Improved Viewing Quality of 3-D Images in Computational Integral Imaging Reconstruction Based on Round Mapping Model

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In this paper, we propose a computational integral imaging reconstruction (CIIR) method using a round mapping model to improve the viewing quality of 3-D images. The proposed CIIR method can overcome the problem of non-uniformly reconstructed images caused by the conventional method. To show the usefulness of proposed method, some experiments are carried out and the results are presented.

Keywords: 3D display, integral imaging, computational reconstruction.

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I. Introduction

Integral imaging (InIm) has been an attractive autostereoscopic three-dimensional (3-D) display technique since it was proposed by Lippmann in 1908 [1]-[10]. It has attracted many researchers because of various merits, such as full parallax continuous viewing angle and full color display. However, it also has disadvantages, including the low resolution of 3-D images and limited viewing angle [2], [3], [11].

In general, an InIm system consists of two parts; recording and reconstruction. In the recording part, the rays coming from a 3-D object through a lenslet array are recorded as elemental images representing different perspectives of a 3-D object. In the reconstruction part, the recorded elemental images are displayed on a display panel and then the 3-D image can be reconstructed and observed through a lenslet array.

Recently, two kinds of reconstruction methods in InIm have been studied for 3-D image display. One is optical integral imaging reconstruction (OIIR) [2]-[4], and the other is computational integral imaging reconstruction (CIIR) [5]-[8]. The OIIR method has some problems due to the physical limitations of optical devices, such as diffraction and aberration. To overcome these problems, a CIIR method based on a pinhole array model has been introduced [7], [10], in which 3-D images are digitally reconstructed at the required output planes by superposition of all of the inversely mapped elemental images by using a pinhole array model. This property of CIIR is useful in object recognition applications using a correlation method to recognize partially occluded 3-D objects [9].

The conventional CIIR method generally yields poor viewing quality of reconstructed images because there are some intensity irregularities with a grid structure at the reconstructed image plane which result from the overlapping of square elemental images. There have been several studies to improve the viewing quality of reconstructed 3-D images in the conventional CIIR method. One proposed solution uses a moving lenslet array technique to obtain many elemental images [10]; however, it requires mechanical movements. Another method uses a modification process based on a lenslet array model instead of a pinhole array model [8].

In this paper, we propose a CIIR method using a round mapping model to improve the viewing quality of 3-D images. The proposed CIIR method can overcome the problems of non-uniformly reconstructed images caused by the conventional method and improve the viewing quality of 3-D images. To show the usefulness of proposed method, some experiments are carried out and their results are presented.

II. CIIR Method Using Round Mapping

Figure 1 shows a conventional CIIR method based on a pinhole array model [7]. In the computational reconstruction process, elemental images are digitally reconstructed by a computer, where 3-D images can be easily reconstructed at any output planes without optical devices. As shown in Fig. 1, the elemental images are mapped onto the image plane inversely through each pinhole. The elemental images are magnified as much as a ratio of z/g, where z is the distance between the reconstruction image plane and the virtual pinhole array, and g is the distance between the elemental images and the virtual pinhole array. The magnified elemental images overlap each other, and the reconstructed 3-D images are finally produced at the reconstruction image plane. However, this pinhole array-based CIIR method mostly yields reconstructed 3-D images which have a poor viewing quality with intensity irregularities due to square elemental images.

Figure 2 shows the proposed CIIR method using a round mapping model. The main difference from the conventional CIIR method is the mapping shape of each elemental image. In the conventional CIIR method, square elemental images are used, while the proposed method uses a round mapping of elemental images after they pass through the pinhole array as shown in Fig. 2. Round mapping is obtained by circular clipping of each square elemental image. In other words, the elemental images are mapped onto the image plane inversely through each pinhole and magnified with a round shape as much as a ratio of $M=z/g$. The magnified elemental images overlap each other to reconstruct 3-D images at the

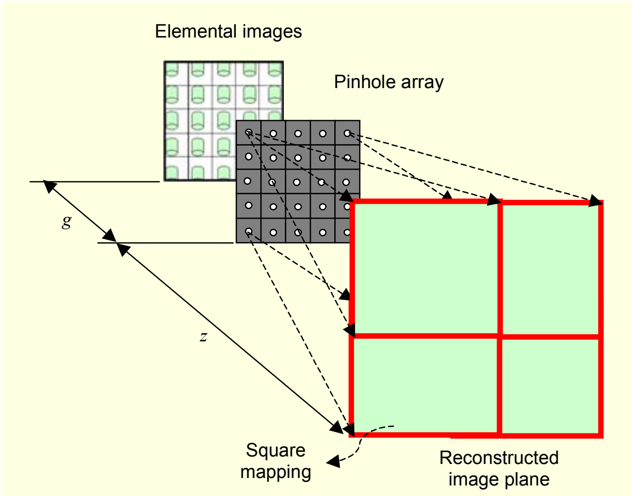

Fig. 1. Principle of conventional CIIR method.

