Computational Integral Imaging with Enhanced Depth Sensitivity

Ganbat Baasantseren, Jae-Hyeung Park*, Nam Kim*, and Ki-Chul Kwon

Abstract

A novel computational integral imaging technique with enhanced depth sensitivity is proposed. For each lateral position at a given depth plane, the dissimilarity between corresponding pixels of the elemental images is measured and used as a suppressing factor for that position. The intensity values are aggregated to determine the correct depth plane of each plane object. The experimental and simulation results show that the reconstructed depth image on the incorrect depth plane is effectively suppressed, and that the depth image on the correct depth plane is reconstructed clearly without any noise. The correct depth plane is also exactly determined.

Keywords : CIIR, 3D image processing, depth detection.

1. Introduction

A basic limitation of a conventional visual display is that the surface of the display screen is two-dimensional, whereas the natural world is three-dimensional (3D). A 3D display has some applications such as in architectural and design models, computer games, and 3D medical images. Several methods of displaying the 3D image are used, as, for example, stereoscopy [1], autostereoscopy, holography, and integral imaging (II) [2 and 3]. The most important parameter of the 3D image system is the depth, because the depth helps humans feel the third dimension. Therefore, depth detection is an interesting research area in 3D image processing. Computational integral imaging reconstruction (CIIR) [4] has recently been actively studied for this purpose. When one plane object is reconstructed at the correct depth plane, that object is focused. In a multi-object case, the object that was reconstructed at the correct depth plane deteriorates due to the additional noise caused by other objects located at different depth planes [5]. In fact, those objects at different depth planes reduce the accuracy of the depth detection.

II, which G. Lippman first proposed in 1908, has been regarded as one of the most attractive 3D imaging and display techniques, because it can provide full-color, full-parallax, and continuously viewable images. The integral imaging technique consists of two processes: pickup and reconstruction [4 and 6], as shown in Fig. 1. The proposed method enhances the depth sensitivity of CIIR using the pixel weight. In the following section, the principle of the proposed method is explained and the results of the simulation and experiment are presented.

2. Principle of the Pixel Weight Method and Simulation Results

The proposed method consists of three steps. The first step involves the depth plane reconstruction using a new pixel weight method. In the second step, a mask of the objects is produced from the reconstructed plane images. In the last step, each detected object is reconstructed at the corresponding correct depth plane.

In Fig. 1, three object points, P_1, P_2, and P_3, which have three different colors, are projected by a lens array on an elemental image plane. P_{C2} and P_{I2} are the reconstructed pixels of object point P_2 on the correct plane and the incorrect plane, respectively. P_{C2} is reconstructed with three pixels, $E_{2\text{-}1}$, $E_{2\text{-}2}$, and $E_{2\text{-}3}$, on three elemental images. P_{I2} on the incorrect plane is reconstructed with five pixels that have different colors.

Manuscript received February 19, 2009; Revised March 19, 2009; accepted for publication March 24, 2009.
This work was supported by the grant of the Korean Ministry of Education, Science and Technology (The Regional Core Research Program / Chungbuk BIT Research-Oriented University Consortium).
* Member, KIDS
Corresponding Author : Jae-Hyeung Park
School of Electrical & Computer Engineering, Chungbuk National University
410 SungBong-Ro, Heungduk-Gu, Cheongju-Si, Chungbuk 361-763, Korea
E-mail : jh.park@cbnu.ac.kr **Tel** : 043-261-3598 **Fax** : 043-261-3598

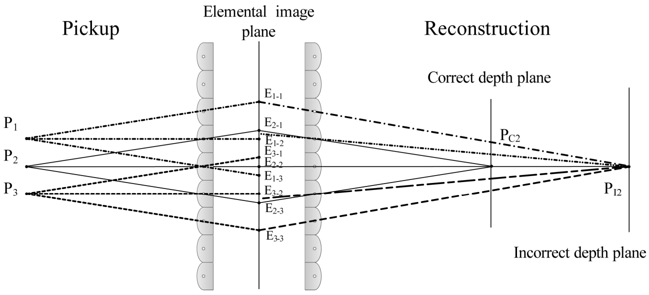

Fig. 1. Pickup of three pixels and ray collection at two different planes.

