Cylindrical 3-D Video Display Observable from All Directions

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Abstract

We propose a 3-D video display technique that allows multiple viewers to observe 3-D images from a 360-degree horizontal arc without wearing 3-D glasses. This technique uses a cylindrical parallax barrier and a one-dimensional light source array. We have developed an experimental display using this technique and have demonstrated observation of 3-D images from a 360-degree horizontal arc without the use of 3-D glasses.

Since this technique is based on the parallax panoramagram, the parallax number and resolution are limited by the diffraction at the parallax barrier. To overcome these limits, we improved the technique by revolving the parallax barrier. We have incorporated this new technique in our new experimental display. The display is capable of displaying cylindrical 3-D video images within a diameter of 100 mm and a height of 128 mm. Images are described with a resolution of 1254 pixels circularly and 128 pixels vertically and are refreshed at 30 Hz. Each pixel has a viewing angle of 60 degrees that is divided into 70 views, so the angular parallax interval of each pixel is less than 1 degree. In such a case, observers may barely perceive discrete parallax. The pixels are arranged on a cylindrical surface to allow the produced 3-D images to be observed from all directions.

1 Introduction

The multiplex-hologram is widely used for art, advertisements, and other applications because multiple viewers can see a 3-D image from all directions, whether front, rear or side. However, the multiplex-hologram can only show static images. Some kinds of volumetric displays can show dynamic images that can be seen from free directions, but their application is limited because their image is a so-called phantom image, where all of the background objects are seen through. On the other hand, it is difficult to make a multi-view display that can be seen from all horizontal directions with conventional methods such as using lenticular sheets due to the limitations of resolution and the shape of two-dimensional display devices such as LCD panels.

We propose a multi-view display technique that allows multiple viewers to observe 3-D images from a 360-degree horizontal arc[1, 2] . This technique is based on the parallax panoramagram and uses a cylindrical parallax barrier and a one-dimensional light source array, which is constructed from semiconductor light sources such as LEDs aligned in a vertical line. The light source array rotates along the inside of the cylindrical parallax barrier and the intensity of each light is synchronously modulated with rotation.

2 Basic Method

2.1 Principle of display

Figure 1(a) is a schematic diagram showing the principle of the proposed method. We consider a parallax barrier and a minute light source that moves along the parallax barrier while keeping a fixed distance. If the aperture width of the parallax barrier is sufficiently narrow, the light that goes through the aperture is a thin flux, and its direction is scanned by the movement of the light source. In this paper, we call this kind of scanning angular scanning. Therefore, when a viewer sees the aperture from a particular direction, the light reaches the viewer's eye only at the moment when the light source passes through a certain position. In Figure 1(b), when the aperture is seen from viewing point 1, the light comes to the eye only at the moment when the light source passes position A, and when the aperture is seen from viewing point 2, the light comes to the eye only at the moment when the light source passes position B.

Therefore, a pixel whose luminosity differs for each viewing direction can be displayed by synchronously changing the intensity with the movement of the light source. Furthermore, one light source can display many pixels by successively passing behind many apertures. From this principle, a cylindrical multi-view display can be made of a cylindrical parallax barrier and a one-dimensional light source array. The light source array consists of semiconductor light sources such as LEDs aligned in a vertical line and rotates along the inside of the cylindrical parallax barrier, as shown in Figure 2.

