Computational Implementation of Asymmetric Integral Imaging by Use of Two Crossed Lenticular Sheets

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We propose an asymmetric integral imaging method to adjust the resolution and depth of a three-dimensional image. Our method is obtained by use of two lenticular sheets with different pitches fabricated under the same F/#. The asymmetric integral imaging is the generalized version of integral imaging, including both conventional integral imaging and one-dimensional integral imaging. We present experimental results to test and verify the performance of our method computationally.

Keywords: 3-D display, integral imaging, lenticular sheet.

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I. Introduction

Integral imaging (II) has been the subject of much research for three-dimensional (3-D) displays [1]-[13]. In II, 3-D images are formed by integrating the rays coming from two-dimensional (2-D) elemental images by use of a lenslet (or pinhole) array. II can provide observers with true 3-D images with full parallax and continuous viewing points. Compared with other popular 3-D display technologies such as autostereoscopy and holography, however, II does not produce 3-D images with competitive resolution, viewing angle, or longitudinal depth. A number of techniques have been presented to overcome the limited 3-D image quality in II [4], [5]. We believe that no II method developed so far can produce 3-D images impressive enough to observers who are already accustomed to well-developed high-resolution 2-D image displays. This belief becomes obvious when we consider the product of depth and resolution square (PDRS) of a 3-D image that can be produced in a display system [6]. The authors [6] show that, in principle, one cannot achieve a PDRS of more than $1/\lambda$ by use of a single ideal diffraction-limited II system without introducing additional system complexity (λ is the illumination wavelength). Therefore, we need to design an optimal system for a given PDRS.

Recently, we proposed a one-dimensional (1-D) II method which is a modified version of conventional II. The 1-D II method can improve vertical resolution by eliminating vertical parallax as in stereoscopic techniques. This is an example of maintaining control between the resolution and depth of a 3-D image for a given PDRS.

In this paper, we propose an asymmetric II method to adjust the resolution and depth of a 3-D image for a given PDRS. In the proposed method, asymmetric elemental images with different ratios of vertical length to horizontal length are used. We obtained an asymmetric elemental image by use of two lenticular sheets of different pitches fabricated under the same F/#. The asymmetric II method is a generalized version of II including both conventional II and 1-D II. We present experimental results to test and verify the performance of our method. In fact, the concept of asymmetric II is not new. A study on the use of an asymmetric lenslet array has been reported [7]. However, the authors used it for an application without considering the relation between resolution and depth.

II. Structure of Asymmetric II

Figure 1 illustrates the proposed asymmetric II method. In our method, two crossed lenticular sheets of different pitches fabricated under the same F/# are used instead of a lenslet array used in a conventional II method. The first lenticular sheet near an image sensor is located vertically, and the second lenticular sheet is located horizontally, as shown in Fig. 1. Suppose that the width of the elemental lens of two crossed lenticular sheets is larger than the length of the image sensor and that the display panel and pitch of the element lens are d_1 and d_2, respectively. Here, the condition $d_2 \geq d_1$ is satisfied. The rays coming from a 3-D image are recorded in an image sensor through two crossed lenticular sheets. The elemental images are asymmetric due to the use of two different lenticular sheets. These elemental images are displayed in a display panel, and a 3-D image is then generated through two crossed lenticular sheets.

An analysis of asymmetric II according to ray optics is shown in Fig. 2. In ray optics, a lenticular sheet and its pitch are represented as a slit array and slit spacing, respectively. Then, the vertical lenticular sheet near the image sensor, as shown in Fig. 1, is considered as a vertical slit array with slit spacing d_1,

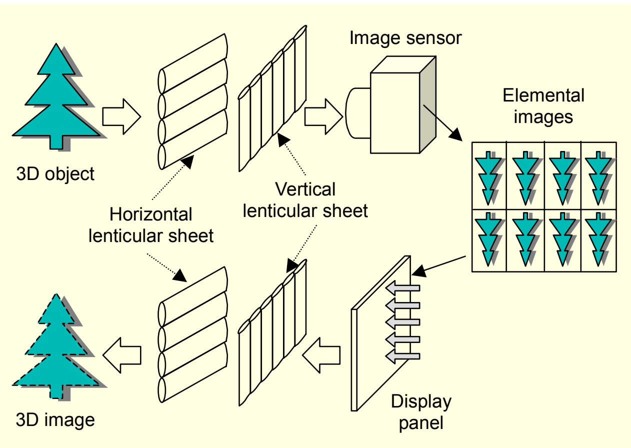

Fig. 1. Pickup and display in asymmetric II.