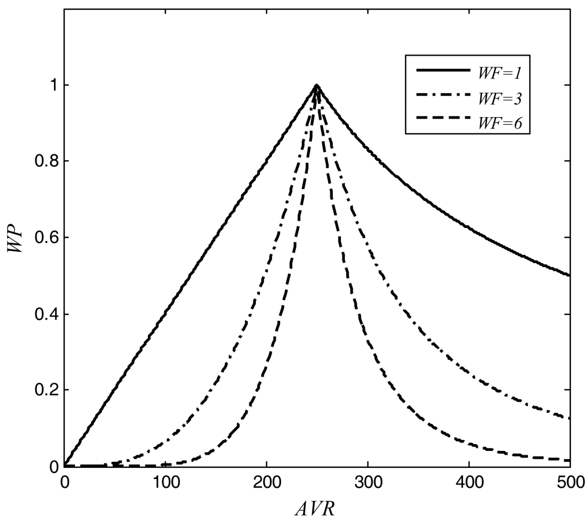

Fig. 2. Relationship between the pixel weight and the average value.

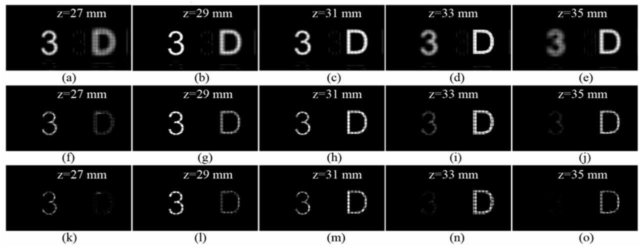

Fig. 3. Simulation results. Depth plane images reconstructed with (a)-(e) the conventional CIIR, (f)-(j) the pixel weight method with $WF = 3$, and (k)-(o) the pixel weight method with $WF = 6$.

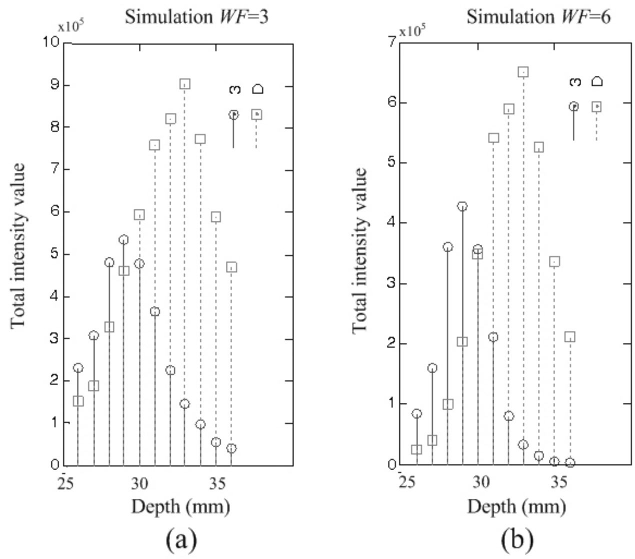

Fig. 4. Determination of the correct depth with the total intensity when (a) $WF = 3$ and (b) $WF = 6$.

For a given reconstruction point, the corresponding elemental image points are collected and averaged. Also, one pixel among the corresponding elemental image pixels is selected and identified as the central elemental image pixel, such that its lateral position is nearest that of the given reconstruction point. If the average value of the color of the collected corresponding pixels is greater than that of the color of the central elemental image pixel, the weight of the given reconstruction pixel is calculated using the following equation:

$$WP(x,y) = \left(\frac{C(x,y)}{Avr(x,y)} \right)^{WF}, \qquad \text{Eq. 1}$$

wherein *Avr(x,y)* is the average value of the color of the corresponding elemental image pixels, WF is the coefficient-determining linearity of the weighting function, and *C(x,y)* is the color of the central elemental image pixel. If the average value of the color of the corresponding elemental image pixels is smaller than or equal to that of the color of the central elemental image pixel, the weight of the reconstruction pixel is calculated using the following equation:

$$WP(x,y) = \left(\frac{Avr(x,y)}{C(x,y)} \right)^{WF}. \qquad \text{Eq. 2}$$

A reconstructed pixel is defined by:

$$I(x,y) = C(x,y) \cdot WP(x,y). \qquad \text{Eq. 3}$$

When a plane image is reconstructed far from the correct depth plane, *WP* is small, and consequently, the reconstructed pixel is suppressed. WP equals one when the image is reconstructed at the correct depth plane. The amount of suppression at the incorrect depth plane depends on the weighting factor *WF*. The relationship between the pixel

Fig. 5. Results of the simulation of the proposed method.

