360°-viewable cylindrical integral imaging system using a 3-D/2-D switchable and flexible backlight

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Abstract — A 360°-viewable cylindrical three-dimensional (3-D) display system based on integral imaging has been implemented. The proposed system is composed of a cylindrically arranged electroluminescent (EL) pinhole film, an EL film backlight, a barrier structure, and a transmission-type flexible display panel. The cylindrically arranged point-light-source array, which is generated by the EL pinhole film reconstructs 360°-viewable virtual 3-D images at the center of the cylinder. In addition, the proposed system provides 3-D/2-D convertibility using the switching of EL pinhole film from a point light source to a surface light source. In this paper, the principle of operation, analysis of the viewing parameters, and the experimental results are presented.

Keywords — Integral imaging, 360° viewable display, 3-D/2-D convertible display.

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1 Introduction

Three-dimensional (3-D) display technology has recently emerged as a new paradigm for the visual-display market, and has received much attention as a next-generation display technology. Many types of 3-D display technologies have been developed and announced.^{1–5} Among them, the 3-D display based on stereoscopy with glasses has been successfully deployed on a commercial scale for 3-D movie theaters, theme parks, and the home-television market.^{4–6} The key issues in the development of 3-D display technology are the question of whether or not to use glasses and the enhancement of the 3-D display characteristics. Therefore, the 3-D display market will evolve from a stereoscopic display to an autostereoscopic display with wide viewing angle and high resolution, and eventually to a 3-D volumetric display. The 360°-viewable volumetric 3-D display will be the final form of the display and the most ideal type in the development of display technology. When observing a reconstructed 3-D image in 360°, the observer's experience will feel more realistic.

Frontier groups and companies are performing research on wide-viewing-angle 3-D volumetric display technologies. The widely used volumetric 3-D display technique is based on the spinning-screen system.^{7,8} The spinning-screen-type volumetric 3-D display can reconstruct the 3-D object at the center of the volume, and the observer can see it whole around the system. However, the system is very complicated because of the use of the motorized spinning screen and synchronized system with a digital micromirror device. Therefore, the system requires a huge size and high cost, and involves safety problems caused by the rotating screen.

In this paper, we propose a 360°-viewable 3-D display system based on integral imaging to overcome the disadvantage of the spinning-screen-based volumetric 3-D display

system. Integral imaging is a 3-D display implementation method which was first proposed by Lippmann in 1908,⁹ and it is composed of a two-dimensional (2-D) display panel and lens array which is a set of elemental lenses. Integral imaging can show a reconstructed 3-D image to the observer without any special viewing aids. By using a 2-D lens array, integral imaging can provide a reconstructed 3-D image with full parallax and motion color image with quasi-continuous viewing points in a simple scheme. However, it also suffers from the issues of insufficient depth, resolution, and viewing-angle problems. Some techniques to overcome its weaknesses have been proposed by many groups.^{10–21}

Among them, the curved-lens-array-based integral imaging is one of the viewing-angle-enhancement methods; it enhances the viewing angle of integral imaging by arranging the lens array in a curve.¹⁵ The modified integral imaging is another enhancement method of integral imaging, which uses a pinhole array instead of a lens array.¹⁶ The use of a pinhole array results in a simple structure and a 3-D/2-D convertibility which is implemented by switching the backlight from a surface light source to a point light source for integral imaging. The most recently proposed method for 3-D/2-D convertible integral imaging is the electroluminescent (EL) pinhole-film-based method which is generated by the pinhole array on the EL film in front of another EL film that is used as a backlight.¹⁷ The system can convert a light source from a surface to a point array by switching the EL pinhole film. In addition, the EL-film-based integral imaging system is modified to a curved-pinhole-array system for viewing-angle enhancement using the flexibility of the EL film.¹⁸

In this paper, we propose the simplest method for 360°-viewable 3-D display with full parallax using the above-mentioned curved structure and EL-pinhole-film-based integral imaging. Figure 1 shows the concept of a

FIGURE 1 — The concept and layer structure of the 360°-viewable cylindrical integral-imaging system.

