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Recent Progress in Three-Dimensional Display Based on Integral Imaging

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In this paper, we describe one of the most attractive techniques in autostereoscopic three-dimensional display-integral imaging. We explain the weak points of the integral photography in the early days and the methods to overcome these problems. Finally we describe the technical trends developed recently.

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I. INTRODUCTION

Various three-dimensional(3D) display systems have been proposed, but there is no standard for them yet. One of the most important properties of three-dimensional display systems is autostereoscopy which means the observer does not need to wear special glasses to see a 3D image. The integral photography(IP) is one of the most attractive techniques in autostereoscopic displays. In addition, IP is the fastest developing technique with progress in CCD camera and display elements. As a result, IP progressed to integral imaging which means real-time IP.

The major advantages of the integral imaging are as follows.

- It needs no special glasses.(autostereoscopic)
- It has multiple-viewing positions.
- It has continuous viewpoints in the range of viewing angle.
- It has both horizontal and vertical motion parallax
- It can support real-time colorful moving images.
- It can provide natural depth imaging without eye-fatigue.
- It has compatibility with present display systems.

In spite of these many advantages, integral imaging has many problems with depth, resolution and viewing angle of the image. Hence it needs more research before becoming commercially available.

II. IP TECHNIQUES IN THE EARLY DAYS

The 3D display system using IP was first proposed by Lippmann in 1908 [1]. The principle was very simple, and it is described in Fig. 1. Using a lens array which is composed of many elemental lenses, an image array of the object by the lens array is recorded on film. Here, each lens is called an elemental lens. We call this process pickup and the image of the object by each elemental lens is called an elemental image. After developing the film, putting lens array and film at the same positions which were selected in pickup process, the viewer can observe the 3D image of the original object. We call this process reconstruction. It can be thought that IP has similarity with holography because it records lots of information on the recording medium and reconstructs recorded contents by using the same optical waves. But IP could not attract much attention when it was first proposed because the lens array was very difficult to manufacture at that time and the film which was used for a recording medium could not display a moving image. And most of all, there is a pseudoscopic phenomenon which means the reconstructed image has inverted depth because the direction of the observer's sight is opposite to that of the pickup process.

In 1931, Ives proposed the double IP method to overcome this pseudoscopic phenomenon [2]. In this method, the second lens array was used to invert the

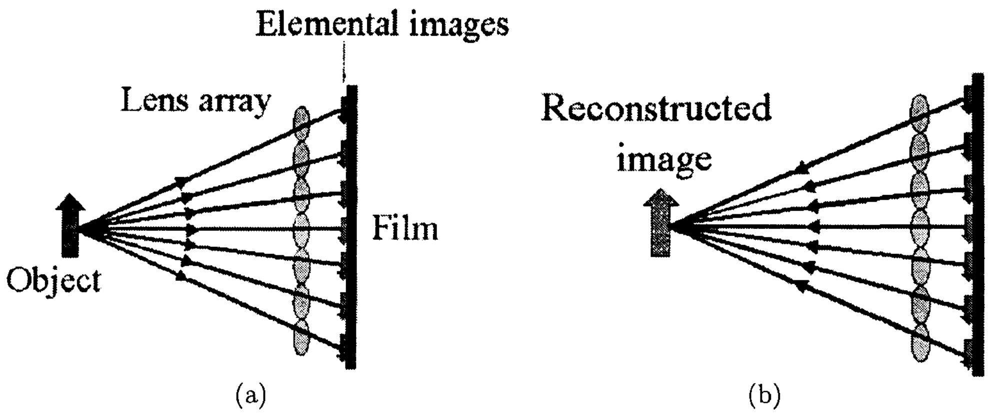


FIG. 1. The basic principle of integral photography. (a)Pickup. (b)Reconstruction.

pseudoscopic image and an orthoscopic image could be obtained.

In 1959, Burckhardt proposed the IP using a beaded plate instead of a lens array [3]. Because of the low technique level, the lens array was very difficult to make and very expensive at that time. Hence Burckhardt used a beaded plate to overcome this problem. The beaded plate was made of small glass balls on an emulsion plate to execute the role of the lens array.(Fig. 2) The refractive index of each glass ball was about two. In experiment, Burckhardt used a beaded plate which was composed of small glass balls with 50-60 mm diameter. Using this beaded plate, he could get a 3D image. But the reconstructed image was not clear at the front and back ends because of diffraction. Using glass balls of bigger size can overcome this problem. However, because of the aberration of bigger glass balls, the quality of the reconstructed image was degraded again.

In 1968, Burckhardt et al. reported optimal parameters and resolution degradation of IP [4]. First they calculated the optical power distribution on an elemental lens and let the width minimize to acquire maximum resolution. As a result they showed that the optimum size of elemental lens φ_{opt} and maximum resolution N_{max} are as follows.

