Depth-enhanced three-dimensional integral imaging systems with compact thickness

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Abstract

We propose novel schemes to enhance the expressible depth range of integral imaging. The implemented system that adopts the mirror barrier array has the compact thickness that is suitable for the practical use. With this system, the expressible depth range of the integral imaging is increased to over 120mm.The system that eliminates the mechanical motion also had been implemented. Experimental results are presented and the way to resolve the problem of occlusion is also discussed.

1. Introduction

Integral imaging (II) is one powerful candidate for the practical three-dimensional (3D) display system proposed by Lippmann in 1908[1]. It has the property of displaying full-parallax, full-color and real-time 3D images within a certain viewing angle without any supplementary devices. It also has an advantage in that its simple concept compared with other 3D display techniques brings about short computation time to calculate data for 3D images.

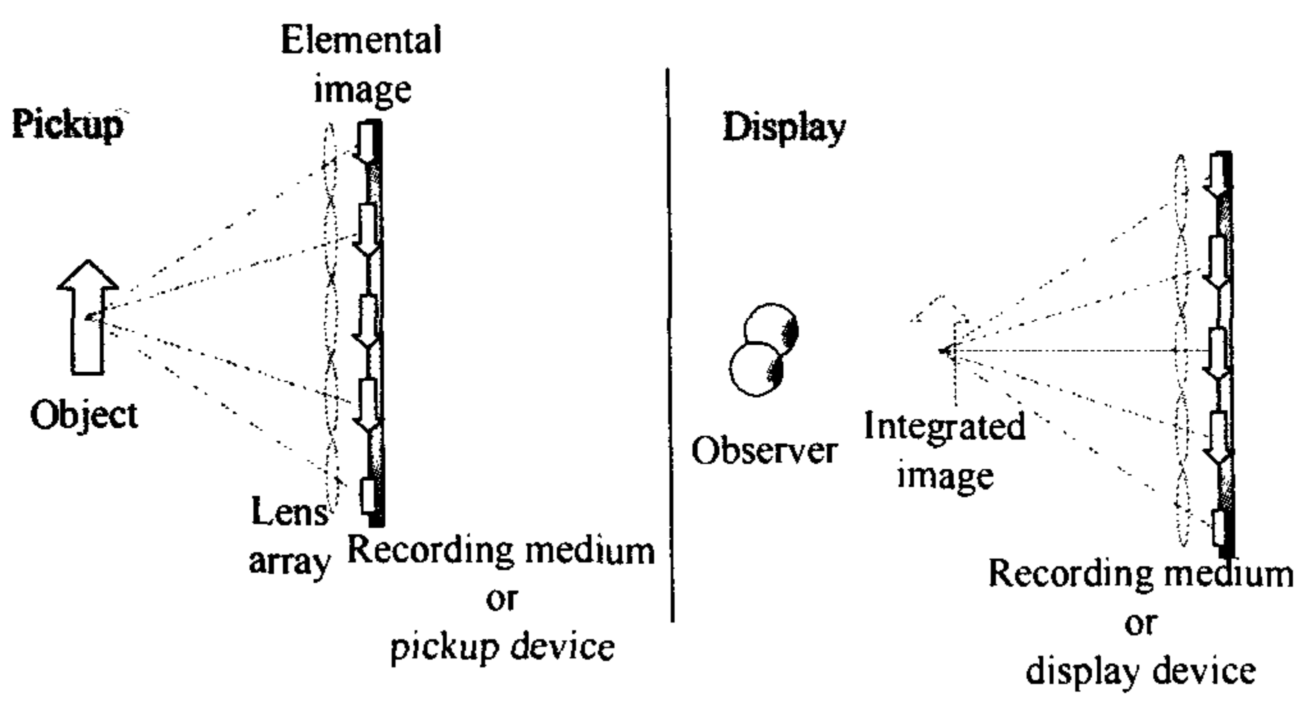


Figure 1. Basic concept of II. Pickup and display processes.