360°-viewable cylindrical integral imaging system using a 3-D/2-D switchable and flexible backlight. As shown in Fig. 1, we used two EL films for generating a point-light-source array in a cylindrical shape using their flexibility. Also, the 3-D/2-D convertibility is obtained by using the EL-pin-hole-film backlight switching. In the proposed system, each point light source is arranged cylindrically instead of flatly. The cylindrical arrangement of the point-light-source array enhances the viewing region to 360° when the reconstructed virtual 3-D image is displayed at the center of the cylinder structure. To prevent the flipping problem, we implemented a barrier structure in each point light source when the transmission-type flexible display panel shows the elemental image. By using this method, 3-D display for many viewers, 3-D signage, and 3-D information display can be easily made in a simple structure.

To begin with, we explain the fundamental principles of the proposed system and show how the 3-D/2-D convertibility is realized in our system. In Sec. 3, we analyze the characteristic parameters of the proposed system and viewing zone where the reconstructed virtual 3-D image can be seen without flipping. In Sec. 4, we present the experimental setup and results of the proposed system.

FIGURE 2 — The 3-D display principle of the proposed system in vertical parallax.

2 Principles of the 360°-viewable cylindrical integral-imaging system

The 3-D display principle of the proposed system is based on modified integral imaging which is based on a point-light-source array instead of a lens array. For 3-D/2-D convertibility and viewing-angle enhancement to 360°, we propose the cylindrically arranged layer structure as shown in Fig. 1. The proposed system is composed of a transmission-type flexible display panel, barrier structure, and cylindrically arranged point-light-source array. To generate a cylindrically arranged point-light-source array, we stacked the EL pinhole film and EL film backlight without any gap

FIGURE 3 — The 3-D display principle of the proposed system in horizontal parallax.

in the cylindrical structure. The barrier structure is located in front of the cylindrically arranged point-light-source array to prevent the flipped image and to keep the gap between the point-light-source array and elemental image. The outermost layer is the transmission-type flexible display panel, which displays the elemental image in a cylindrical shape using its flexibility.

The proposed system reconstructs the virtual 3-D image at the center of the cylinder while each ray from the cylindrically arranged point light source passes through the elemental image, which is bound by the barrier structure. The more-detailed 3-D display principle of the proposed system is shown in Figs. 2 and 3. The cross section of the proposed

system in the yz plane shows the 3-D display principle in vertical parallax as shown in Fig. 2. The point-light-source array is generated by the EL film backlight and EL pinhole film, which is in non-emitting mode and acts like a pinhole array. In this situation, the cross-sectional structure of the proposed system in yz plane is the same as the modified integral imaging^{15–18} and each elemental image is integrated at the center of the cylinder and reconstructs the virtual 3-D image which has the vertical parallax as shown in Fig. 2.

The other cross section of the proposed system in the xy plane shows the 3-D display principle in horizontal parallax as shown in Fig. 3. Each point light source gives the horizontal parallax which is limited by the viewing angle in modified integral imaging. However, the cylindrically arranged point-light-source array gives the continuous horizontal parallax in 360° . Therefore, the observer can see the virtual 3-D image all around the cylinder structure and experience virtual reality as shown in Fig. 3.

In addition to the 360° viewing angle, the proposed system has 3-D/2-D convertibility which is based on the backlight switching from the point light source to the surface light source as shown in Fig. 4. Two sheets of EL film generate the point-light-source array when the EL pinhole film is in non-emitting mode and the EL film backlight shines behind the EL pinhole film in 3-D mode as shown in Fig. 4(a). In this situation, the transmission-type flexible display panel shows the elemental image set of the virtual 3-D image, and the principles are the same as Figs. 3 and 4. In 2-D mode, the EL film and EL pinhole film emit light together and generate the surface light source as shown in Fig. 4(b).