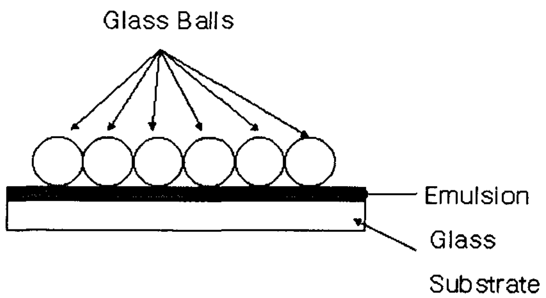


FIG. 2. Beaded plate.

$$\varphi_{opt} = 1.24a\left(\frac{\lambda}{b}\right)^{1/2} \tag{1}$$

$$N_{max} = \frac{B}{1.59(\lambda b)^{1/2}} \tag{2}$$

The parameters used in these equations are described in Fig. 3 with λ the wavelength. They also showed the maximum viewing angle given by

$$\psi_{max} = 2\arctan(\varphi/2c) \approx \varphi/c \tag{3}$$

The use of double IP to overcome the pseudoscopic phenomenon degrades the resolution by a factor of $\sqrt{2}$. Hence it was necessary to acquire the orthogonal pickup image by one process because the reconstructed image was distorted seriously.

In 1971, Okoshi proposed a new analysis method for systems using lens sheets [5]. He studied the optimum values of various parameters and calculated the effect by diffraction and abberation. As a result, he reported the position of 3D image where resolution degradation did not occur and calculated the optimum aperture in aperture-plate IP and the optimum lens size in lens-array IP.

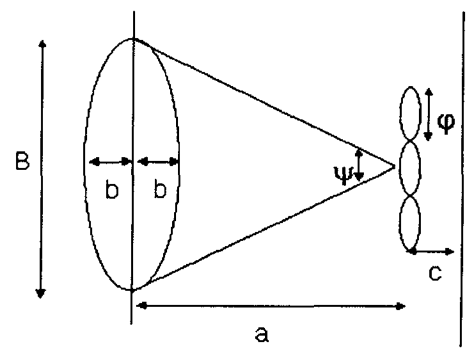


FIG. 3. Parameters used in calculation.

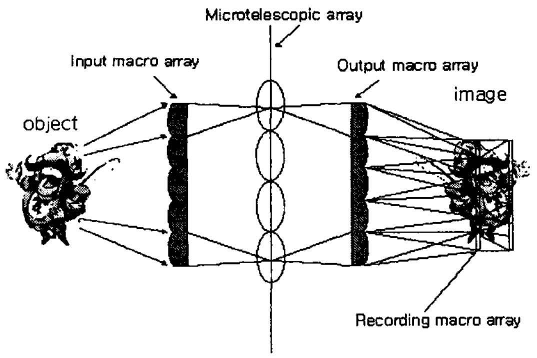


FIG. 4. Two-tier optical combination.

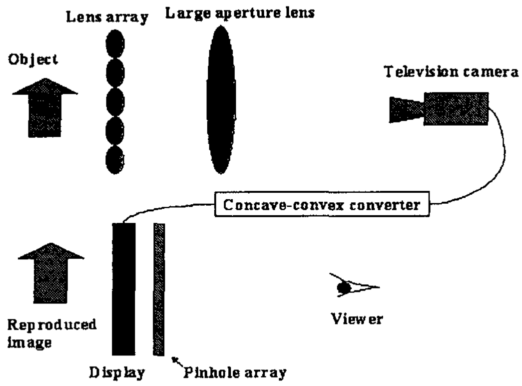


FIG. 5. The integral imaging system.

III. IP TECHNIQUE NOWADAYS

1. De Montfort University(UK)

The Montfort group has studied the IP technique since the 1980's [6–9]. In 1994, they proposed a new method named 'two-tier optical combination' to overcome the problem of pseudoscopic phenomenon.(Fig. 4) In the past, one must pickup the object two times to avoid the pseudoscopic phenomenon. As a result, the quality of the reconstructed image was very low. The Montfort group used afocal combination of two lens arrays to manage the image inside the IP system. And they reported that using a segment lens array which was composed of small telescopic units instead of using a large aperture lens array which was very difficult to manufacture, they could acquire high-resolution images. They also performed research on fields such as the generation of integral 3D images with computers, compression techniques of 3D data, and drawing depth information from integrated images.

2. NHK(Japan)

When IP was first proposed, it was not a very attractive technique because the lens array which was the essential element of IP was very difficult to manufacture. In addition, it was impossible to record and play moving images. But recently IP came to attract much attention again with the development of low-cost lens arrays and high-resolution active displaying elements.