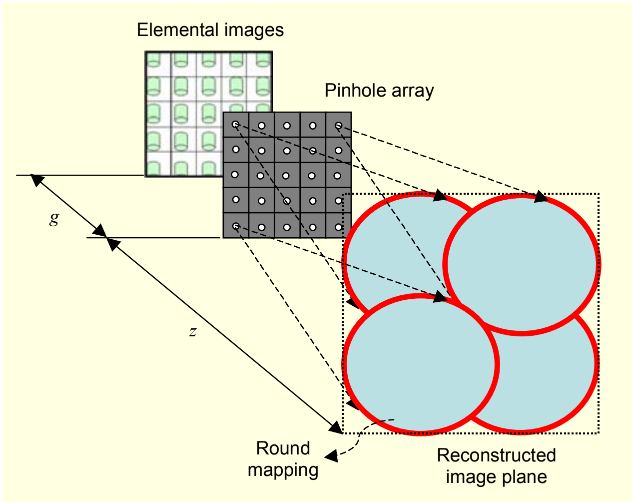

Fig. 2. Principle of the proposed CIIR method.

reconstruction image plane. As shown in Fig. 2, the proposed method can avoid the superposition of a square boundary in each magnified elemental image seen in Fig. 1. This can improve the viewing quality by reducing intensity irregularities in the reconstructed images. The rectangular projections of the conventional method create a regular grid-shaped artifact in the reconstruction plane, while the round projections of the proposed method create more homogenously spread artifacts because the superposed boundaries are spread in all directions.

The reconstruction procedure of the CIIR method can extract voxel information at coordinates (x, y, z) for the construction of a 3-D object from the elemental images. Figure 3 is a detailed illustration of the proposed method. We consider $m\times n$ elemental images and the one-dimensional coordinate of the reconstruction plane according to the i-th elemental image. This can be extended to two-dimensional coordinates to obtain

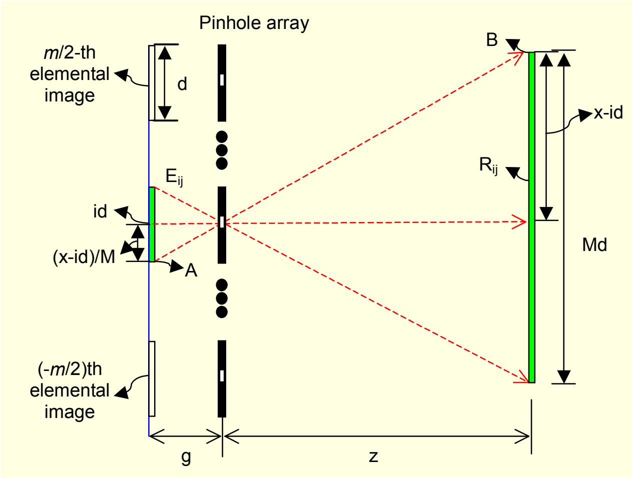

Fig. 3. Mapping diagram of elemental images

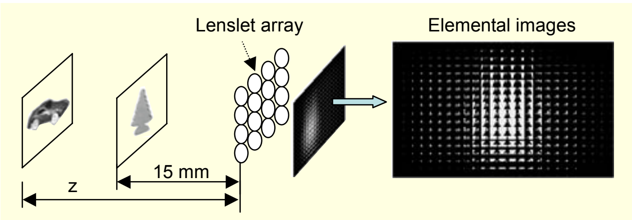

Fig. 4. Experimental structure.

voxel information at (x, y, z). Let $E_{ij}(x,y)$ be the (i, j)th elemental image, and let $R_{ij}(x, y, z)$ be the reconstructed plane image at the distance z, where, integer $i = -m/2$ to $m/2$ and integer $j = -n/2$ to $n/2$. As shown in Fig. 3, $R_{ij}(x, y, z)$ is represented in terms of elemental image E_{ij}. Point A in E_{ij} is mapped onto point B in the reconstructed plane through the i-th pinhole and is represented by id-$(x$-$id)/M$. Then, R_{ij} is given by

$$R_{ij}(x,y,z) = \frac{1}{M^2} E_{ij}\left(id - \frac{x-id}{M}, jd - \frac{y-jd}{M} \right)$$

