic of Figure 11-34, this curved output focal plane may be generated in conjunction with relatively wide fields of view to permit observer or eye station motion about the projected focal plane and coincident image such that human cognition will tend to synthesize and interpret a three-dimensional effect.

5.3 DFL-based projection display system

Recently a large-scale DFL-based 3D projection display system called 'Holocube' has been implemented with a LCD projector, curved screen and DFL system as shown in Figure 11-35[40-43]. In this system, 2D video image is projected from the LCD projector in a rear projection mode and reflected from the curved screen and then, this image is floated into the space through the DFL system.

![Schematic diagram of a DFL-based 3D projection display system](image)

Figure 11-35. Schematic diagram of a DFL-based 3D projection display system

This system can be divided into two functional units; the display and rear-projection unit. The display unit consists of a DFL system and a dark film. The dark film could be used for improving the floated image contrast and observation condition. A pair of large planar Fresnel lens is placed behind this dark film. A commercial LCD projector is used for projecting the 2D video image onto the curved screen. The curved screen reflects the input
image back to the center of the DFL. Meanwhile the DFL was manufactured in all one form and its diagonal size was made to be 100 inch.

Figure 11-36 shows the original image on the video projector and its floated 3D image onto the space through the implemented projection display system.

![Image](image)

(a) Original image
(b) Projected 3D image

*Figure 11-36. Original image and its projected 3D image*

A typical image size at the screen is 30 inches high and 40 inches wide. The output focal plane of the DFL is positioned about 35-47 inches in front of the exit aperture of the Fresnel lenses. The active size of the Fresnel lenses is 70 and 94 inches in height and width, respectively. The size of the 3D image is found to be approximately 35-47 inches and the viewing angle is also found to be approximately 60 degrees.

6. HOLOGRAPHIC PROJECTION DISPLAY

6.1 Introduction

Recently Harold R. Garner have constructed a system that projects true dynamic 3D holographic images from computer-generated holograms utilizing the lowest orders of diffracted light from a laser illuminated DMD[46]. They have demonstrated the utility of the DMD as a 3D image holographic medium by producing virtual and real 3D images at finite distances, an essential condition for image reconstruction with depth. Their aim is to create a real-time, multi-color projection system for all digital holograms.
6.2 Optical system

An optical system for reconstruction of dynamic holographic images by use of a DMD has been constructed as shown in Figure 11-37(a). It is composed of a 15 mW HeNe Laser, spatial filter, collimating lens with a focal length of 10 cm, DMD, converging lens with a focal length of 40 cm and an image reconstructor for real image viewing.

The real image reconstructor could be a frosted glass plate, fiber optic magnifier, or CCD/digital camera for visualization of a planar cross-section of a 3D image; or it could be a translucent block such as a thick Agarose gel to create a suspension of micro-scatter bodies to simultaneously view the whole 3D real image. The “original image” depicted in the upper left in Figure 11-37(a) is a bitmap of a 2D irregular perspective object. Its computed interferogram is represented on the computer monitor. The picture at the “image reconstructor” is a CCD camera photo of the actual image reconstructed on a frosted glass plate. This is an illustration of the DMD’s capability to reconstruct 2D irregular perspective objects as well as full 3D holographic scenes.

The 3D holographic virtual image can be observed by looking directly into the DMD as shown in Figure 11-37(b). The convergent lens and image reconstructor are removed from the optical system and the laser intensity is substantially reduced with neutral density filters for viewing directly by eye. The DMD functions as a reflective holographic medium in either projection mode.

*Figure 11-37. Schematic of DMD hologram projection system for (a) real and (b) virtual images.*
6.3 System demonstration

For system demonstration, a simple scene containing two objects has been considered, which is shown in Figure 11-38. That is, a bitmap-image of a jet is placed at the rear plane \((z = 27.5 \text{ cm})\), and a bitmap-image of a helicopter is placed at the front plane \((z = 30 \text{ cm})\). For calculation of each interferogram, every pixel in the image at each plane was treated as a point source of light with intensity equal to its gray scale value.

![Figure 11-38. Bipmap-image layout to demonstrate 3D image projection with a DMD hologram.](image)

The calculated interferograms can be scaled in software to adjust the size of the displayed scene and to associate them with physical spatial coordinates. Here in calculations of the hologram, a laser wavelength of 633 nm and a converging lens with a focal length of 25 cm and the bit-maps located as shown in Figure 11-38 were used.

In case the computer-generated hologram is transcribed to a HeNe laser illuminated DMD, a real and a virtual 3D image of the jet and helicopter can be seen as shown in Figure 11-38. For this demonstration, they located a 10 cm collimating lens 10 cm in front spatial filter, the DMD 28 cm from the collimating lens, and the 40 cm converging lens 11.5 cm from the DMD. The angle between the incident illumination axis and the image axis is about 20 degrees due to the cant angle of the mirrors [47, 48]. A frosted glass reconstructor was translated in front of the converging lens to image different slices of the real images produced at the two different focal \((z = 27.5 \text{ cm and } z = 30.0 \text{ cm from the 40 cm lens})\) positions, thus validating that the whole computer-generated scene was 3-dimensional. By taking photographs at each focal position, the original helicopter and jet was
obtained as shown in Figure 11-39(a) and 11-39(b), respectively. The different diffraction orders result in multiple images separated by the appropriate diffraction angles relative to the brightest diffraction order. Likewise for each diffraction order, there is a corresponding inverted image. The normal and inverted images occur at equal distances, plus or minus, from the focal distance of the lens. These other diffraction order images around the edges of the photos have been cropped for presentation.

![Figure 11-39. Reconstructed real and virtual holographic images (a) reconstructed real 3D image at 30 cm from the converging lens, (b) reconstructed real 3D image at 27.5 cm from converging lens, and (c) the virtual image looking into the DMD](image)

The more traditional way to visualize the reconstructed 3D scene is to directly view the virtual image that appears in the DMD as shown in Figure 11-38(c). The helicopter could be appeared in front of the fighter just as in the real image. The camera was positioned in front of the DMD to capture the virtual image and focused for a distance of 3 ft and placed 22 cm in front of the DMD for this picture. The depth of field of the camera was maximized to simultaneously capture both objects in the virtual image volume.

**REFERENCES**


Three-Dimensional Projection Display System