In 1997, Okano et al. proposed a real-time IP technique (which was later called integral imaging(II) [10]) and showed the possibility of IP application to 3D TV [11]. Instead of using the film, they used active elements - a high resolution CCD camera and an LCD panel as pickup and displaying elements. By using this element they constructed a 3D integral imaging display system that could pickup and reconstruct moving images. And the problem of pseudoscopic phenomenon was overcome by modifying the elemental images from the CCD camera digitally. The integral imaging system which Okano proposed is described in Fig. 5.

Because the elemental images from pickup process can be transmitted to a displaying element in real time, recording and playing 3D moving images can be possible. And it can also be possible to modify the elemental images digitally in real time. But if the position of the CCD camera is just behind the lens array, unlike the case of using a film, the pickup direction of each elemental image is not parallel - it varies according to elemental lens position. Hence, they solved this problem by putting a lens with large aperture between the lens array and the CCD camera. Each elemental image recorded by the CCD camera is rotated by 180 degrees in symmetry with respect to each center of the elemental image (Concave-convex converter in Fig. 5). These modified elemental images are displayed on the LCD panel and the integral image is reconstructed by the lens array. By this process, the reconstructed 3D image takes its position behind the LCD panel (the opposite side of observer) and the inverted depth (pseudoscopic) problem is overcome. Okano used a lens array which is composed of 64 × 51 elemental lenses with 1.5 mm lens pitch, 10 mm focal length on pickup and 64 × 51 pinhole array on reconstruction process.

IP 3D-display by using a CCD camera and an LCD panel was able to record and display moving images and showed a new possibility of IP 3D-display. But the 3D-display by using the IP technique has another problem - the interference of between elemental images. The interference occurs when each elemental image is overlapped by neighboring images. Because overlapped

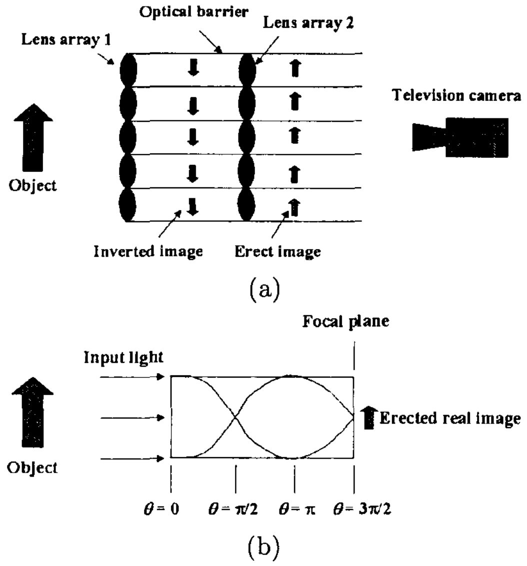


FIG. 6. (a)Complex lens-array method. (b)GRIN lens-array method.

elemental images can not be divided ideally, the reconstructed image is also overlapped or distorted. To overcome this problem, Okano et al. proposed methods of using a complex lens-array and a graded index(GRIN) lens-array in 1998 [12,14].

The method of the complex lens-array uses lens arrays as described in Fig. 6(a). By using optical barriers between the elemental lenses, the interference can be prevented. The second lens array behind the first lens array makes the image inverted. By this process, the convex-concave transformation which had been executed electrically in the previous systems was optically executed. We can substitute these two lens arrays and the optical barrier with one GRIN lens-array. In the GRIN lens-array method, there is no interference between each elemental image because the GRIN lens prevents it. And is also possible to execute the convex-concave transformation by controlling the length of the GRIN lens. This process is described in Fig. 6(b). In the experiment, Okano et al. used the GRIN lens array for pickup and a pinhole array for reconstruction.

Though Burckhardt and Okoshi have studied point spread functions of reconstructed images, Okano et al. focused on angular spatial frequency at the position of the observer and calculated the resolution which the observer might feel [13]. They calculated the angular spatial frequency as follows by considering the sampling effect by the lens array and the frequency limitation of the reconstructed image.

$$\beta_{max} = \beta_{nyq} min\left(\frac{\alpha_{i,max}}{\beta_{nyq}}\frac{z_i}{|L - z_i|}, 1\right) \quad (4)$$

In this equation, β_{nyq} is the Nyquist frequency of the sampling by an exit pupil, $\alpha_{i,max}$ indicates the maximum frequency that can be transmitted by the exit pupil and display panel observed at the exit pupil, L means the distance between the lens array and the observer, and z_i is the distance between the lens array and the reconstructed 3D image.