$$\text{for} \sqrt{[id-(x-id)/M]^2 + [jd-(y-jd)/M]^2} \le \frac{Md}{2}, \quad (1)$$

where d is the size of the elemental images in the lateral direction. The boundary of the elemental images is determined to satisfy a round mapping condition. The reconstructed 3-D image at (x, y, z) is the summation of all the inversely mapped elemental images and is represented by

$$R(x,y,z) = \sum_{i=-m/2}^{m/2} \sum_{j=-n/2}^{n/2} R_{ij}(x,y,z) . \quad (2)$$

III. Experiments and Results

To test the performance of the proposed CIIR method, experiments using two kinds of elemental images from both computational recording and optical recording were carried out.

Figure 4 shows the structure of the experiment using elemental images recorded by computation, where we wanted to calculate the exact numerical analysis. In the experiment, a 3-D test object was used, which is composed of two image patterns: "tree" and "car." Each of the character patterns has $p \times q$=1020×750 pixels. The tree and car patterns were longitudinally located at z=15 mm and z=36 mm, respectively. The lenslet array, which has 34×25 lenslets, was located at z=0 mm. Each lenslet, whose size d is 1.08 mm, is composed of 30×30 pixels. The gap g between the display panel and the lenslet array was 3 mm.

The elemental images were synthesized by simple ray geometry [8]. The resulting synthesized elemental images are shown to the right in Fig. 4. In the next step, the 3-D images were computationally reconstructed from the synthesized elemental images by using two CIIR methods. Figure 5 shows the computationally reconstructed images at various display planes. Reconstructed images at the distance of z = 15 and 36 mm, which are the image display planes of the patterns, are shown in Fig. 5. For comparison, the results for both the conventional method and the proposed method are presented. We can see clear images at all positions.

To quantitatively estimate the viewing quality enhancement of the reconstructed images in the proposed method, peak signal-to-noise ratio (PSNR) was employed as an image quality parameter. It was calculated between the original object image O and each reconstructed image R. The PSNR used was defined as

$$PSNR(O,R) = 10\log_{10}\left(\frac{255^2}{MSE}\right), \quad (3)$$

where the mean square error (MSE) was given by

$$MSE(O,R) = \frac{1}{pq}\sum_{x=1}^{p}\sum_{y=1}^{q}[O(x,y)-R(x,y)]^2 . \quad (4)$$

The calculated PSNR values are presented above each image in Fig. 5. For the proposed method, the PSNR values of the two objects were 24.01 dB and 22.56 dB, respectively. From the PSNR results, image quality might be improved by more than 1.9 dB (55%) in the image reconstructed by the proposed CIIR method over those of the conventional CIIR method. For visual comparison, partial "tire" images were enlarged as shown in Fig. 5. As the figure demonstrates, the tire image reconstructed by the proposed method is much clearer.

To investigate the reconstructed images according to the object distance z, we carried out a computational simulation. In Fig. 4, the distance of the car pattern was changed from 18 mm to 51 mm. Figure 6 shows a comparison of the PSNRs of the

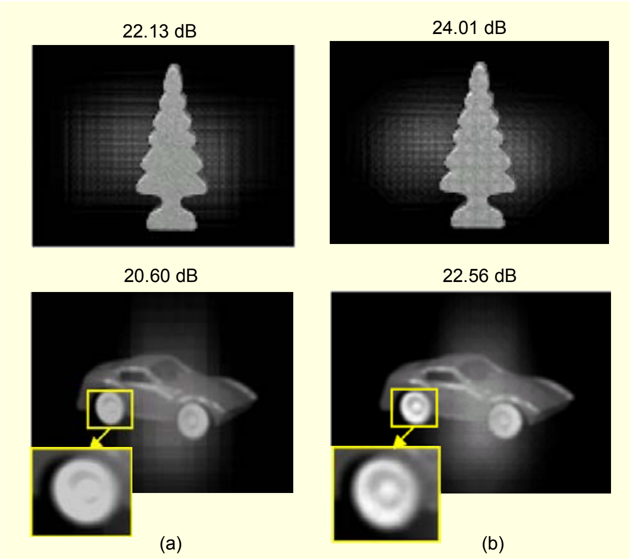

Fig. 5. Reconstructed images by CIIR: (a) conventional method and (b) proposed method.

