

Depth-enhanced integral imaging by use of optical path control

Jisoo Hong, Jae-Hyeung Park, Sungyong Jung, and Byoung-ho Lee

National Research Laboratory of Holography Technologies, School of Electrical Engineering, Seoul National University, Kwanak-Gu Shinlim-Dong, Seoul 151-744, South Korea

Received March 23, 2004

The image depth of integral imaging is enhanced by doubling the number of central depth planes by use of optical path control. To accomplish this, the optical path lengths are changed by controlling whether reflections occur behind the lens array. We propose three schemes that use mirrors, a combination of beam splitters and polarizers, and polarization beam splitters, respectively. In experiments we implement the systems that are completely electronically controllable, are compact, and provide two central depth planes with 50.4-mm separation. © 2004 Optical Society of America

OCIS codes: 110.2990, 100.6890, 220.2740.

Integral imaging (II), which was first proposed by Lippmann¹ in 1908, has been considered as one possibility for realizing a practical three-dimensional (3D) display system. Without any supplementary instrument it provides observers with real-time 3D images that have various advantageous features, such as full-parallax and full-color properties. It led many researchers to devote themselves to the study and development of such a system.²⁻⁴ However, there still exist several limitations, including image depth, which is a major bottleneck. Because the key component of an II 3D display system is a lens array composed of many elemental lenses, the image reconstructed by the system has the best quality at one plane parallel to the lens array, and the location of such a plane, which is referred to as the central depth plane, is determined by the well-known lens law.⁵ Because the quality of image degrades with distance from the central depth plane, the thickness of the image is limited. Although many successful research results reported improvement on this limitation,⁶⁻⁹ application to a practical 3D display system is still problematic. For practical use a compact system that does not require high-speed devices and maintains a certain level of resolution of the reconstructed image is needed.

In this Letter we propose novel methods based on the concept of path-length control that are capable of enhancing the thickness of a 3D image by giving the systems double central depth planes. One way to achieve this is to utilize the reflections between mirrors. This can be implemented by a system composed of many elemental mirrors, which is referred to as a mirror barrier array. The principle of the proposed method based on a mirror barrier array is shown in Fig. 1. The mirror barrier array is inserted between the lens array and the display panel, and each elemental mirror is placed so that it separates each column of elemental lenses. Two states of the mirror barrier array scheme are described in Figs. 1(a) and 1(b). In Fig. 1(a) the elemental mirrors are perpendicular to the lens array, so the 3D image is integrated in the same way as in the conventional scheme for the observer within the viewing angle. In other words, the distance between the lens array and central depth plane 1, d_1 , is determined by only gap g between the lens array and

the display panel. On the other hand, in Fig. 1(b) elemental mirrors (reflective on both sides) are placed at an angle of 45° to the lens array. In this state the elemental images are reflected between adjacent mirrors, and they traverse an increased optical path length $g + \varphi$ before reaching the lens array. Therefore the distance between central depth plane 2 and the lens array, d_2 , is smaller than d_1 , as shown in Fig. 1(b). By switching rapidly between these two states we can obtain two different central depth planes simultaneously, and the thickness of the 3D image can be enhanced. Note that the mirror barrier array is inserted between the lens array and the display panel, so it does not affect the size of the system.

However, the mirror barrier array scheme has the drawback that it requires high-speed mechanical motion. This led us to propose another way to enhance the thickness of a 3D image based on the principle of the mirror barrier array but in which operations are completely electronically controllable. Figure 2 shows the system configuration and the principles of the

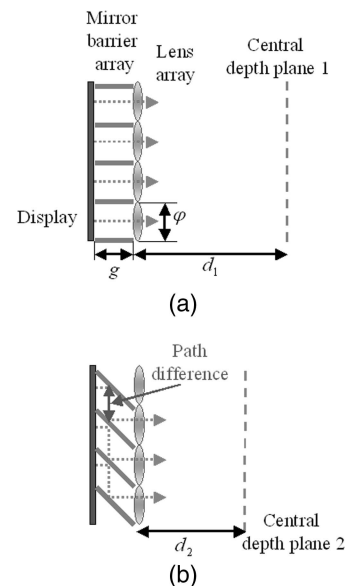


Fig. 1. Concept of the mirror barrier array: (a) perpendicular-mirror state and (b) tilted-mirror state.