II has two steps to display 3D images as shown in Fig. 1. In the pickup process, each elemental lens of the lens array samples two-dimensional (2D) scenes of 3D object from various directions. A set of these 2D images is called elemental image and it is picked up by a pickup device such as a charge-coupled device (CCD). In the display process, this elemental image is displayed by a display device such as a liquid crystal display (LCD) and the rays emitted from the elemental image retrace original routes to form 3D images that resemble the original 3D object in the pickup process. However, the problem that the image depth of II is severely limited makes it difficult to apply II for the practical use[2]. Because of the fixed focal length of each elemental lens, the quality of the reconstructed image is best at the central depth plane whose location is determined by the simple lens law, and it degrades as the image goes farther from the central depth plane. Therefore, the thickness of the reconstructed image is confined around the central depth plane to avoid the severe degradation of the image quality. Previously, many successful research results proposed the schemes to overcome such limitation[3-7]. Most of them are based on the concept of the multi-central depth plane II. It is to generate two or more central depth planes by adopting additional physical systems. Then the expressible depth range of each central depth plane is cascaded and the entire expressible depth range is effectively increased. However, all of them do not satisfy the conditions for the practical use. They are too bulky or demand impractically high-speed performance. One scheme that does not utilize the multiple central depth planes has the problem that the resolution of the reconstructed image is severely degraded[8].

In this paper, the novel schemes that enhance the expressible depth range with systems of compact thickness are proposed. They are based on the concept of optical path control to realize multi-central depth plane II. They also do not demand impractically high-speed performance. The system configurations and experimental results are provided in the following.

2. System Configuration

2.1. Mirror barrier array

The location of the central depth plane is mainly determined by the gap between the display panel and the lens array. Therefore the multi-central depth plane II can be implemented with the possibility of controlling gap. The basic idea is to utilize reflections to change the optical path between the display panel and the lens array.

One way to achieve it is to insert mirrors between the lens array and the display panel as shown in Fig. 2(a). The set of mirrors is named as the mirror barrier array. For more detailed description, the top view of the system is shown in Fig. 2(b) and (c). In the first state, each elemental mirror of the mirror barrier array is laid to be perpendicular to the lens array as shown in Fig. 2(b). Then the observer in a certain viewing angle can observe the integrated images that are not affected by the mirror barrier array. In other words, the elemental image is directly integrated through the lens array to form the integrated image around the central depth plane 1. The optical paths for this case are indicated as arrows in Fig. 2(b). Each elemental mirror can change its pose to express another central depth plane. In the second state, each elemental mirror makes an angle of 45 degrees with the lens array as shown in Fig. 2(c). Then each column of the elemental image is reflected between neighboring mirrors before passing through the lens array.