FIGURE 4 — The principle of the 3-D/2-D convertibility in the proposed system: (a) 3-D mode, (b) 2-D mode.

FIGURE 5 — The viewing parameters of the proposed system.

3 Analysis of the characteristic parameters and viewing zone of the 360°-viewable cylindrical integral-imaging system

The parameters for the analysis of the characteristics of the proposed system are shown in Fig. 5. The point-light-source array is located on a cylinder with radius r , and the transmission-type flexible display panel has a gap g distant from the point-light-source array. When the point light source is arranged at a regular interval p , each elemental image region without flipping p_E is fixed, and each diverging angle of point light source θ is derived as follows:

$$\theta = 2 \arctan \left\{ \frac{(r+g) \sin\left(\frac{p}{2r}\right)}{(r+g) \cos\left(\frac{p}{2r}\right) - r} \right\}. \quad (1)$$

To prevent the flipping problem, the viewing angle of each point light source is limited by Eq. (1), and the imple-

FIGURE 6 — The 360°-viewable cylindrical integral imaging (a) without a barrier structure and (b) with a barrier structure.

mentation of the barrier structure is essential to block the rays.

Figure 6 shows the necessity of the barrier structure. As shown in Fig. 6(a), the rays in the viewing angle of each point-light-source interfere with each other in the system without a barrier structure. In this situation, t is the thickness of the EL pinhole film, d is the diameter of the pinhole, and the viewing angle of each point light source without a barrier structure θ_r is derived as follows:

$$\theta_r = 2 \arctan \left(\frac{d}{t} \right). \quad (2)$$

From Eq. (2), the elemental image regions of each point light source interfere with each other, and the flipped regions appear as shown in Fig. 6(a). To overcome these problems, we implement the barrier structure in the interval of each elemental image region without flipping as shown in Fig. 6(b). Each elemental image region for the point light source without flipping p_E is derived as follows:

$$p_E = \frac{p(r+g)}{r}. \quad (3)$$

As shown in Fig. 6(b), the observer can see the 3-D image without flipping when each viewing angle of point light source is limited by Eq. (1).

However, the size of the reconstructed virtual 3-D image is limited by each viewing angle of the point light sources as shown in Fig. 7. The total overlapped area of maximum viewing angles in each point light source is located at the center of the cylinder structure with radius r_v , which is defined as the viewing zone. The observer can see the reconstructed 3-D image without flipping in 360° when it is integrated in the viewing zone. Through some calculations

FIGURE 7 — The viewing zone of the proposed system.

TABLE 1 — The specifications of the experimental setup.

Barrier structure	
Width (gap)	4 mm
Thickness	1.5 mm
Radius	117 mm
Height	140 mm
EL pinhole film	
Size	710 mm × 136 mm
Thickness	0.4 mm
The number of pinholes	236 × 45
The diameter of pinholes	200 μm
The pinhole interval	3 mm
The radius of the cylinder structure	113 mm
Operation voltage	DC 12 V to AC 110 V
Current consumption	18 mA/mm ²
Luminance	150 cd/m ²
Elemental image	
Resolution	1200 DPI (21.2 μm)

using the tangent line at the boundary of the viewing zone, the maximum radius of the viewing zone r_v can be expressed as

$$r_v = r \sin\left(\frac{\theta}{2}\right) = r \sin\left[\arctan\left(\frac{(r+g)\sin\left(\frac{p}{2r}\right)}{(r+g)\cos\left(\frac{p}{2r}\right) - r}\right)\right]. \quad (4)$$

FIGURE 8 — The experimental setup.

From Eq. (4), we find that we can enhance the viewing zone using a larger cylinder radius and shorter gap.

4 Experiment

We performed experiments to verify the feasibility of the proposed system as shown in Fig. 8. The system is composed of the EL pinhole film, EL film backlight, barrier structure, transmission-type flexible display panel, and DC–AC inverter as the power supply. Each specification of the proposed system component is shown in Table. 1. In order to generate the cylindrically arranged point-light-source array, we

(a)

(b)

FIGURE 9 — The experimental result of backlight switching: (a) 3-D mode, (b) 2-D mode.