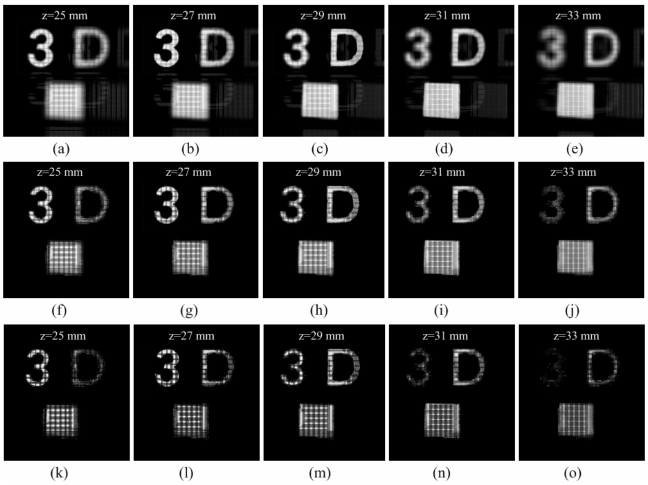

Fig. 6. Experimental results. Depth plane images reconstructed with (a)-(e) the conventional CIIR, (f)-(j) the pixel weight method with *WF* = 3, and (k)-(o) the pixel weight method with *WF* = 6.

weight and the average value of the pixel when *C(x,y)* is 250 is shown in Fig. 2.

Fig. 3 shows the simulation results. An image of two objects is used, and their depth is 29 mm for “3” image and 33 mm for “D” image. Figs. 3 (a)-(e) show the results of the conventional CIIR at five different depth planes; Figs. 3 (f)-(j) show the results of the proposed CIIR with *WF* = 3; and Figs. 3 (k)-(o) show the results of the proposed CIIR with *WF* = 6.

Fig. 3 shows that if *WF* is high, the unfocused plane image is more effectively suppressed, but the quality of the image on the focused plane is not good. When there is only one plane object, by measuring the total intensity value of the reconstructed depth images, the correct depth plane can be determined and a clear reconstructed depth plane image can be obtained by performing conventional CIIR at the detected correct depth plane. When there are multiple plane objects, however, the depth cannot be detected by simply measuring the total intensity value. Moreover, in a multi-object case, when one plane object image is reconstructed

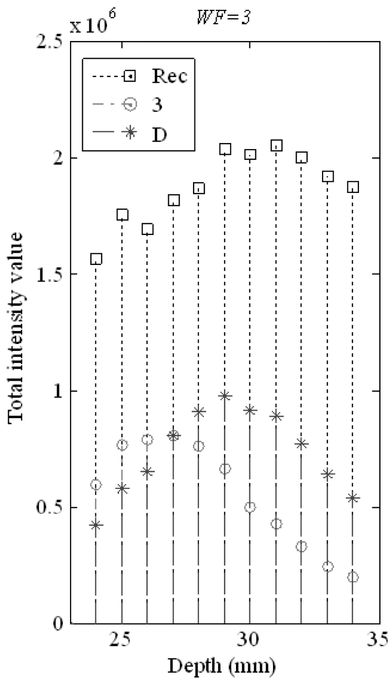

Fig. 7. Total intensity of each object in the reconstructed depth plane image to determine the correct depth.

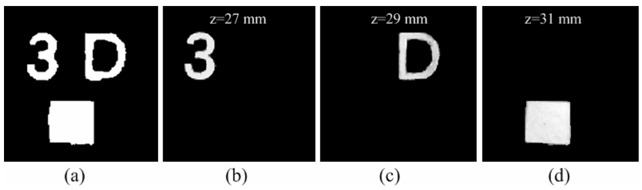

Fig. 8. Object mask and results of the experiment on the proposed method. (a) Object mask, (b) “3” object at 27 mm, (c) “D” object at 29 mm, and (d) the rectangular object at 31 mm.

on the correct depth plane, the blurred and unfocused images of other objects are also reconstructed, which gives additional noise to the focused image. This reduces the depth detection accuracy and the quality of the correct depth plane image.

To solve this problem, the pixel weight method is applied to mask each object and detect the correct depths of all the objects. For object masking, the image that was reconstructed using the pixel weight method is converted into a binary image. If that binary image is located on the unfocused plane, many individual pixels and separate regions will appear in the binary image in the pixel weight method. For example, there are black lines and some pixels in Fig. 3 (k). Those black lines and pixels make it difficult to produce a complete object mask. Therefore, the morphological-image-closing algorithm [7], which can remove the gaps and smooth the edges of a binary region, is used to combine the individual pixels and eliminate the black lines.