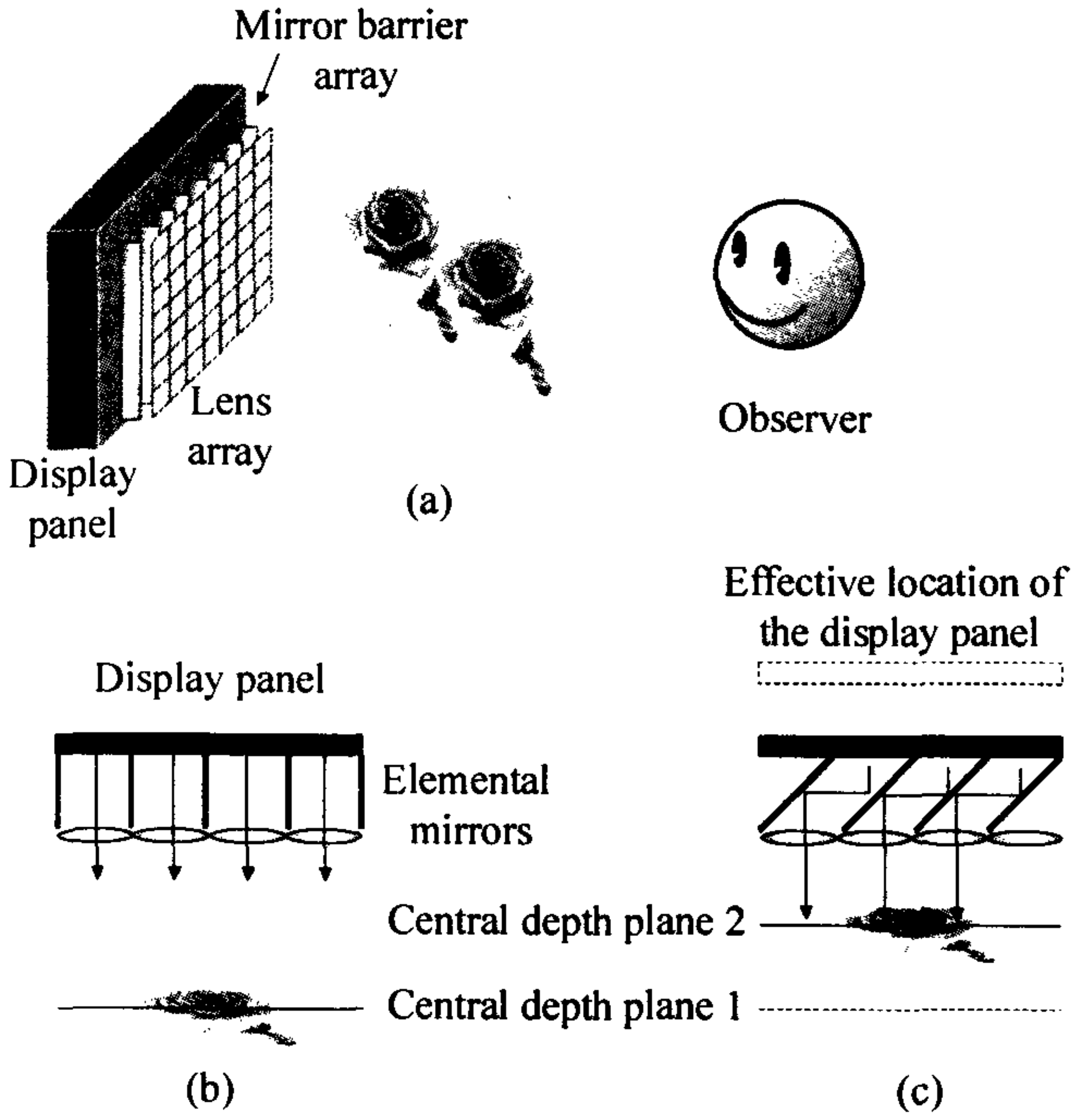


Figure 2. System configuration of the mirror barrier array scheme. (a) Entire system. (b) State 1 and (c) state 2.

The optical paths for this case are indicated as arrows in Fig. 2(c). The optical path length is increased by the distance between neighboring elemental mirrors as indicated in the figure. Therefore the integrated image is formed around the central depth plane 2 that is nearer to the lens array than the central depth plane 1. In Fig. 2, the distance between neighboring mirrors is set to the pitch of each elemental lens of the lens array. Of course, this distance can be determined appropriately to adjust the locations of two central depth planes.

With the rapid change between these two states, two different central depth planes, the central depth plane 1 and 2, can be expressed simultaneously. The main advantage of this scheme is that the thickness of the entire system is maintained because the mirror barrier array is inserted between the lens array and the display panel. This property is especially beneficial for wide screen system because the size of the proposed system increases two-dimensionally as the size of the screen increases. However, this scheme has a drawback that it demands fast mechanical motion.

2.2. Mechanical-motion-eliminated system

To eliminate the mechanical motion of the mirror barrier array scheme, we propose another scheme that utilizes the reflection to control the optical paths but the mirrors are replaced with the combination of polarizers and beam splitters.

Figure 3 shows the system configuration of the proposed scheme. In Fig. 3(a), some symbols are defined. The combination of a beam splitter and two p-polarizers is named as p-set while the combination of a beam splitter and two s-polarizers is named as s-set in Fig. 3(a). The proposed scheme inserts these p-sets and s-sets alternatively between the lens array and the display panel of the conventional II as shown in Fig. 3(b) and (c). Then, each column of the elemental image is separated by the beam splitter to