3. Seoul National University

A. Fresnel lens array

Based on the computer-generated integral imaging (CGII) method, we have been improving the IP technique. Instead of using a pickup image, CGII generates elemental images by a computer (Fig. 7). The pseudoscopic problem can be easily overcome in the CGII.

We proposed to use a Fresnel lens array to acquire a wider viewing angle which is an important property of 3D display systems [16]. In general, the viewing angle in IP systems decreases with the increase of the f-number of the lens array. But the usual spherical lens array experiences larger aberration with small f-number. As a result, the integrated image is distorted at the boundaries of each elemental lens. This distortion limits the viewing angle of the IP system. We solved this problem by using an aspheric Fresnel lens array instead of a common lens array. The well-designed Fresnel lens array can have not only small f-number but also little abberation. Fig. 8 shows the integrated images reconstructed by a usual lens array and a Fresnel lens array. Though there are some blur noises in using the Fresnel lens array, it can be confirmed that the image distortion at the boundaries of each elemental lens is decreased by a large factor.

With the use of the Fresnel lens array, we constructed a 14-inch 3D display system that can play moving images. The Fresnel array was composed of 26 × 24 elemental Fresnel lenses of 10 mm size each and 22 mm focal length. Fig. 9(a) shows an elemental image array constructed by computer graphics and Fig. 9(b) shows the reconstructed image. This integrated image is located at 10 cm distance from

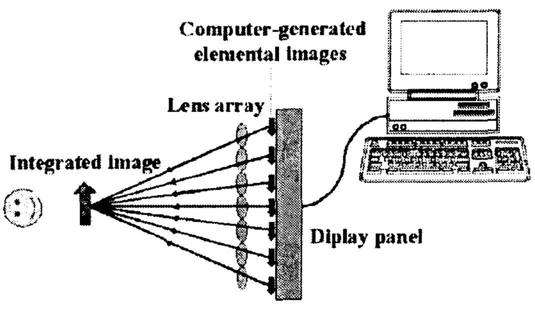
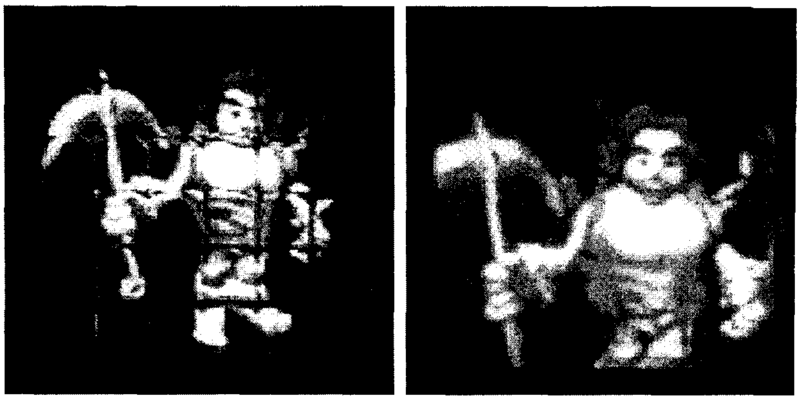


FIG. 7. Computer-generated integral imaging.



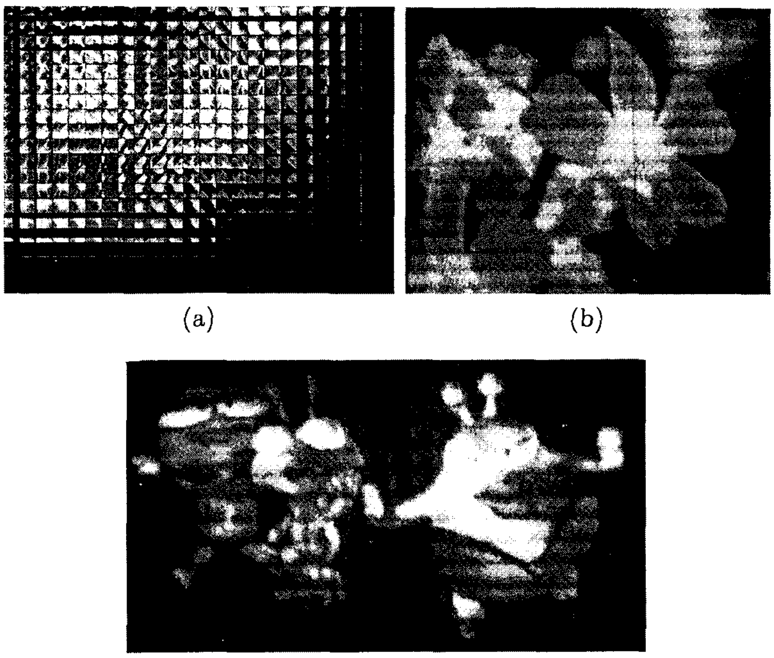
(a) (b)

FIG. 8. (a)Integrated image by usual lens array. (b)Fresnel lens array.

the lens array. We can acquire multi-plane images by composition of different depth plane images as in Fig. 9(c). In Fig. 9(c), the image of each character is placed at 8 cm, 10 cm, and 12 cm in front of lens array. The viewing angle of the system is about 20 degrees. The size of the system can be further enlarged by using a larger lens array and a larger display panel.