The object mask is determined for each depth plane by finding the boundary of the morphologically closed image obtained in the previous step. The mask of one depth plane image cannot identify all the objects, because some reconstructed images of the plane object disappear at some depth planes, such that the corresponding object of that image cannot be identified. For example, a "3" object disappears in Fig. 3 (o), and the "3" object cannot be identified. By repeating this process for all the reconstructed images at all the different depth planes, the correct mask of the multiple objects can be determined.

The last step involves the object depth detection and reconstruction. The mask of the objects and the reconstructed images at all the depth planes were used via the pixel weight method to determine the correct depth plane of each object. The proposed pixel weight method suppressed some pixels that were reconstructed at incorrect depth planes, such that those pixels were fewer than the pixels that were reconstructed on the correct depth plane. Therefore, the total value of the colors on the correct depth plane for one object is higher than on the incorrect depth plane. When *WF* is 3 and 6, Fig. 4 shows the total intensities of "3" object and "D" object. Fig. 4 also shows that the highest intensity of "3" object was 29 mm. Therefore, the correct depth plane of "3" object was determined as 29 mm. Also, the highest intensity of "D" object was 33 mm, so the correct depth plane of "D" object was 33 mm. Fig. 4 further shows that a step in the depth detection was 1 mm, so the accuracy of the depth detection was 1 mm. The precision of the depth detection can be improved. When *WF* is large, the difference between the total intensity values of two adjacent depth planes is higher than when *WF* is small, as shown in Fig. 4 (a) and (b). Finally, each object was reconstructed at the corresponding correct depth plane while other objects were masked. The simulation results are shown in Fig. 5.

3. Experimental Results and Discussion

"3" object, "D" object, and a rectangular object, which were located at 27 mm, 29 mm, and 31 mm from the lens array, respectively, were captured. A lens array consists of 33×33 elemental lenses, each of which is a $1\times1mm^2$ rectangular lens with a 3.3mm focal length. The resolution of each elemental image is 36×36 pixels. Fig. 6 (a)-(e) show the results of the conventional CIIR at five different depth planes; Fig. 6 (f)-(j) show the results of the proposed CIIR with *WF* = 3; and Fig. 6 (k)-(o) show the results of the proposed CIIR with *WF* = 6. The suppression at the incorrect depth plane was not visually obvious, because the captured objects were not exactly planes and there was some environmental noise. Still, however, the proposed method detected the correct depth plane of each object. After all the objects were masked, the total intensity value of each object was calculated to determine the correct dept planes. Fig. 7 shows the total intensity value of each masked object at different depth planes from 24 mm to 34 mm, when *WF* was 3.

Fig. 7 shows the correct depths of "3" object, "D" object, and the rectangular object as 27 mm, 29 mm, and 31 mm, respectively. It is believed that the rectangular object showed a slight irregularity because it was not aligned exactly parallel to the lens array plane in the experiment. Note, though, that despite this irregularity, the correct depth of the object was found, without any problem. Finally, the reconstruction was performed on the three aforementioned depth planes using the object mask, which resulted in a clear object image, as shown in Fig. 8.

4. Summary

The pixel weight method successfully suppressed the pixels of one plane object image at an unfocused plane, such that the total pixel intensity dropped. Such method was used to detect the focused plane. In the multi-plane object case, the pixel weight method was combined with the object detection method. The proposed method successfully detected and reconstructed a clear object image without noise from the unfocused plane image. The accuracy of the depth detection in the experiment was 1 mm.

References

[1] L. Lipton. *Stereographics Developers' Handbook* (Stereographics Corporation, 1997), Ch. 2.

[2] G. Lippmann. Comptes-Rendus Academie des Sciences. **146**, 446 (1908).

[3] B. Lee, J. H. Park, and S. W. Min. In *Digital Holography and Three-dimensional Display,* edited by T. Ch. Poon (Springer, New York, 2006), p. 333.

[4] S. H. Hong, J. S. Jang, and B. Javidi. *Opt. Express.* **12**, 483

(2004).
[5] K. J. Lee, D. C. Hwang, S. C. Kim, and E. S. Kim. *Appl. Opt*. **47**, 2859 (2008).
[6] F. Okano, H. Hoshino, J. Arai, and I. Yuyama. *Appl. Opt*. **36**, 1598 (1997).
[7] R. C. Gonzalez and R. E. Woods. *Digital Image Processing, 2nd edition* (Prentice Hall, New Jersey, 2002), p. 519.

※ Parts of this work were presented in Proceedings of IMID 2008.