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

Shenwu Yang, Xinzhu Sang*, Xin Gao, Xunbo Yu, Binbin Yan, Jinhui Yuan, and Kuiru Wang

State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications (BUPT), 100876 Beijing, China

**Corresponding author: xzsang@bupt.edu.cn*

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 facet braiding in the display process, but also seriously depends on the pickup process. Only the pickup 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 beneficial for designing the InIm display system.

Keywords: Integral imaging, facet braiding, depth of field, pickup process

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 device (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 overcome, 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 braiding. The DOF was

the region where the constructed 3D image showed a high 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 reconstruct 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 pitch 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.

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

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 image 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.

Fig.2.DOF of the InIm system in the pickup process

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 points P_1 and P_2 in 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 as w'_1 and w'_2 . According to the relationship of the similar triangular, the diameters of speckles can be calculated as

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

Fig.3. Schematic of the correct perspective distance

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

$$\tan \alpha = h / l = \tan \alpha' = h' / L \quad (2)$$

The correct perspective distance L can be calculated as

$$L = lh' / h = \beta l \quad (3)$$

$\beta = l' / l = h' / h$ is the magnification factor of 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

$$w_1' = w_2' = L\varepsilon = \beta l\varepsilon, \quad w_1 = w_2 = w' / \beta = l\varepsilon \quad (4)$$

ε denotes 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 derived as

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

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

$$DOF = \frac{2pl^2\varepsilon}{p^2 - l^2\varepsilon^2} \quad (6)$$

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 the lens array.

3. DOF calculation results with different parameters

According to Eq.(6), the DOF is related to the diameter of entrance pupil p , the pickup/reconstructed distance l , and the minimum angular resolution of human eyes ε ($1' \sim 2'$). In the following part, the minimum angular resolution is set as $\varepsilon = 1' = 0.000291 \text{ rad}$.

The DOF is calculated with different parameters. The variation of DOF with different p and l is shown in Fig.4. With increasing p , the DOF is decreased, and with increasing l , the DOF is increased. So we can increase l or decrease p to obtain larger DOF.

Fig.4. Variation of DOF with changing the diameters of entrance pupil (p) and the pickupdistance (l)

4. Experiments and results

In order to verify the accuracy of the proposed method, simulation experiment and optical experiment are carried out. The parameters of the InIm display system are listed in Table.1. DOF_{FB} and DOF_p represent the DOF calculated by considering the facet braiding and the proposed method in the pickup process, respectively. As discussed in section.2, with the same lens in the pickup process, the display process has identical DOF with the pickup process. Thus, DOF_p can denote the DOF in the display process. In experiments, we obtained the elemental image array with the virtual camera array. The DOF and the parameters in the experiment are listed in Table.2, where p , g and l denote the pitch of lens, distance between LCD and lens array, and the pickup/reconstructed distance, respectively.

Firstly, the simulation experiment is carried out with the computational integral imaging (CIIR) technique. A 3D scene consists of five capital letters 'A' with different colors, which are located at different depths, and the distances away from the focusing plane are presented as g_1 , g_2 , g_3 and g_4 , as shown in Fig.5. All the letters 'A' are within the range of calculated DOF_{FB} . Fig.6(a) is the elemental image array obtained by processing the images captured with virtual camera array. The elemental image array contains 43×24 elemental images, each with resolution of 89×89 pixels. Fig.6(b) shows the reconstructed 3D image with the CIIR technique, and we can see that the reconstructed image is clear without facet braiding.

Table.1. Parameters of the designed InIm display system

Parameters	Values
Total number of lens-array ($M \times N$)	43×24
Focal length of the micro-lens (f)	16mm
Resolution of each elemental image	89×89 pixels
Resolution of the LCD	3840×2160 pixels
Shooting distance	2000mm
Minimum angular resolution of human eyes	$\varepsilon = 1' = 0.000291 \text{ rad}$
Pixel pitch of LCD	$P_p = 0.1359 \text{ mm}$
Size of LCD	23.6inch

Table.2. DOF and the parameters in the experiment

Parameters(mm)	$p = 10, l = 300, g = 17$	
DOF(mm)	$DOF_{FB} = 71.95$	$DOF_p = 5.24$

Fig.5. Arranged 3D scene

Fig.6.(a)Elemental image array (b)Different perspectives of simulation result

Then, an optical reconstruction experiment is carried out as shown in Fig.7, and the same elemental image array in the simulation experiment is used. The lens array for the display has identical parameters used in the pickup process. According to the arranged 3D scene in Fig.5 and the calculated DOF in Table.2, only the red letter 'A' is within the range of DOF_P , and all other letters 'A' are within the range of DOF_{FB} . The reconstructed 3D image is captured with the Canon EOD 60D camera at a viewing distance of 2000mm, as shown in Fig.8. Although all the letters 'A' are within the range of DOF_{FB} , we can see only the red letter 'A' located in range of DOF_P is clear, and other letters are blurry. Although the same elemental image array was used in simulation and optical experiments, the result of optical experiment is different from that of the simulation experiment. The experimental phenomenon agrees well with the calculated DOF_P . It is demonstrated that the DOF of InIm system depends on DOF_P . Experimental result demonstrates the accuracy of the proposed method.