B. Variable image plane integral imaging

In the IP method, the integrated image can be reconstructed in two ways - the real IP and virtual IP. In the real IP, the integrated image is reconstructed as a real image in front of the lens array. In contrast, the integrated image is reconstructed as a virtual image behind of the lens array in the virtual IP. Of course we must use different elemental images in the real and the virtual IP. And the distances between the lens array and display panel should be different, too. That is, in the real IP, the distance between the lens array and the display panel should be longer than the focal length of the lens array, while it should be shorter than the focal length in the virtual IP. We have the following lens equation.



(a) (b)

(c)

FIG. 9. 14-inch CGII display using Fresnel lens array. (a)Elemental image array. (b)Integrated image. (c)Multi-plane integrated image.

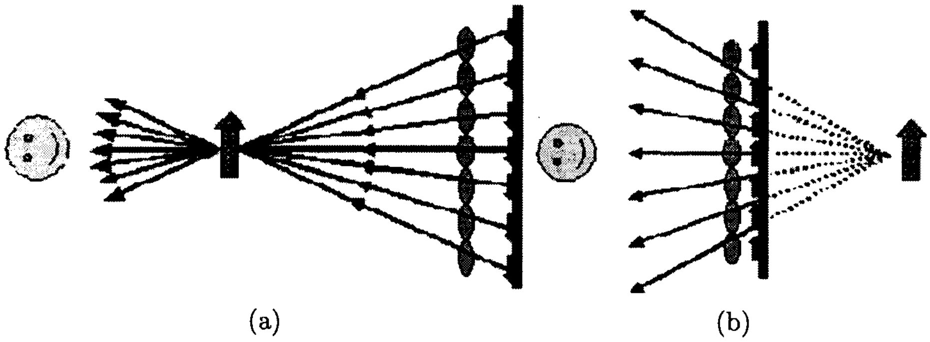


FIG. 10. (a)Real IP. (b)Virtual IP.

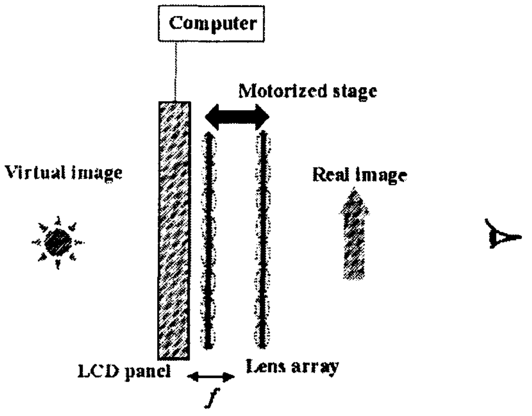
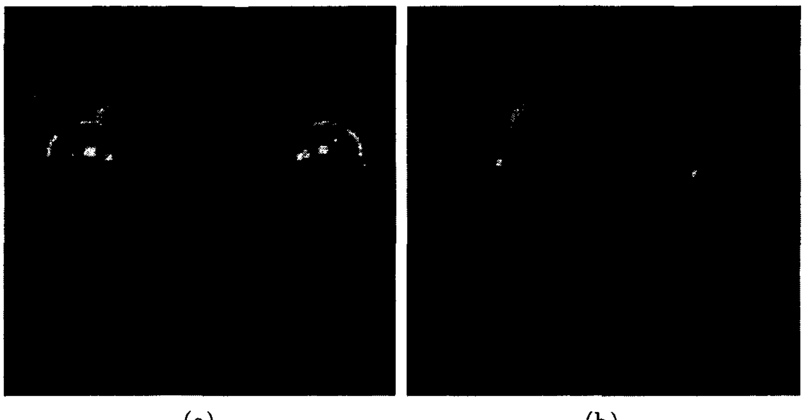


FIG. 11. Variable-image-plane integral imaging.

$$\frac{1}{d}+\frac{1}{g}=\frac{1}{f} \tag{5}$$

where g is the distance between the lens array and the display panel, d is the distance between the integrated image and the lens array, and f is the focal length of the elemental lenses which compose the lens array. As we can see from the equation, the value of d is positive for the real IP ($g > f$) and negative for the virtual IP ($g < f$) (see Fig. 10). As d determines the value of g (the location of the image plane), the resolution of the integrated image is limited by focusing error from the image plane [19]. The focusing error comes from the depth of a 3D image. When reconstructing 3D moving images with different depth, the fixed g method is not compatible. Hence we need a system that can control the distance g by the depth d. Especially, if we can vary the distance g near the focal length f, we can express real IP and virtual IP images together [18]. In Fig. 11, the concept of the variable-image-plane CGII is described.