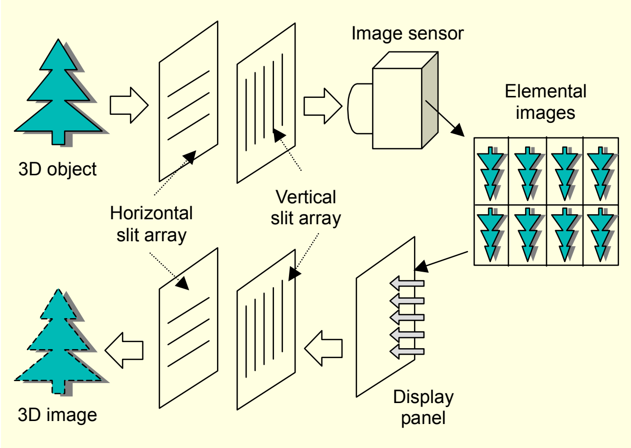

Fig. 2. An analysis of asymmetric II.

and the horizontal lenticular sheet is considered as a horizontal slit array with slit spacing d_2. We assume that the distance between the vertical slit array and the image sensor is z_1, and the distance between horizontal slit array and the image sensor is z_2. To obtain nonoverlapping elemental images from a 3-D object, two slit arrays should be located to satisfy the condition $d_2/d_1 = z_2/z_1$. We then obtain asymmetric elemental images by a d_2/d_1 factor. They are displayed in the display panel to generate a 3-D image through the two crossed lenticular sheets.

In asymmetric II, we can obtain conventional II when d_2 is the minimum value, $d_2 = d_1$. We can consider two slit arrays as a pinhole array because two crossed slit arrays with the same pitch are located at the same position [8]. On the other hand, when d_2 is the maximum value, a horizontal slit array is presented as a single slit. This case becomes 1-D II. Therefore our asymmetric II method is a generalized version of II including both conventional II and 1-D II.

For our asymmetric II method, we analyze the maximum resolution and maximum depth limit [6]. The analysis is performed separately for the x and y axes. The maximum resolutions R_x and R_y of any integral image that can be obtained at the plane ($z=L$) become

$$\frac{R_y}{R_x} = \frac{d_2}{d_1}. \tag{1}$$

From (1), we know that horizontal resolution R_x and vertical resolution R_y depend on d_1 and d_2, respectively. As d_2/d_1 increases, R_y is larger than R_x as plotted in Fig. 3.

On the other hand, the maximum depth limit of 3-D images D_x and D_y that can be displayed in asymmetric II are given by [6]

$$\frac{D_y}{D_x} = \frac{d_1^2}{d_2^2}. \tag{2}$$

The maximum depth limit also depends on d_1 and d_2. D_y is proportional to D_x inversely when d_2/d_1 increases as shown in Fig. 3.

From (1) and (2), we know our method provides control between resolution and depth limit by adjusting the proper d_1 and d_2 values. And the PDRS $R_x^2 D_x = R_y^2 D_y$ is constant regardless of d_1 and d_2, as shown in Fig. 3.

III. Experiments and Results

We performed computational implementation of our asymmetric II based on an inverse mapping method [9]. Figure 4 shows the computational conditions of the inverse mapping method. The 3-D scene used in the experiment is a '+' pattern whose size is 12 mm. The distance between the 3-D scene and the elemental image plane is 36 mm, and the distance z_1 between vertical slit array and elemental image plane is 3 mm. The pitch of the vertical slit is 1 mm. We analyze the effects on the distance z_2 between horizontal slit array and elemental image plane. We used four different z_2 values; 3, 9, 15, and 18 mm. The pitches of the horizontal slit array then become 1, 3, 5, and 6 mm, respectively. When z_2=3 mm, a conventional II method is obtained because two slit arrays are located at the same position. When z_2=18 mm, it becomes a 1-D II method because one-to-one mapping is obtained by placing a horizontal slit array at the center of the distance between 3-D scene and the elemental image plane.

We obtain 3:1 and 5:1 asymmetric elemental images when z_2=9 and z_2=15 mm, respectively. These asymmetric elemental images, whose pixels are 465 × 465, are shown in Fig. 5. Each elemental image is 31 × 31 pixels. The 15 column × 15 row elemental images created computationally are shown in Fig. 5(a). Figure 5(b) shows the 5 column × 15 row elemental images when z_2=9 mm. Figure 5(c) shows the 3 column × 15 row elemental images when z_2=15 mm. And the 1 column × 15 row elemental images, which are the 1-D elemental images when z_2=18 mm, are shown in Fig. 5(d).

Next, we reconstruct a 3-D image computationally by use of the created elemental images. The asymmetric elemental images are represented in the elemental image plane. The ray information from the elemental images is converged through two slit arrays to reconstruct the 3-D image. Figure 6 shows computationally reconstructed images at z_2=36 mm. The size of the reconstructed image is 500 × 500. The reconstructed image when z_2=3 mm is shown in Fig. 6(a). Figures 6(b) and 6(c) show the reconstructed images when z_2=9 mm and 15 mm, respectively. The reconstructed image of the 1-D II method is shown in Fig. 6(d). To compare the resolution of all

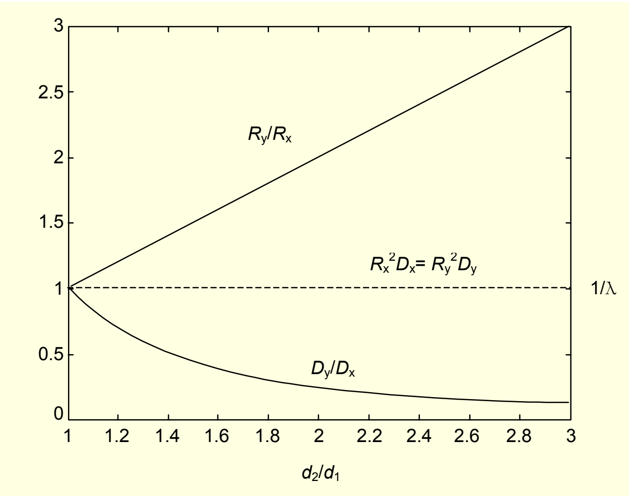

Fig. 3. Plot of asymmetric II parameters.