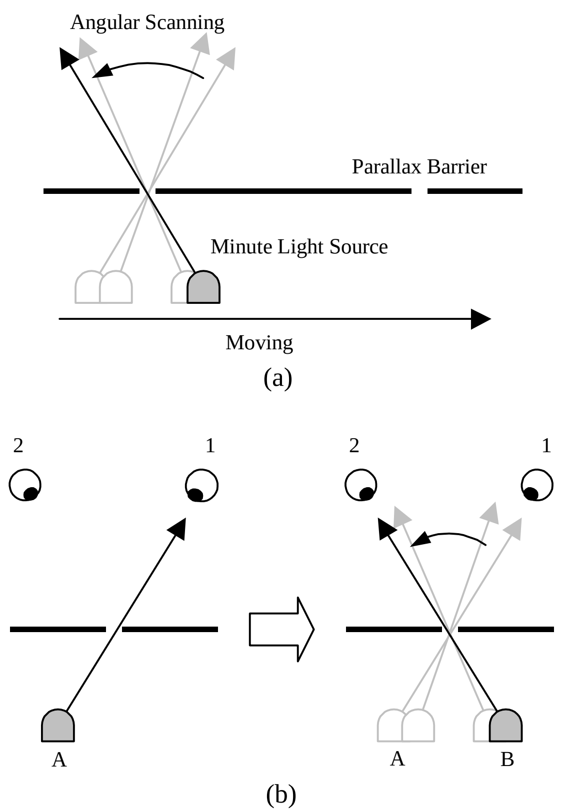


Figure 1. (a) Light going through the aperture is scanned by the movement of the light source. (b) When the aperture is seen from position 1, light reaches viewer's eye only at a moment when the light source passes position A. When the aperture is seen from Position 2, light reaches the viewer's eye only when the light source passes position B.

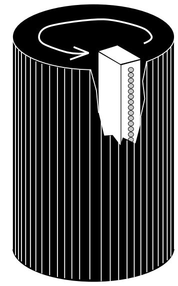


Figure 2. Cylindrical multi-view display made of a cylindrical parallax barrier and a one-dimensional light source array. Display rotates along inside of cylindrical parallax barrier with synchronous intensity modulation.

2.2 Image size

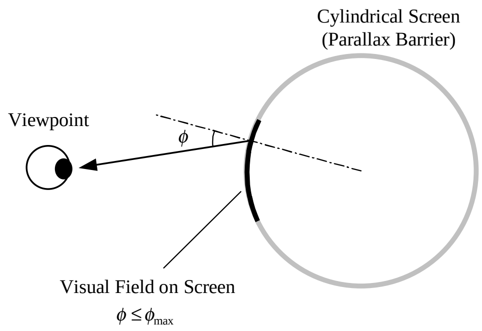
The angular range of emission from the light source should be limited so that light may not go through two apertures simultaneously. Consequently, the range of the lights angular scanning is limited. Here, we write this range as $\pm\phi_{\max}$. With this limit, viewers see images not on the entire screen but on a part of the middle region. Figure 3(a) shows the visible region of the screen. This region is a set of points that satisfy the condition that ϕ is within $\pm\phi_{\max}$. ϕ indicates the angle between two straight lines. One is a line between a point in the set and the viewing point and the other is a normal line of the screen surface at a point in the set. In this case, the viewing angle $\pm\theta$ is expressed as follows.

$$\theta = \sin^{-1}\frac{r\sin\phi_{\max}}{R} \qquad (R > r) \tag{1}$$

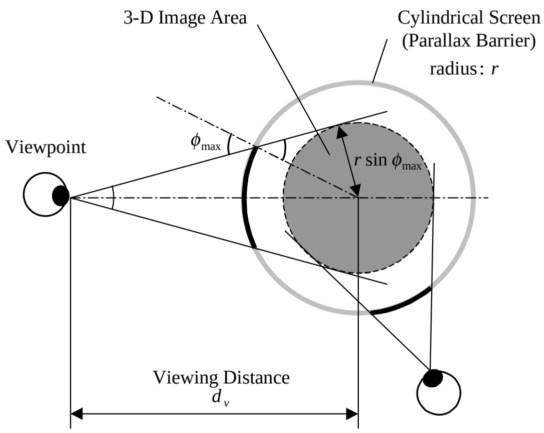
In this equation, R is the viewing distance from the center of the cylindrical screen and r is the radius of the cylindrical screen. Although the viewing angle θ depends on the viewing distance R, we can define a 3-D image area independently of the viewing distance. The 3-D image area is the cylindrical space within which 3-D images observable from a 360-degree horizontal arc can be displayed. The radius of this area is $r\sin\phi_{\max}$. Figure 3(b) shows this area.

2.3 Resolution of images and number of parallax

In this section, we describe the resolution of images, the number of parallax, and various related mechanical parameters. Of particular importance are aperture interval p, aperture width w_a, light source width, w_l and distance c between the light source and the parallax barrier. Figure 4 shows these parameters.