We can see the integrated images in Fig. 12. The images are pictures of a car integrated at distances of $\pm$ 70 mm from the lens array. We can find that the integrated image size of real IP is larger than virtual IP. This is because the real image is closer to the observer than the virtual image. As a result, the observer feels that the integrated image is moving forward or backward and can feel increased depth because the depth difference between real and virtual images is 140 mm. In this experiment, we used only two integrated images. But it is also possible to display many images which have various depths. And if we want to display



(a) (b)

FIG. 12. Integrated image in (a) real IP and (b) virtual IP.

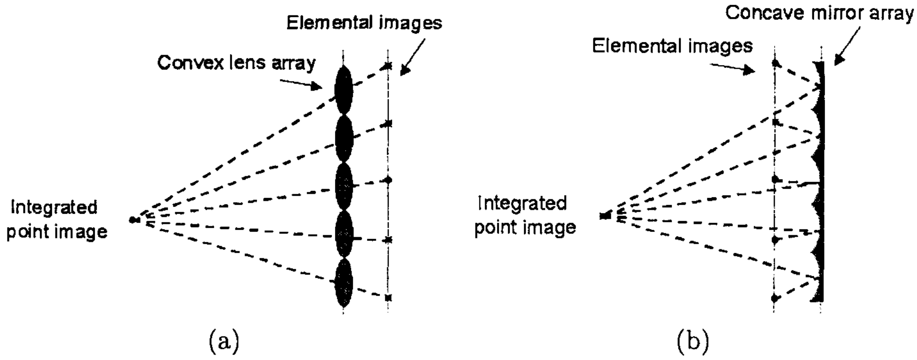


FIG. 13. Integral imaging of (a)transmission-type (b)reflection-type.

moving images of various depths we can display them by reconstructing each snap image in front of or behind the lens array using IP or virtual IP. As a result, variable-image-plane integral imaging can greatly increase the depth of the IP.

C. The reflection-type integral imaging

All proposed IP methods until now are of a transmission-type, which means that elemental images from a display panel transmit through the lens array and reconstruct a 3D integrated image. Therefore if we want to construct a large-size display system, we must prepare a large-size display element.

We recently proposed 3D display by using reflection-type integral imaging [17]. In this type of IP, the convex lens array is replaced with a concave mirror array and the 3D image is reflected and integrated from the mirror array. Basically the concave mirror only reverses the direction of the optical beam and it plays the same role as the convex lens. In Fig. 13, the reflection-type IP is compared with the transmission-type IP. The displaying element can be either a panel-type or a projection-type. However there is a problem in the projection-type in which the light rays from the projection-type displaying element are not in parallel but diverge. Because of this problem it is difficult to observe integrated images directly.

In the experiment, we used a concave mirror array which was composed of 7 × 7 square elemental mirrors with size of 2 cm each and focal length of 10 cm. We used an LCD panel as a displaying element and the mirror array was located at 10 cm from the LCD panel. And the image of two spheres with different depths is used for the elemental image array and it is shown in Fig. 14(b). Generally, the LCD panel covers the integrated image in the system described in Fig. 13(b) and it is impossible to observe the integrated image. Hence we inserted a beam splitter between the mirror array and the LCD panel for easy observation. Of course, tilting the mirror array can solve this problem but it needs more complex elemental images.

In Fig. 15, two captured images of the same 3D image integrated from the elemental image of Fig. 14(b) are shown. The two spheres have depth difference of 12 cm. We can see from Fig. 15 that the integrated image is an autostereoscopic image which has both horizontal and vertical parallaxes.

In this experiment we showed the possibility of the reflection-type integral imaging but we could not make sufficient use of its advantages. We expect that the