FIGURE 10 —The 3-D modeled letters of a computer-generated image.

stacked the EL film and EL pinhole film, and the barrier structure for preventing flipped image is implemented by acryl. The proposed system displays the elemental image on a transmission-type flexible display panel. However, the transmission-type flexible display panel is in the developmental stage and not yet commercially available. Therefore, we used an overhead projector (OHP) film and printed elemental images on it using a laser printer. In this situation, although OHP film cannot display moving images and change the elemental image, it can verify the feasibility of the proposed method. If the flexible display panel is applied in the proposed method, the moving image can be displayed. However, the resolution and brightness of the integrated 3-D image will be lower, and the thickness of the system will be thicker than the OHP film-based method. Therefore, the pinhole specification and viewing characteristic need to be recalculated by the specification of the flexible display panel.

Figure 9 shows the experimental results of the backlight conversion for the 3-D/2-D convertibility. To reconstruct 3-D image, the EL film backlight emits light and the EL pinhole film is in non-emitting mode, and the point-light-source array is generated as shown in Fig. 9(a). The use of a pinhole array leads to brightness degradation in 3-D mode, and the barrier structure also dims the backlight. The brightness of the proposed method is 150 cd/m^2 in 2-D mode and 2.1 cd/m^2 in 3-D mode. Therefore, the optical efficiency of the 3-D mode is 1.4% of the 2-D mode and nearly the same as the aperture ratio of the EL pinhole film.

The difference in brightness for the 2-D and 3-D modes might be reduced if the brightness of the backlight is increased in 3-D mode. Or, some devices such as plasmonic devices might be developed in the future for higher light transmission through the use of small-sized metallic holes.²² The viewing angle of each point light source is 42.54° from Eq. (1) in the ideal case and 38.8° in the experimental result. Therefore, the width of the observed viewing zone is about 75 mm, which is near the width of the calculated viewing zone of 81.98 mm from Eq. (4). Figure 9(b) shows the surface light source for the 2-D mode which is generated by the EL film backlight and EL pinhole film in emission mode. Some degradation in surface light source is incurred by the thickness of the barrier structure. However, it can be resolved by using a thinner barrier structure.

For experiments in 3-D mode, we generate the elemental image set of a virtual 3-D image and print it on the OHP film at 1200 dpi. The elemental image is generated by computer using OpenGL for the virtual 3-D images at the center of the cylinder, which are 3-D modeled letters '3' and 'D'. Figure 10 presents the 3-D modeled letters using OpenGL at different viewing positions.

Figure 11 shows the experimental results in 3-D mode, and the observer can see the different perspectives in the different viewing positions around the cylinder in 360° . The 3-D modeled letters '3' and 'D' are formed 25 mm in front of and behind the center position, respectively. Thus, the proposed system can reconstruct the virtual 3-D image in the viewing zone without flipping.

FIGURE 11 — The experimental results for a 3-D mode: (a) example of reconstructed virtual 3-D image observed from a specific direction, (b) reconstructed virtual 3-D images at different viewing positions around the z axis.

FIGURE 12 — The experimental results of the 2-D mode.

After switching the EL film backlight to surface-light-source mode, we perform an experiment in 2-D mode as shown in Fig. 12. The 2-D image on OHP film instead of the elemental image is displayed using the surface-light-source mode of the EL film backlight of the cylindrical structure.

5 Conclusion

In this paper, we proposed a 360°-viewable cylindrical integral-imaging system using EL films. It is based on a cylindrically arranged point-light-source array which is generated by the EL film backlight and the EL pinhole film. Using this method, a 360°-viewable 3-D display can be made easily and

cheaply with a simple structure. Moreover, the proposed system has 3-D/2-D convertibility. Therefore, this structure could be competitive for 3-D display for multiple viewers, 3-D signage, and 3-D information display.

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