(a)



(b)

Figure 3. (a) Images are seen not on the entire screen but in the region that consists of points satisfying $\phi \leq \phi_{\max}$. (b) 3-D image area within which 3-D images observable from 360-degree horizontal arc can be displayed. This cylindrical space has a radius of $r \sin \phi_{\max}$.

Horizontal and vertical resolutions of images depend on the aperture interval p and the vertical interval of the light source array, respectively. The diameter of the image area is determined by the range of angular scanning $\phi_{\max}$ as mentioned above. The light source itself always spreads light within $\pm\phi_{\max}$. Therefore, in order to prevent light from going through two adjoining apertures simultaneously, there is the following condition among c, p, w_a, w_l, and $\phi_{\max}$.

$$\phi_{\max} \leq \tan^{-1} \frac{p - w_l - w_a}{2c} \tag{2}$$

This technique uses angular scanning, so the parallax interval depends on the frequency of the intensity modulation and the moving speed of the light source. However, since the light that goes through the aperture of the parallax barrier has some divergence, the angular resolution is limited. If the influence of diffraction at the apertures of the parallax barrier is neglected, the divergence angle $\Delta\phi$ of the light that goes through an aperture depends on the width w_l of the emitting part of the light source, the aperture width w_a, and the distance c between the light source and the parallax barrier. When the light source is positioned right in front of the aperture, the divergence angle is largest and described as follows.

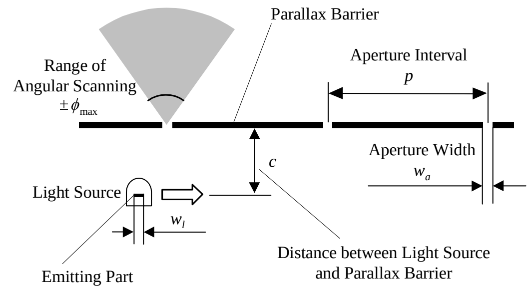


Figure 4. Mechanical parameters determine resolution of images and number of parallax.

$$\tan \Delta\phi = \frac{w_l + w_a}{2c} \tag{3}$$

2.4 Experimental display model 1

We have developed an experimental display (model 1) to confirm the technique explained above. The display consists of a cylindrical parallax barrier, an LED array, a drive circuit, a photo-reflector, an induction motor, and other components. The LED array, the drive circuit and the photo-reflector are rotated by the motor. The photo-reflector senses passing light by the apertures, and the intensity of the LED array is synchronously controlled with the rotation. The drive circuit has a ROM that stores binary image data instead of relying on transmission from the outside, and the image is static. The LED array has 32 LEDs with a 2-mm interval. The cylindrical parallax barrier has 221 apertures with a 2-mm interval and its diameter is 146 mm. The pixel interval is 2 mm horizontally and vertically and the parallax number is 22. Specifications, block diagram and photograph of this display is shown in Table 1, Figure 5, and Figure 6, respectively.

Figure 7 shows the images taken from three adjacent viewing points. As these photographs show, the images for all viewing points were observed from around the display. We confirmed that the 3-D images displayed by the proposed method could be seen from 360 degrees horizontally.

Table 1. Specifications of the experimental displays

	Model 1	Model 2
Pixel interval	2×2 mm	0.5×1 mm
Number of pixels	221×32	1254×128
Range of angular scanning	±30 degree	±30 degree
Number of Parallax	22	70 per pixel
Parallax interval	16.4 degree	≤ 1 degree
Diameter of Parallax Barrier	146 mm	230 mm
Image size	$\phi 70 \times 64$ mm	$\phi 100 \times 128$ mm
Refresh rate	30 Hz	30 Hz
Case dimension	300(W)×200(D)×420(H) mm	450(W)×350(D)×500(H) mm

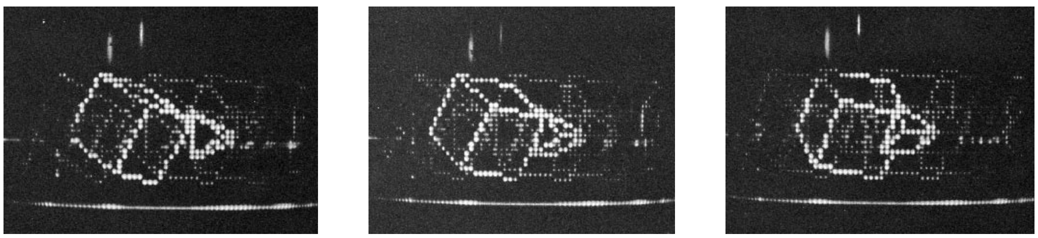


Figure 7. Images taken from three adjacent viewing points.