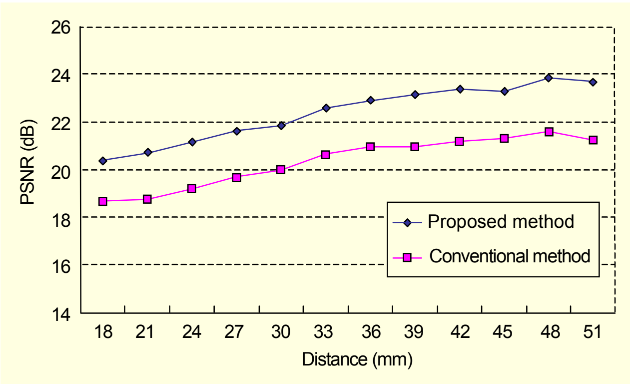

Fig. 6. Comparison of PSNRs according to the distance z.

proposed method and the conventional method. The proposed method improved the PSNR value by 2 dB on average by removing the regular grid-shaped artifact shown in Fig. 5(a).

Next, an experiment using optically recorded elemental images of a real object was carried out. The test object was composed of a pattern of the numeral 3 and a pattern of the letter D. The 3 and D patterns were longitudinally located at z=12 mm and z=33 mm, respectively. The lenslet array with 16×17 lenslets was located at z=0 mm. Each lenslet size d is 1.08 mm and a single elemental image is composed of 70×70 pixels.

The optically recorded elemental images are shown in Fig. 7(a). Figures 7(b) and (c) show the computationally reconstructed images at z=33 mm for the conventional method and the proposed method, respectively. It must be noted here that there is a big difference between the two reconstructed images. In the image reconstructed by the conventional method

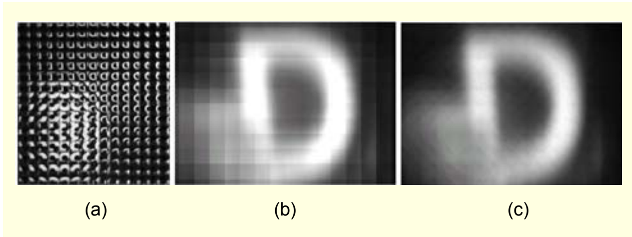

Fig. 7. (a) Optically recorded elemental images, (b) image reconstructed by conventional CIIR method, and (c) image reconstructed by the proposed CIIR method.

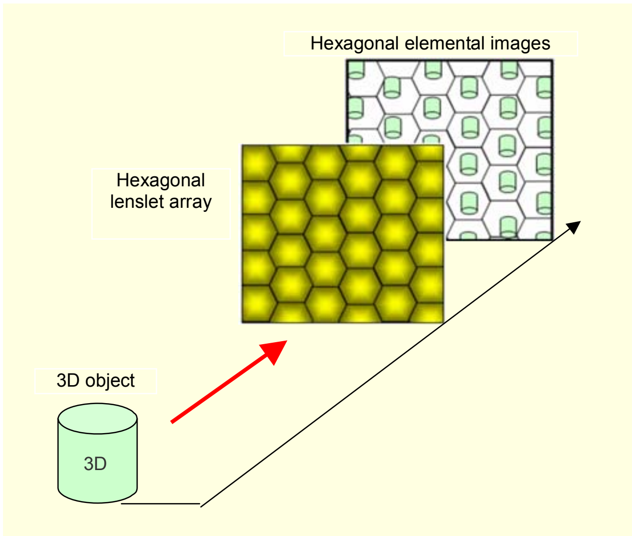

Fig. 8. Recording of hexagonal elemental images.

shown in Fig. 7(b), we can see the intensity irregularities with a grid structure caused by the square mapping of elemental images. For this reason, the visual quality of the 3-D reconstructed image is degraded by the conventional method. The proposed method can provide better results as shown in Fig. 7(c). This is due to the superposition of round elemental images rather than square boundaries for each magnified elemental image.

IV. Discussion and Conclusion

Although the proposed CIIR method was demonstrated successfully, the full information of recorded elemental images was not used due to the round clipping of the square elemental images when the 3-D images were reconstructed. This may cause loss or distortion in reconstructed images. To overcome this problem, a hexagonal lens array may be considered as depicted in Fig. 8. Due to the hexagonal structure, which makes the interval between round elemental images dense, the information lost from elemental images can be reduced and the number of elemental image can be increased for a given CCD device. We will carry out further study on CIIR using a hexagonal lens array in the future.

Improvement of viewing quality using the proposed CIIR method was achieved by avoiding the common grid-shaped artifact of reconstructed images caused by the conventional method. For the proposed method, both computational and optical experiments were carried out. We showed that image quality was improved by about 1.1 dB (28.8%) in PSNR for images reconstructed by the proposed CIIR method over those of the conventional CIIR method.

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