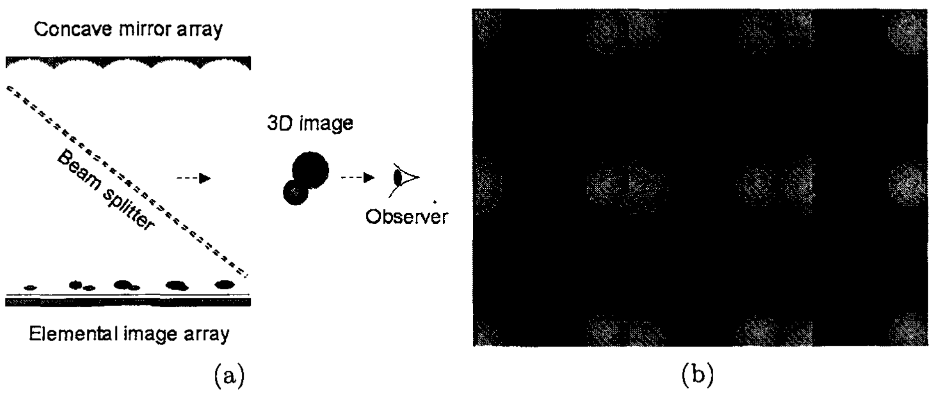
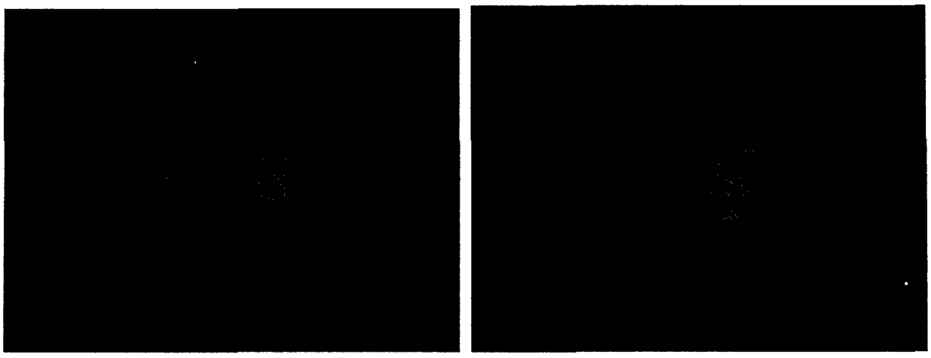


FIG. 14. (a)Reflection-type integral imaging experiment system. (b)Elemental image array.



(a) (b)

FIG. 15. (a)Left-downward view. (b)Right-upward view.

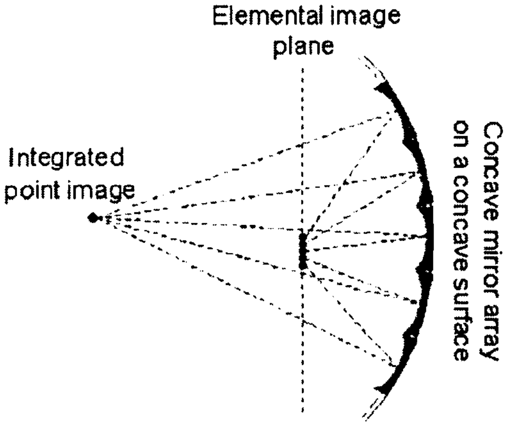


FIG. 16. Reflection-type integral imaging for large display system.

system described in Fig. 16 can maximize the merit of the reflection-type integral imaging - the large display system. Here, we can use a projection-type display element instead of a panel display element and we place the concave mirror array on a curved surface. This curved surface can accumulate the light from the entire mirror array and the observer may see the integrated image directly. Therefore this system has advantages with which to construct a large size display system with low cost using a small elemental image displaying element - for example, a beam projector. Of course we can acquire parallel light by locating a convex lens with large aperture. But this method has limitation in application to a large display system because it needs a convex lens with a large aperture of mirror array size.

D. Viewing-angle-enhanced integral imaging

The viewing angle is one of the most important properties in 3D display using integral imaging. But there is a limitation in viewing angle, originating from not only the limitation of elemental image displaying area but also interference between elemental images. The image flipping plays a critical role in limiting the viewing angle. We proposed a new structure that implements a mask to switch the elemental lens, and we proved experimentally that the new structure can enhance the viewing angle [15].

Image overlapping or image flipping occurs when each elemental image is integrated through the neighboring(wrong) elemental lens. Therefore, the system needs a lens-switching device to prevent this problem. An LCD shutter which can control the switching of the lens array electrically may be the ideal device. But in our experiment, we used a mask that has a vertical aperture array whose aperture pitch and spacing are the same as the elemental lens pitch. Moving this mask along the horizontal direction as in Fig. 17(a), we could obtain two snapshots of the integrated images as shown in Fig 18(a). If the moving velocity of the mask is fast enough to cause the afterimage effect, the two snapshot images will be combined and the viewing angle will be almost doubled. Extending this method, we used one-column opened mask and moved it along the horizontal axis to obtain the snapshot of

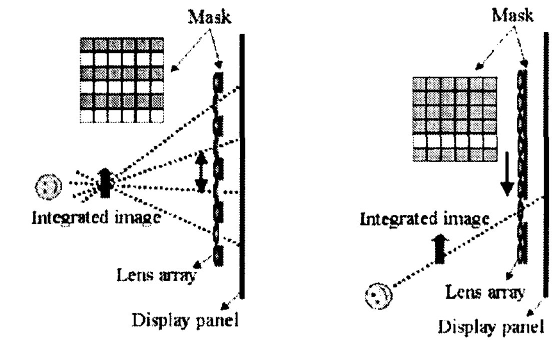


FIG. 17. Viewing-angle-enhanced integral imaging. (a)With a mask of alternately on/off patterned array. (b)With a mask of one on-patterned array.