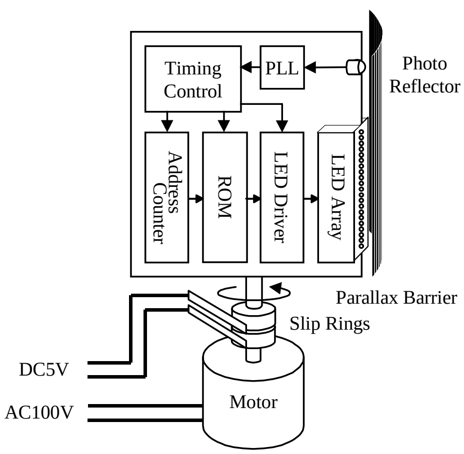


Figure 5. Block diagram of model 1

3 Improvements

3.1 Limitations of basic method

According to the inequality (2), between the light source and the parallax barrier is fixed, decreasing pixel interval p causes the range of angular scanning to decrease $\phi_{\max}$. This implies a trade-off between resolution and the size of images. To increase resolution and size simultaneously, the distance c between the light source and the parallax barrier needs to be shortened. However, as this distance is shortened, the divergence angle of the light $\Delta\phi$ enlarges and the angular resolution decreases according to equation (3). In short, there is a trade-off relationship among resolution, image size, and the number of parallax.

To improve resolution, image size and the number of parallax simultaneously, the emitting part width w_l and the aperture width w_a need to be decreased. Assume that the pixel interval is 0.2 mm, the range of the scanning angle is ±30 degrees, the number of parallax is 50, and the emitting part width equals the aperture width. In this case, the aperture width is about 0.01 mm. However, this value is around ten times the wave length of visible light, and the angular resolution is lowered by the influence of diffraction at the apertures.

This problem is not peculiar to this method, and it has been pointed out as a fundamental limtation of the parallax panoramagram [3]. However, this limitation can be overcome by refining the scanning technique, which is one of the advantages of this method. We describe this in the following subsection.

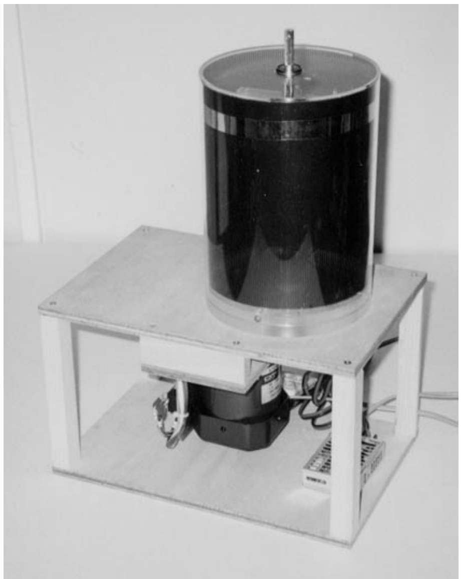


Figure 6. Photograph of model 1

3.2 Parallax barrier movement method

We propose a parallax barrier movement method that moves not only the light source but also the parallax barrier. Accordingly, the resolution can be higher in spite of the limit mentioned above. Figure 8 is a schematic diagram of this method. As the figure shows, when the parallax barrier moves in the direction opposite to the movement of the light source, the light that comes out through the aperture is scanned as if there existed a virtual parallax barrier that is finer than the actual one.

The aperture interval p_v of the virtual parallax barrier is expressed as

$$p_v = \frac{V_1}{V_1 - V_2} p_0 \tag{4}$$

where p_0 is the aperture interval of the real parallax barrier, $V_1(> 0)$ is the velocity of the light source, and $V_2(< 0)$ is the velocity of the parallax barrier.