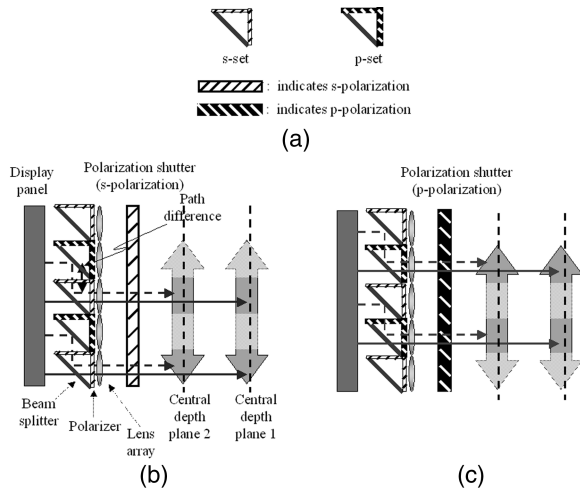


Fig. 2. System configurations with mechanical motion eliminated: (a) *s*-set and *p*-set, (b) state 1, (c) state 2.

proposed method. Elemental mirrors are replaced by a combination of beam splitters, polarizers, and a polarization shutter to eliminate mechanical motion. Two *s* polarizers and one beam splitter form a set called an *s*-set, and two *p* polarizers and one beam splitter form a set called a *p*-set, as shown in Fig. 2(a). These *s*-sets and *p*-sets are arranged alternately between the lens array and the display panel, and each set covers one column of the lens array. Figures 2(b) and 2(c) show two states of this scheme. In Fig. 2(b), only the light that passes through each column of the lens array in front of an *s*-set can be transmitted through the *s*-polarized polarization shutter, and other light is blocked. Each column of the elemental image behind an *s*-set can be integrated around central depth plane 1 traveling along the direct path indicated by solid arrows in Fig. 2. However, to be integrated over the polarization shutter, each column of the elemental image behind a *p*-set must be reflected between adjacent beam splitters following the path indicated by dashed arrows, increasing the optical path length. Therefore the elemental images are integrated around central depth plane 2, which is closer to the lens array than central depth plane 1. In this state parts of the integrated image can be reconstructed. In Fig. 2(c) the other parts of the integrated image can be displayed through the *p*-polarized polarization shutter in a similar way. By switching between the two states in Figs. 2(b) and 2(c) at a rate of 120 Hz, we can obtain the integrated image located around central depth planes 1 and 2 simultaneously. Of course, the polarization shutter can be located in front of the display panel (instead of the location in Fig. 2) without affecting the performance of the system.

We constructed an II 3D display system based on the proposed scheme and also performed experiments using that system. The lens array is composed of 13×13 elemental lenses with a pitch φ of 10 mm and a focal length of 22 mm. The beam splitters are 14 mm in the horizontal direction, 130 mm in the vertical direction, and 1.1 mm thick. As the polarizers, we used a linear polarizing laminated film with dimensions of $10 \text{ mm} \times 130 \text{ mm} \times 0.74 \text{ mm}$. The elemental images were dis-

played on a flat-panel CRT display that switched the image at a rate of 120 Hz. The polarization shutter used in the experiment is a modified NuVision 21SX for linear polarization with a switching speed of 120 Hz. Gap g was set to 28 mm to form target central depth plane 1 at a distance of 102.7 mm from the lens array and corresponding central depth plane 2 at a distance of 52.3 mm from the lens array, which is determined by the effective gap $g + \varphi$ of 38 mm. All the elemental images used in the experiments were generated by computer graphics. For comparison the experimental results obtained by the conventional scheme are shown in Figs. 3(a) and 3(b). The star and the flower are located at 52.3 and 102.7 mm, respectively, from the lens array. The central depth plane is located at the star in Fig. 3(a) and the flower in Fig. 3(b). In these figures the integrated image located out of the central depth plane was severely distorted. In Figs. 3(c) and 3(d) the experimental results obtained by the proposed method (the polarization technique) are shown, and the locations of the star and the flower are the same as in Figs. 3(a) and 3(b). Parallax can be seen from the different integrated images obtained from different viewpoints, as shown in Fig. 3(c) for a right view (3.5°) and in Fig. 3(d) for a left view (3.5°) without any distortion of the images. The vertical gaps appear in Figs. 3(c) and 3(d) due to the insertion of polarizers between the lenses. The fill factor reduction is $\sim 7.4\%$. By use of thin polarizers, this reduction can be lessened.

In Fig. 4 some modifications that replace the beam splitters and polarizers with polarization beam splitters (PBSs) are shown. The PBSs are assumed to transmit *p* polarization and reflect *s* polarization. In the state shown in Fig. 4(a), in which the polarization