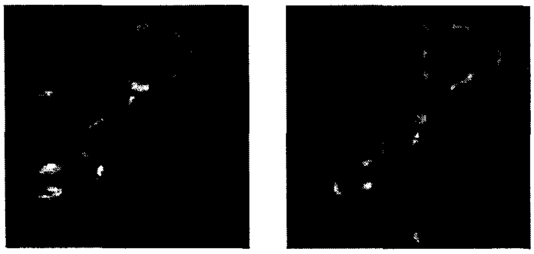
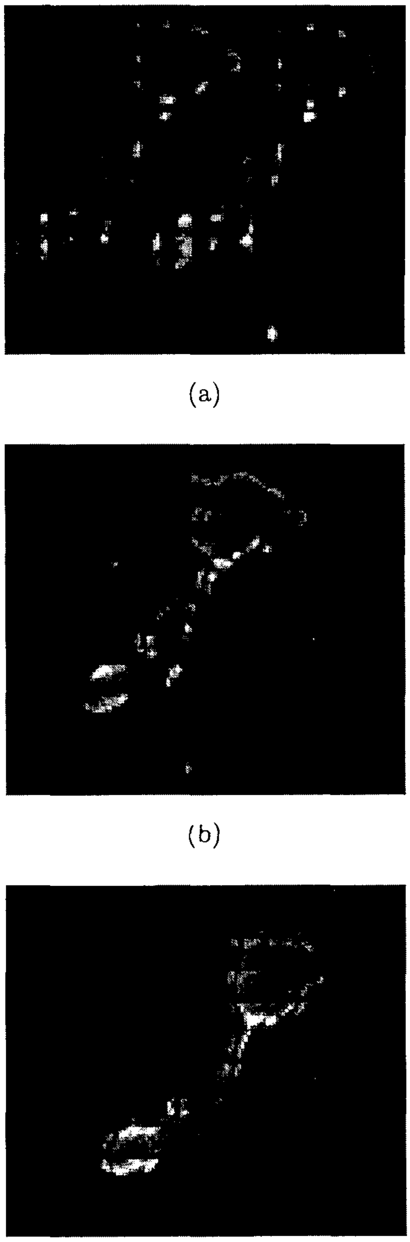


FIG. 18. Snapshot of the integrated image of two states.

the integrated images as in Fig. 17(b). By this method we could obtain integrated images with viewing angle widened by more than two times.

These two methods are similar in that each part of the integrated image is time-multiplexed. However the algorithms for generating the elemental images are different in two methods. In the method depicted in Fig. 17(a), the elemental image region corresponding to each elemental lens is extended to the half of the neighboring elemental image region along the horizontal direction. On the other hand, there is no horizontal limitation of the elemental lens region in the method shown in Fig. 17(b).

The enhancement of viewing angle is described in Fig. 19. With the conventional method, the observer had to experience the image overlapping at viewing angle of 10.6 degrees as seen in Fig 19(a). But we could improve the viewing angle by using the method we proposed. When we used the method described in Fig 17(a), there was no image overlapping at the same viewing angle and it appeared at the angle of 15.8 degrees. By using the method depicted in Fig 17(b), the image overlapping was not observed even at 15.8 degrees. As we proved by this experiment, the elemental lens switching could provide a wider horizontal viewing angle in a 3D display system using the integral imaging.



(a) (b) (c)

FIG. 19. (a)observed at 10.6 degrees(by the conventional method). (b)observed at 10.6 degrees(using the method in Fig. 17(a)). (c)observed at 15.8 degrees(using the method in Fig. 17(b)).

IV. CONCLUSION

In this paper, we discussed recent advances in 3D display using integral imaging. The integral imaging was proposed by Lippmann in 1908. But it had many problems. For example the lens array was too difficult to manufacture at that time. Also the depth of integrated image was inverted(pseudoscopic). And the film which was used for recording was not suitable for displaying moving images. But these problems have been overcome by using various modern techniques. Especially the use of an aspheric Fresnel lens and the lens switching method provide enhanced viewing angles. And the depth of image which the observer can feel is increased by using the variable-image-plane method. Continuing research will provide commercial dynamic 3D integral imaging systems in the near future.

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