This equation means that the movement of the parallax barrier decreases the pixel interval to $V_1/(V_1 - V_2)$ times the pixel interval in the still parallax barrier case. On the other hand, the range of angular scanning and the divergence angle of the light that goes through the aperture depends only on the distance from the light source to the real parallax barrier and on the shape of the parallax barrier. This means that the image size and the number of parallax is independent of the movement of the parallax barrier. As described above, this method enables an increase in resolution independent of the image size and the number of parallax.

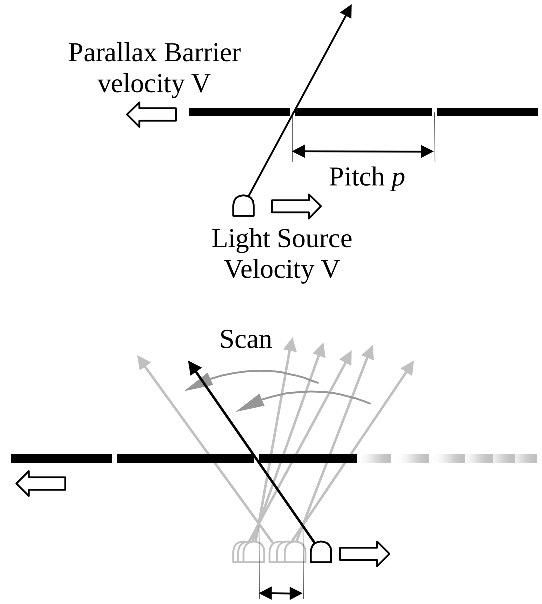


Figure 8. The light source moves to the right at the velocity $V_1(> 0)$, and the parallax barrier (aperture interval is p_0) moves to the left at the velocity $V_2(< 0)$. Then the light going through the apertures is scanned as if there existed a virtual parallax barrier with an aperture interval p_v narrower than that of the real one.

3.3 Multiple light source arrays

In the parallax barrier movement method, the resolution depends on the velocity ratio of the light source to the parallax barrier. Considering the rotational speed of the parallax barrier, higher resolution is possible if the light source array rotates more slowly. However, since the rotational frequency of the light source array equals the refresh frequency of the images, the rotational frequency cannot be significantly reduced.

Consequently, we considered using multiple light source arrays. When the number of light source arrays is n, an image is refreshed n times per rotation of the light source arrays. In this case, we can reduce the rotational frequency to $1/n$ of the refresh frequency, which increases the displaying time allotted to each pixel to n times. Therefore, the luminosity of images is increased to n times. Moreover, since the modulation frequency of each light source is reduced, the operating frequencies of light emitting devices and drive circuits also become lower. For a very narrow parallax interval such as the Super-Multi-View region of the Stereogram[7], this advantage is particularly important.

3.4 Experimental display model 2

We have designed the experimental display model 2 using the parallax barrier movement method and multiple light source arrays described above. Table 1 shows its specifications. Although the refresh frequency is 30 Hz, the rotating rate has been reduced to 56.25 rpm by using 32 LED arrays. The cylindrical parallax barrier has 38 apertures and its diameter is 230 mm. The barrier rotates at 1800 rpm, which is 32 times the speed of the LED arrays, in the opposite direction; the number of pixels in a rotation is $38 \times (1 - (-1800)/56.25) = 1254$. A photograph of this model is shown in Figure 9.

Figure 10 shows photographs of images produced by the model 2 taken from various directions as shown in Figure 11. We could see the 3-D image naturally in reachable distance area by both eyes. Images had strong depth cues of natural binocular disparity. When we moved around the display, we see corresponded images to our viewing position, therefore we perceived just as if objects are floating in the air.

Figure 9. Photograph of model 2

4 Discussion

Due to its capability to display an image that is observable from all directions, we believe that the cylindrical display is suitable for applications that require detailed observation, for example medical imaging or displaying works of art. In such use, it is expected that viewers move their eye positions actively to utilize the motion parallax. Accordingly, a very narrow parallax interval is needed so that the discontinuity of parallax is not conspicuous. However, it is difficult to make a parallax interval so narrow that viewers do not perceive a sense of discreteness. As a result, there have only been a few reports on this: FLA[4], using anamorphic optics [5], using FLCD aperture forming panel[6], etc.