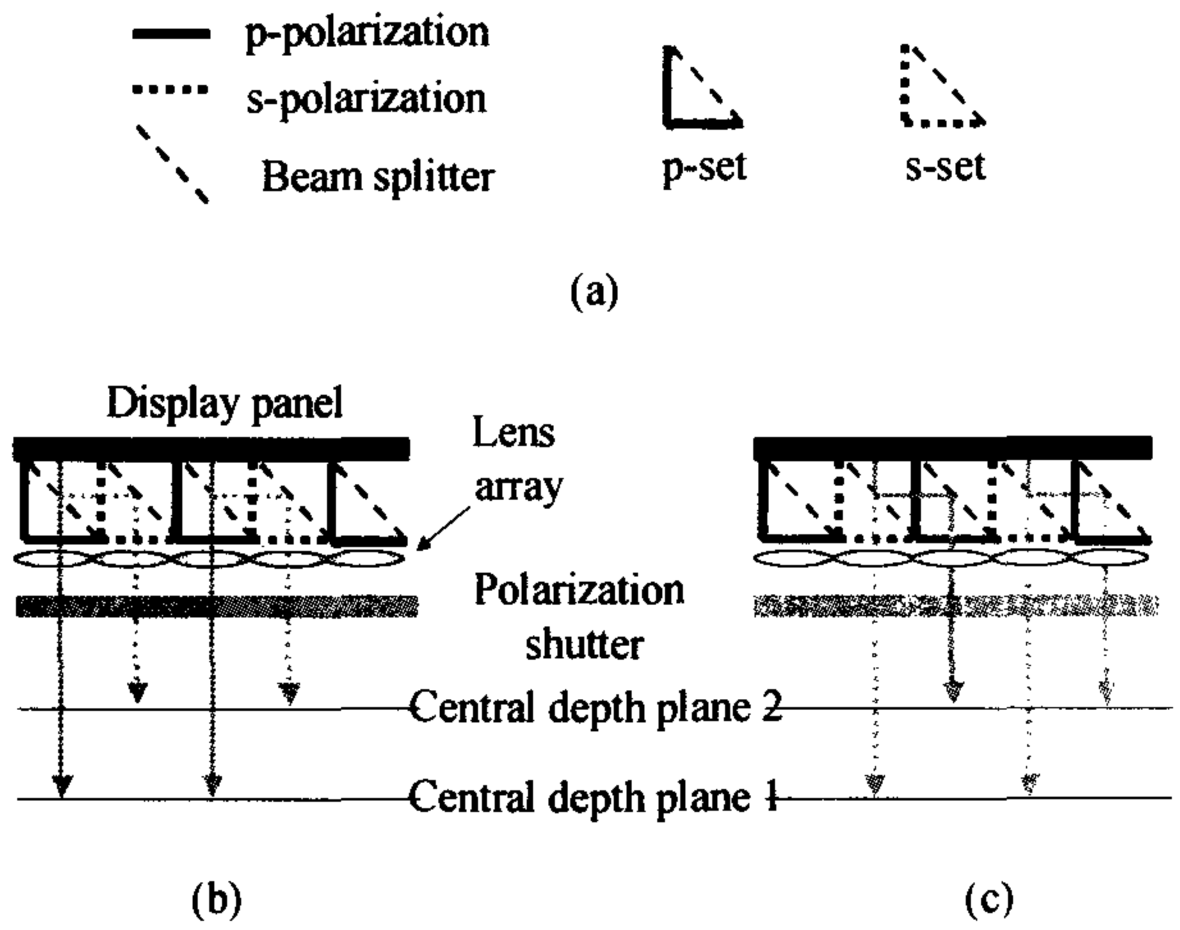


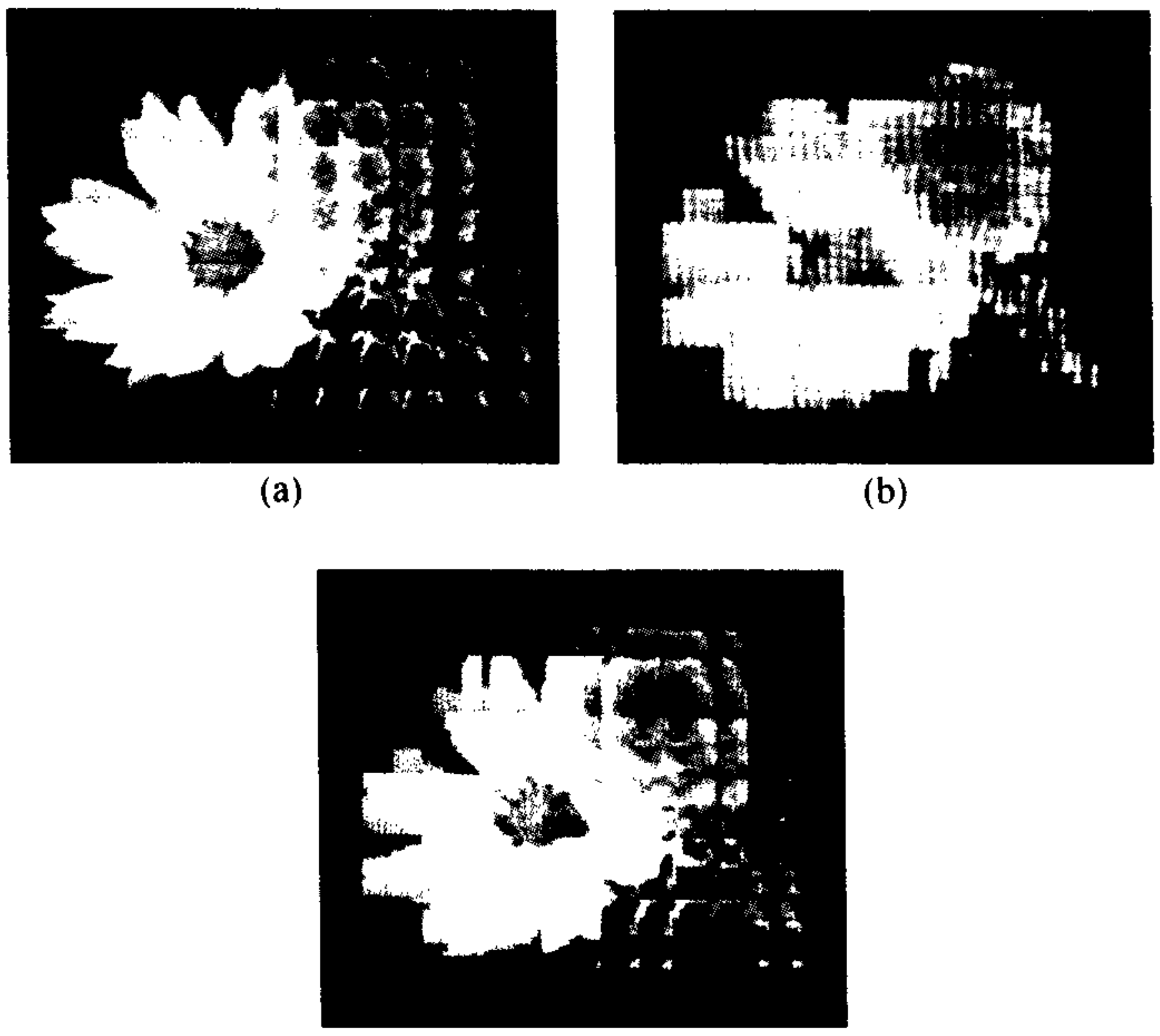
Figure 3. Mechanical motion eliminated system. (a) Definition of symbols. (b) Optical paths for odd columns of the elemental image and (c) even columns of the elemental image.

have two optical paths. One is to directly pass through the lens array and the other is to be reflected between neighboring beam splitters before passing through the lens array. These two paths form two different central depth planes. Polarizers around beam splitters impose different polarization states to these optical paths. In Fig. 3(b), the optical paths and their polarization states for the odd columns of the elemental image is indicated by the solid and dashed arrows. The solid arrow indicates p-polarized optical path and the dashed arrow indicates s-polarized optical path. Figure 3(c) describes the situation for the even columns of the elemental image. By the polarization shutter located in front of the lens array, we can select only one polarization state to transmit. Therefore each column of the elemental image is integrated around different central depth planes according to the polarization states of the polarization shutter. By changing the states of the polarization shutter over the rate of 120Hz, we can express two central depth planes simultaneously without any mechanical motion.

Though the proposed system is completely electronically controllable, the loss of luminosity is severe because there are many beam splitters and polarizers along the optical paths. However, this scheme is also capable of enhancing the expressible depth range of II by a system with compact thickness.

3. Experimental results

We performed the experiment to display the integrated image around two different central depth planes with the system based on the mirror barrier array. The lens array used in the experiment is composed of 13×13 elemental lenses. The pitch φ of each elemental lens of the lens array is 10mm and the focal length is 22mm. The mirror barrier array used in the experiment is composed of 13 elemental mirrors whose states are changed manually, and the distance between neighboring elemental mirrors is set to φ. Therefore the optical path difference obtained by the mirror barrier array is φ or 10mm. Considering the second state of the mirror barrier array, the horizontal dimension of the elemental mirror should be $\sqrt{2}\varphi$ as the elemental mirrors are inclined with the angle of 45 degrees in that state. However the value was determined as 14mm because the exact value is a irrational number. The slight error less than 1mm did not largely affect the experimental results. The gap g for the experiment was determined to be 25mm, so the central depth plane 1 is located about 183mm distant from the lens array in this case. When the mirror barrier array is in its second state, the effective gap between the lens array and the display panel becomes $g+\varphi$ or 35mm, and the central depth plane 2 is located about 59mm distant from the lens array.