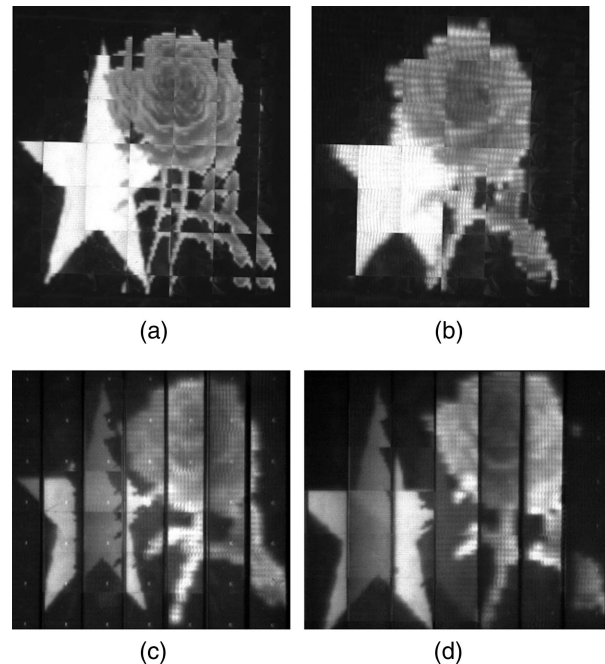


Fig. 3. Integrated images of a star and a flower at distances of 52.3 and 102.7 mm, respectively. Conventional scheme with the central depth plane at (a) 52.3 mm and (b) 102.7 mm. (c) Right view (3.5°) and (d) left view (3.5°) of the proposed scheme.

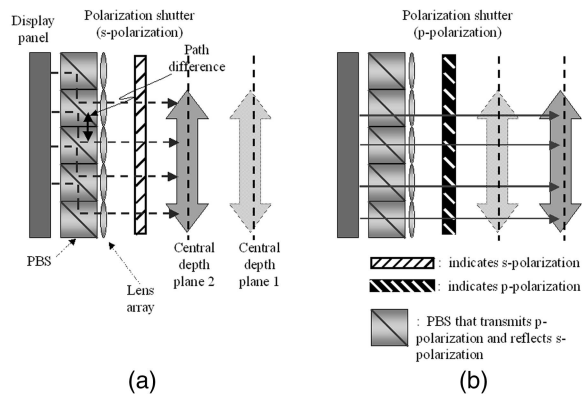


Fig. 4. Modified system configuration: (a) state 1 and (b) state 2.

shutter is *s* polarized, elemental images can be integrated over the polarization shutter, tracing the path that includes reflections between adjacent PBSs and indicated as dashed arrows. On the other hand, in Fig. 4(b) the elemental images that pass through the PBSs directly can be integrated over the *p*-polarized polarization shutter. Therefore a 3D image around central depth plane 2 is expressed in Fig. 4(a), and one around central depth plane 1 (that is farther from the lens array than central depth plane 2) is expressed in Fig. 4(b). By switching between these two states at a sufficient rate, this scheme can also produce two central depth planes. The elemental image in the state shown in Fig. 4(a) has no loss of luminosity in the second reflection at the PBS because of the property (ideally 100% of reflectance for the polarization state determined at the first reflection) of the PBS, and the luminosity of the integrated image can be improved.

In conclusion, we have proposed novel methods for enhancing the thickness of an integrated image by use of optical path control. One of them adopts a mirror barrier array and has the advantage that there

is no loss of luminosity. Although it has the compactness that is favorable for an II 3D display system with a large screen, it requires fast mechanical motion that can be an obstacle for practical use. Therefore we have proposed and experimentally verified a system that uses beam splitters, polarizers, and a polarization shutter to eliminate mechanical motion. This system is practical because of its compactness and electronically controllable feature. However, the luminosity of the image integrated by the proposed system is not so good. We have also proposed a modified scheme to enhance the luminosity. We expect that these new schemes can be applied as a depth-enhanced II system for practical use.

This work was supported by the Next-Generation Information Display Research and Development Center, one of the 21st Century Frontier Research and Development Programs funded by the Ministry of Science and Technology of Korea. B. Lee's e-mail address is byoungcho@snu.ac.kr.

References

1. G. Lippmann, *C. R. Acad. Sci.* **146**, 446 (1908).
2. T. Okoshi, *Appl. Opt.* **10**, 2284 (1971).
3. N. Davies, M. McCormick, and L. Yang, *Appl. Opt.* **27**, 4520 (1988).
4. F. Okano, H. Hoshino, J. Arai, and I. Yuyama, *Appl. Opt.* **36**, 1598 (1997).
5. J.-H. Park, S.-W. Min, S. Jung, and B. Lee, *Appl. Opt.* **40**, 5217 (2001).
6. B. Lee, S. Jung, S.-W. Min, and J.-H. Park, *Opt. Lett.* **26**, 1481 (2001).
7. B. Lee, S.-W. Min, and B. Javidi, *Appl. Opt.* **41**, 4856 (2002).
8. J.-H. Park, S. Jung, H. Choi, and B. Lee, *Opt. Express* **11**, 1862 (2003), <http://www.opticsexpress.org>.
9. J.-S. Jang, F. Jin, and B. Javidi, *Opt. Lett.* **28**, 1421 (2003).