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Influences of the pickup process on the depth of field of integral imaging display

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ABSTRACT

A typical integral imaging (InIm) display consists of the pickup process and the display process. In the InIm display process, the facet braiding phenomenon influences on the depth of field (DOF). Actually, the DOF of the InIm system not only depends on the the facet braiding in the display process, but also seriously depends on the pickup process. Only the pickuped object within the certain region can capture clear elemental images, and blurry elemental images could be attained outside the region. The region that can be recorded clear elemental images is called the pickup DOF of InIm, which influences on the total DOF of the InIm display. The pickup DOF calculation formula of InIm is presented, which is compared with the DOF caused by facet braiding. Experimental results agree with the theoretical analysis, which is benificial for designing the InIm display system.

1. Introduction

Integral imaging (InIm) is a promising three-dimensional (3D) technology that was firstly proposed by Lippman in 1908 [1], which can provide full-parallax and continuous-viewing 3D images without the convergence-accommodation conflict [2–7]. The typical InIm system is composed of a lens-array, a charge coupled devive (CCD) and a display device. In the recording process of InIm, the information of 3D objects is recorded on the CCD through the lens-array. The recorded images on the CCD are called the elemental images which contain various perspective view images. In the display process of InIm, 3D images are reconstructed with the elemental images displayed with the lens-array [8–11]. In recent years, InIm has attracted extensive attentions [2–5].

For practical applications of InIm, there are some limitations to be overcomed, such as low viewing resolution, narrow viewing angle and the shallow DOF [11–17]. To address these problems, computational integral imaging reconstruction (CIIR) technique was proposed. The resolution of the reconstructed images was degraded due to the partial occlusion of other reconstructed images. The occlusion and blur noise originating from the CIIR technique were investigated [18–20]. Meanwhile many researches aimed to improve DOF, a method for displaying the image throughout real and virtual image fields was presented without introducing dynamic movements or additional devices [12]. In [13], the distant and large objects were captured with a curved pickup device. A time multiplexed integral-imaging method was proposed by the use of an array of lenslets with different focal lengths and aperture sizes [14]. Martínez-Cuenca et al. enhanced the depth of field by reducing the fill factor of each lenslet and using an amplitude-modulated lenslet array and a deconvolution operation [15,16]. The DOF was defined as the distance between the rear and front marginal depth plane located at two positions where the spot sizes equaled to the pixel sizes on the central depth plane (CDP) [17]. The DOF was evaluated in terms of the Rayleigh range [16]. Those two methods were concise. However, only the depth range in front of and behind the CDP as equal was considered, which is suitable for the actual situation. Meanwhile, the DOF was investigated by considering the facet braiding phenomenon [21–23]. The condition is that the pickup device, display device and the reference image plane are conjugate, and only the reconstructed images in the reference plane are correct without facet brading. The DOF was the region where the constructed 3D image showed ahigh quality [23]. However, the real DOF of InIm is not just decided by the factor in the display process, but also influenced by the pickup process.

Actually, the DOF of InIm system depends on pickup process seriously. With a certain pickup device, only the object within the certain region can be recorded as clear elemental images, and the object outside this region will be recorded as blurry elemental images. When these elemental images are displayed with the same lens-array as that in the pickup process, the clear elemental images would recon-

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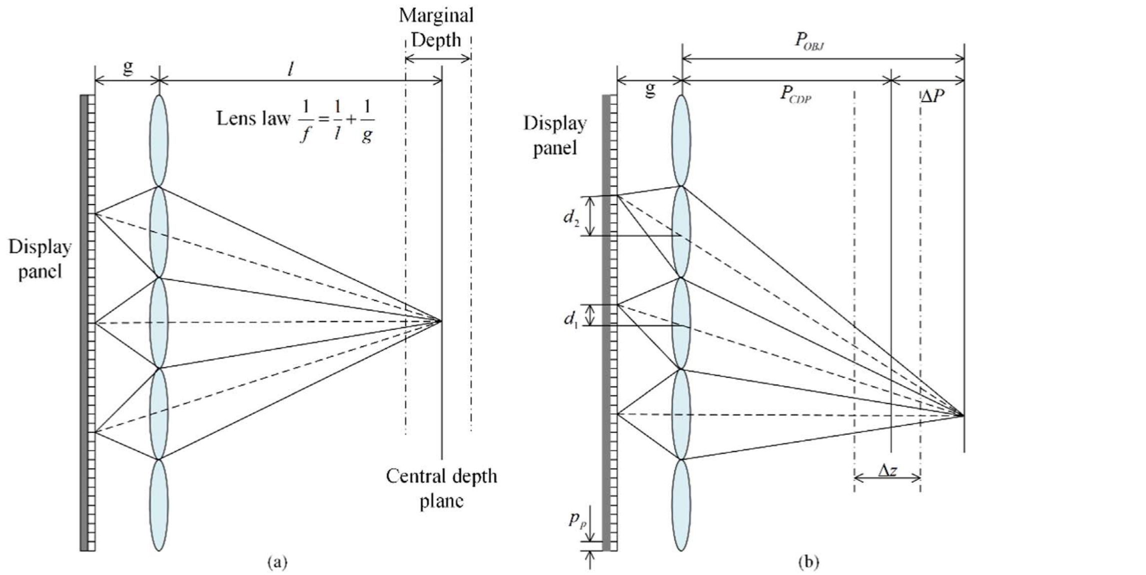

Fig. 1. (a) schematic of central depth plane (b) DOF of InIm based on facet braiding.

struct clear 3D images, and the blurry elemental images can only display unclear 3D images. The region where the object can be recorded as clear elemental images is called the pickup DOF of InIm, which will influence the total DOF of InIm display. Here, the pickup DOF calculation formula is deduced from the InIm system, which is compared with the DOF caused by facet braiding. Experimental results verify the accuracy of the proposed method.