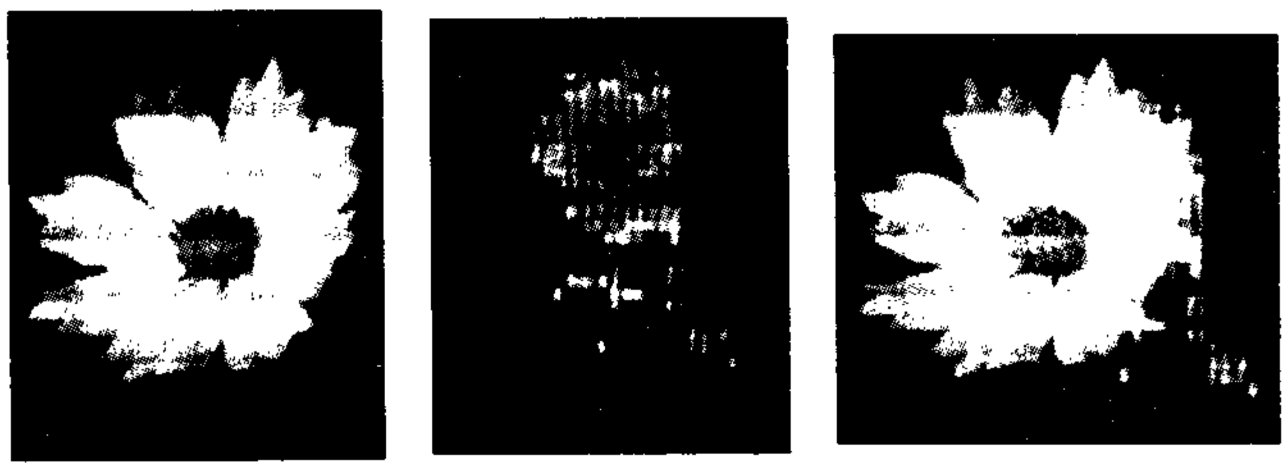


(a) (b) (c)

Figure 4. Integrated image obtained by the conventional scheme. Flower in the left is located 59mm distant from the lens array, while the right flower is 183mm distant from the lens array. The central depth plane is set to (a) 59mm, (b) 183mm, and (c) 121mm.

For the comparison, we performed the preliminary experiment with the conventional II system. All the specifications of the conventional system are the same as the proposed system except that the mirror barrier array was not inserted. Figure 4 shows the experimental results for the various locations of the central depth plane. The location of the left white flower is 59mm distant from the lens array, and the location of the right red flower is 183mm distant from the lens array. In Fig. 4(a), the central depth plane is set to the location of the left flower, and the right flower is distorted severely. On the contrast, the central depth plane is set to the location of the right flower, and the left flower is distorted in Fig. 4(b). It may be the best choice for the conventional scheme to locate the central depth plane at the middle of the integrated images. In Fig. 4(c), the central depth plane is located at the middle of two flowers, 121mm distant from the lens array. Both of two flowers are distorted, but the distortion is reduced compared with the experimental results in Fig. 4(a) and (b). However, it is obvious that these two flowers are over the expressible depth range of the conventional II system.

Figure 5 shows the experimental results obtained by the proposed system. Figure 5(a) is the white flower located 59mm distant from the lens array with the second state of the mirror barrier array. In Fig. 5(b), the red flower is located 183mm distant from the lens array with the first state of the mirror barrier array.