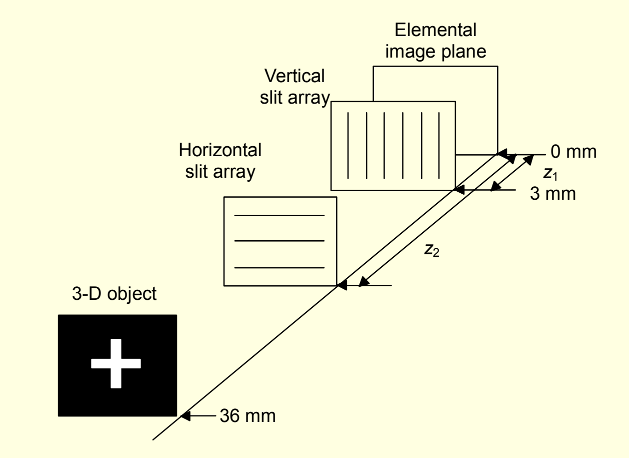

Fig. 4. The computational conditions for asymmetric II.

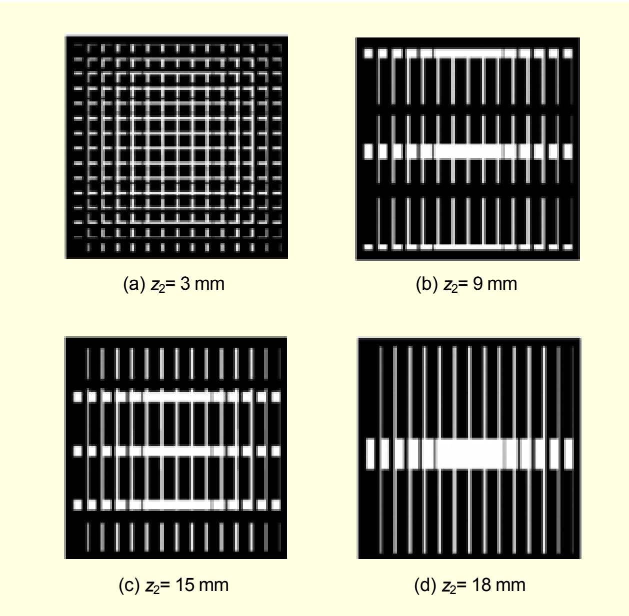

Fig. 5. Asymmetric elemental images.

reconstructed images, we present the intensity distribution profiles of reconstructed pixels in a specific vertical line of the reconstructed images, as shown in the bottom of Fig. 6. These profiles indicate how much the reconstructed pixels are similar to the original pixels. We calculated the values of mean-square error between these reconstructed pixels and original pixels. They were 0.34, 0.31, 0.27, and 0 for z_2=3, 9, 15, and 18, respectively. Because a high value of mean-square error indicates a large reconstruction error, we know large asymmetric II provides higher vertical resolution. However, in this case we lose depth effect as expressed in the previous chapter.

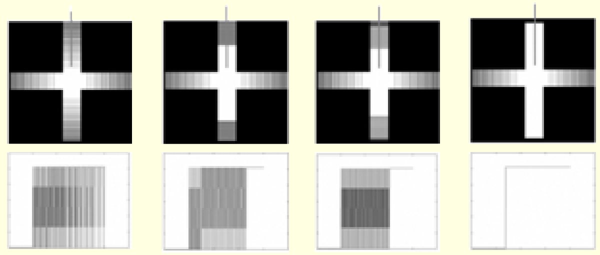

Fig. 6. Reconstructed images.

IV. Conclusion

As a conventional II technique, our asymmetric II also has a pseudoscopic problem because of opposition between viewing direction and pickup direction. To overcome this problem, several methods have so far been reported [10]-[13]. We think that some of these methods can be adopted usefully in our method to overcome the pseudoscopic problem.

When the proposed method is implemented optically, we believe that the function of depth controlling can be useful for some image processing techniques such as depth extraction [7] and 3-D pattern recognition. Also, we believe that 1-D II without vertical parallax will be one of the good solutions for a large-scale 3-D display system because of the horizontal-only arrangement of multiple display devices.

In conclusion, we proposed an asymmetric II method, which is a generalized version of II including both conventional II and 1-D II, by use of two crossed lenticular sheets with different pitches. The rays coming from a 3-D object are recorded through two crossed lenticular sheets and are displayed again to generate the 3-D images. We presented experimental results to test and verify the performance of our method.

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