2. Principle of the DOF of InIm

The DOF of InIm based on facet braiding were analyzed [21–23], and a 3D image constructed with an InIm system showed a good quality only in a specific region known as the marginal depth region [23]. This region covers the area of a single plane from one end to the other, which is called the central depth plane(CDP), and light rays from display pixels are focused on this plane by a lens array, as shown in Fig. 1(a). The depth range of InIm based on facet braiding is calculated as $\Delta z = \frac{P_{CDP}^2}{g} \times \frac{P_p}{p}$ [23], as shown in Fig. 1(b), where P_{CDP} represents the position of CDP calculated by the lens law$P_{CDP} = \frac{fg}{g-f}$, and $P_p$and$p$represent the display pixel pith and lens pitch, respectively. g is the gap between the display panel and the lens array. The DOF calculation method is easy to use but with low accuracy, because it does not consider the effect caused by the lens.

According to the characters of the ideal optical imaging system, there is only one conjugate plane in the imaging space for the object plane. Only the point in the focusing plane can image a clear image point on the imaging plane, and speckles occur for imaging points for other object points. Considering the minimum angular resolution of human eyes, when the diameter of speckles is less than a certain value, it can be recognized as a clear image point. Therefore, with a entrance pupil of the lens, only the objects in the certain DOF in the object space can image clear images in the imaging plane.

Here, the DOF of the InIm system is defined as the depth of field where objects can image clear images in the imaging plane. As shown in Fig. 2, the farthest plane which can image clear images is called the far object plane, and the nearest plane which can imagie clear images is called the near object plane. Distances between them and the focusing plane is named as the far object depth DOF_1 and the near object depth DOF_2, respectively.

For the DOF of the InIm system, the total$DOF = DOF_1 + DOF_2$, where -$l$denotes the distance between the focusing plane and entrance pupil, and -$l_1$and -$l_2$are the distances from the entrance pupil to the far and near object planes. Distances between the conjugate planes where the imaging space and emergent pupil are denoted by l', $l_1'$and l_2', respectively. The diameter of the entrance pupil and emergent pupil is expressed as$p$. As shown in Fig. 2, points$P_1$and$P_2$are located outside the focusing plane, and their image points$P_1''$and $P_2''$are located outside the imaging plane. Diameters of the speckles of pointsP_1andP_2in the focusing plane are denoted as w_1 and w_2, and their corresponding speckle diameters of image points$P_1''$and P_2''in the imaging plane are denoted asw_1' and w_2'. According to the relationship of the similar triangular, the diameters of speckles can be calculated as

$$w_1 = p\frac{l_1 - l}{l_1}, \quad w_2 = p\frac{l - l_2}{l_2} \tag{1}$$

As shown in Fig. 3, in order to acquire correct 3D images without distortion, the field angle $\alpha$of the speckle in the imaging plane for human eyes should be equal to the filed angle $\alpha'$of the object in the object space, and the relationship is given as

$$\tan\alpha = h/l = \tan\alpha' = h'/L \tag{2}$$

The correct perspective distance$L$can be calculated as

$$L = lh'/h = \beta l \tag{3}$$

$\beta = l'/l = h'/h$is the magnification factorof the optical system. According to Eq. (3) and the geometrical relationship, the maximum diameter of the speckle that human eyes can recognize in the imaging plane can be expressed as

$$w_1' = w_2' = L\varepsilon = \beta l\varepsilon, \quad w_1 = w_2 = w'/\beta = l\varepsilon \tag{4}$$

εdenotes the minimum angular resolution of human eyes. As shown in Fig. 2, combining Eqs. (1) and (4), the far object depth $DOF_1$and the near object depth DOF_2 can be derivedas

$$DOF_1 = l_1 - l = \frac{lw_1}{p - w_1} = \frac{l^2\varepsilon}{p - l\varepsilon}, \quad DOF_2 = l - l_2 = \frac{lw_2}{p + w_2} = \frac{l^2\varepsilon}{p + l\varepsilon} \tag{5}$$

We can see that the far object depth $DOF_1$is larger than the near object depth DOF_2. The total DOF in pickup process is given as

$$DOF = \frac{2pl^2\varepsilon}{p^2 - l^2\varepsilon^2} \tag{6}$$

With the same lens array which used in the pickup process, the display process has identical DOF with the pickup process. Thus, the DOF of InIm system can be expressed as Eq.(6), where l denotes the distance that reconstructed images away from