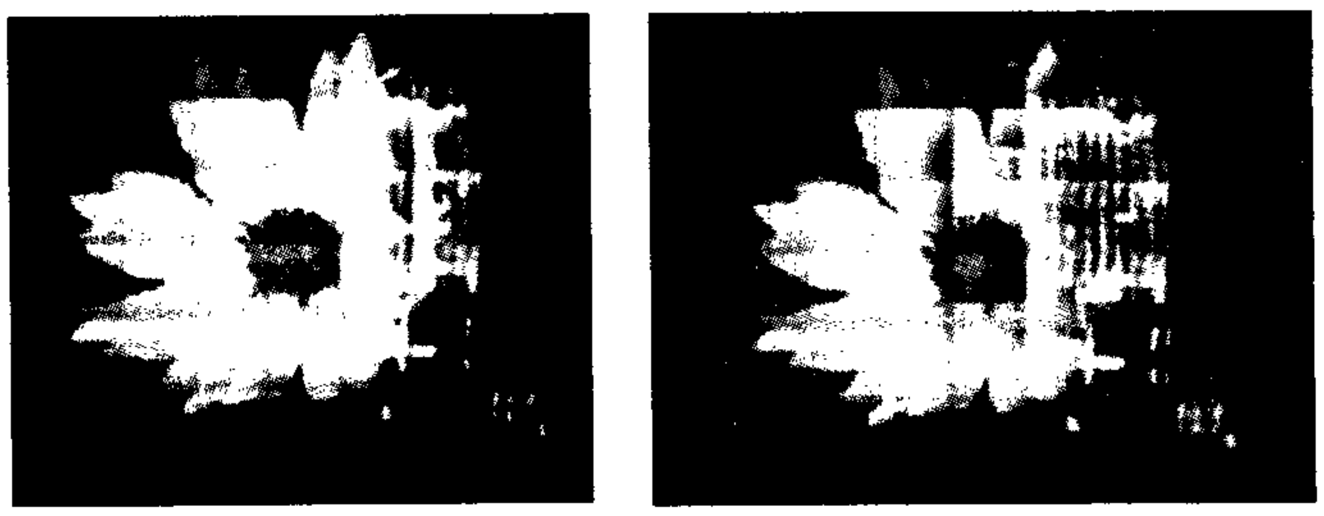


(a) (b) (c)

Figure 5. Integrated image reconstructed by the mirror barrier array. (a) State 2 and (b) state 1. (c) Digitally overlapped image.

Therefore, two images located out of the expressible depth range in the conventional scheme are expressed well with the fixed gap in the proposed scheme. If the mirror barrier array changes its states rapidly, those two images can be displayed simultaneously just like the digitally overlapped image in Fig. 5(c).

Though the expressible depth range is enhanced with the mirror barrier array, there exists a problem of occlusion that occurs by adopting the concept of multi-central depth plane II. Because two central depth planes in the proposed scheme express different expressible depth ranges independently, the integrated image around the central depth plane 1 is transparent for the integrated image around the central depth plane 2. In Fig. 5(c), the part of white flower is shown through the red flower in the overlaps of them. To avoid this, we should produce the elemental image for the central depth plane 2 considering the occlusion that would occur by the central depth plane 1. Figure 6(a) shows the experimental results that consider occlusion. However the integrated image around the central depth plane 1 is distorted when it is expressed by the central depth plane 2. Therefore the occlusion is also distorted, and the mismatch occurs in the overlap as shown in Fig. 6(a). To reduce this mismatch, some correction should be done to the elemental images. The basic idea can be understood roughly as giving intended blur effect around the occlusion. In Fig. 6(b), the experimental result obtained by giving correction is shown. As shown in Fig. 6(b), the occlusion is expressed better than the results shown in Fig. 5(c) and 6(a).



(a) (b)

Figure 6. Problem of occlusion. (a) Distorted occlusion. (b) Elemental-image-corrected scheme.

We also performed the experiment for the mechanical-motion-eliminated system that was introduced in Sec. 2.2. The lens array used in the experiment is the same as that used for the mirror barrier array system. The beam splitters have the dimension of 14mm in the horizontal direction and 130mm in the vertical direction with the thickness of 1.1mm. The linear polarizing laminated film that has the dimension of 10×130×0.74mm was used for the polarizers. For the display device, the flat panel cathode-ray tube (CRT) display that is capable of switching two images at the rate of 120Hz was used. The polarization shutter used in the experiment is a modified product of NuVision 21SX for linear polarization that has the switching speed of 120Hz. The gap is set to 28mm to generate the central depth plane 1 at the location 102.7mm distant from the lens array. With the increased optical path length of 10mm between the lens array and the display panel, the effective gap becomes 38mm to form the central depth plane 2 at the location 52.3mm distant from the lens array. In Fig. 7, the experimental result that has been obtained by the implemented mechanical-motion-eliminated system is shown. The left white flower is 52.3mm distant from the lens array, and the right red flower is 102.7mm distant from the lens array. Though they are located over the expressible depth range of the conventional II, they are expressed well with the implemented system. However the loss of luminosity is severe in this case compared with the mirror barrier array scheme.