In our proposal, a very narrow parallax interval is enabled by a parallax barrier movement method. We demonstrated 3-D images at a parallax interval of less than 1 degree (this value corresponds to a 5-mm interval at a 300-mm distance) with the experimental display model 2, those had smooth motion parallax.

Moreover, a narrower parallax interval is possible by increasing the number of light source arrays or using other techniques. In addition, there is the possibility that an accommodation stimulus for the viewer's eyes is produced by the effect of the monocular parallax[7] in the super-multi-view region.

Rotation of light source arrays enables the system to display in all horizontal directions easily, but this makes it difficult to transmit image data from external sources because the light source array cannot be directly wired. Since many pictures are needed to display in all horizontal directions, the transmission of large amounts of picture data at high speed to the rotating part poses a significant problem.

5 Conclusions

To realize a multi-view 3-D display that is observable from all directions, we proposed a technique that rotates a one-dimensional light source array inside the cylindrical parallax barrier. Moreover, the experimental display model 1 was developed, and we confirmed that the image it produces is observable from a 360-degree horizontal arc. This technique is based on the parallax panoramagram, which was improved to display in all horizontal directions by introducing mechanical scanning. The parallax panoramagram imposes limitations on the resolution of images and the number of parallax, which are caused by the effect of diffraction at its apertures. To overcome these limitations, we proposed an extension of the parallax barrier movement method and aubsequently developed the new experimental display model 2. Produced 3-D images are observable from 360-degree with smooth motion parallax, therefore potential of our proposed techniques was demonstrated.

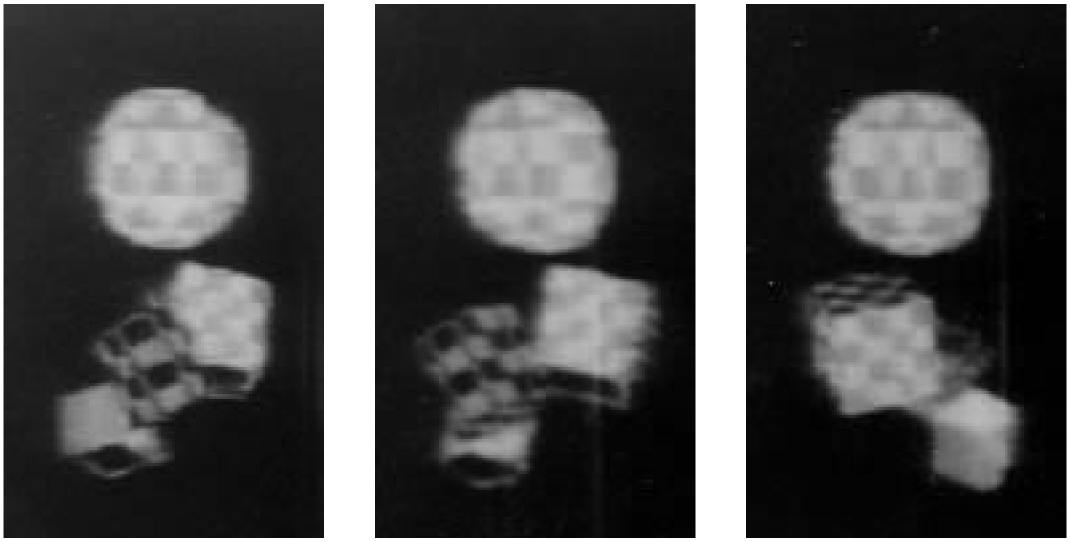


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Figure 10. Produced Images by Model 2.

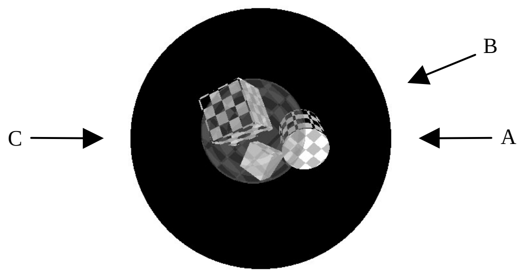

Figure 11. Photographs of The Images Are Taken from These Directions. (Top View)

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