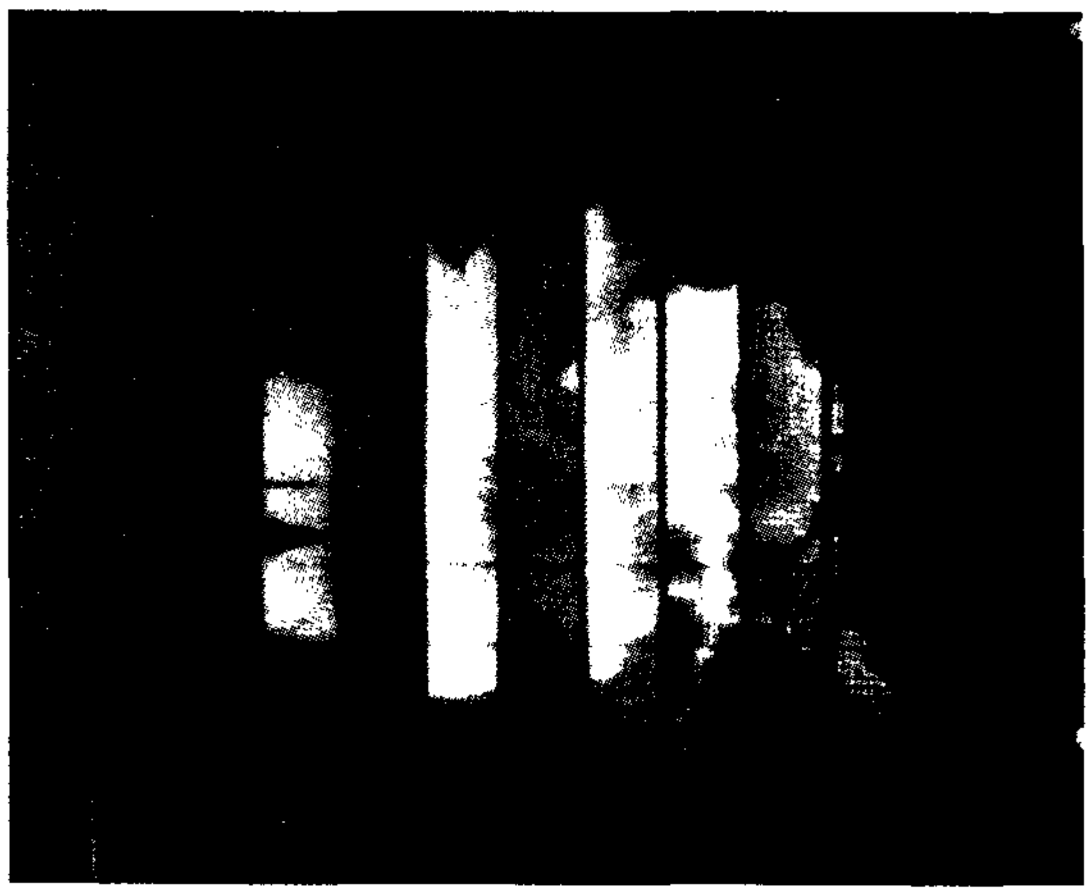


Figure 7. Experimental result obtained by the mechanical-motion-eliminated system.

4. Conclusion

We proposed the novel schemes to enhance the expressible depth range of II based on the optical path control. The main advantage of the proposed scheme is that the implemented system has the compact thickness. We realized the system based on the mirror barrier array and presented the experimental results. The system that eliminates the mechanical motion was also proposed and implemented. We also discussed the problem of occlusion, and proposed the scheme to overcome the problem. We believe that the proposed scheme will make it easy to apply II for the practical use.

5. Acknowledgments

This work was supported by the Next-Generation Information Display R&D Center, one of the 21st Century Frontier R&D Programs funded by the Ministry of Science and Technology of Korea.

6. References

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