Fig.7. Schematic of the InIm system

Fig.8. Experimental result, (a) center viewpoint (b) different perspectives of reconstructed images

5. Conclusion

In summary, the DOF of integral imaging with the assembled InIm display system is analyzed in the pickup process. Firstly, the calculation method of the DOF of integral imaging is derived according to the pickup process with considering the diameter of entrance pupil of the lens and the minimum angular resolution of human eyes. Then, the DOF_P and the DOF_{FB} are compared. Obviously, the DOF_P is more accurate from the experimental result. The presented analysis method can be beneficial for designing of the InIm display system.

Acknowledgments

This work is partly supported by the “863” Program (2015AA015902), the National Science Foundation of China (61575025), the fund of the State Key Laboratory of Information Photonics and Optical Communications.

References

1. G. Lippmann, La photographie integrale, C. R. Acad. Sci. 146(1908)446–451.
2. M. Cho, M. Daneshpanah, I. Moon, and B. Javidi, Three-dimensional optical sensing and visualization using integral imaging, Proc. IEEE. 99(2011)556–575.
3. Adrian Stern and Bahram Javidi, Three-Dimensional Image Sensing, Visualization, and Processing Using Integral Imaging, Proc. IEEE. 94(2006) 591–607.
4. B. Javidi, F. Okano, and J.-Y. Son, Three-Dimensional Imaging, Visualization, and Display Technology, New York: Springer-Verlag, 2008.
5. Myungjin Cho, Mehdi Daneshpanah, Member IEEE, Inkyu Moon, and Bahram Javidi, Three-Dimensional Optical Sensing and Visualization Using Integral Imaging, Proc. IEEE. 99(2010)556–575.
6. Yasuhiro Takaki* and Kyohei Ikeda, Simplified calculation method for computer generated holographic stereograms from multiview images, Opt. Express. 21(2013) 9652–9663.
7. N. Chen, J.-H. Park, and N. Kim, Parameter analysis of integral Fourier hologram and its resolution enhancement, Opt. Express. 18(2010)2152–2167.
8. J.-S. Jang and B. Javidi, Three-dimensional integral imaging of micro-objects, Opt. Lett. 29(2004) 1230–1232.
9. I. Moon and B. Javidi, Three-dimensional visualization of objects in scattering medium by use of computational integral imaging, Opt. Express. 16 (2008) 13080–13089.
10. R. Martínez-Cuenca, G. Saavedra, M. Martínez-Corral, and B. Javidi, Progress in 3-D multiperspective display by integral imaging, Proc. IEEE. 97 (2009) 1067–1077.
11. J. H. Park, Y. Kim, J. Kim, S. W. Min, and B. Lee, Three-dimensional display scheme based on integral imaging with three-dimensional information processing, Opt. Express. 12 (2004) 2032–2020.
12. J.-S. Jang, F. Jin, and B. Javidi, Three-dimensional integral imaging with large depth of focus by use of real and virtual image fields, Opt. Lett. 28 (2003) 1421–1423.
13. J.-S. Jang and B. Javidi, Depth and lateral size control of three-dimensional images in projection integral imaging, Opt. Express. 12(2004)3778–3790.
14. J.-S. Jang and B. Javidi, Large depth of focus time-multiplexed three-dimensional integral imaging by use of lenslets with nonuniform focal lens and aperture sizes, Opt. Lett. 28(2003)1925–1926.
15. R. Martínez-Cuenca, G. Saavedra, M. Martínez-Corral, and B. Javidi, Extended depth-of-field 3-D display and visualization by combination of amplitude-modulated microlenses and deconvolution tools, J. Disp. Technol. 1(2005) 321–327.
16. R. Martínez-Cuenca, G. Saavedra, and M. Martínez-Corral, Enhanced depth of field integral imaging with sensor resolution constraints, Opt. Express. 12 (2004) 5237–5242.
17. S. W. Min, J. Kim, and B. Lee, New characteristic equation of three-dimensional integral imaging system and its applications, Jpn. J. Appl. Phys. 44 (2005) 71–74.
18. X.-W. Li, S. Jin Cho, S. T. Kim, Combined use of BP neural network and computational integral imaging reconstruction for optical multiple-image security, Opt. Commun. 315(2014) 147–158.
19. X.-W. Li, Q.-H. Wang, S. T. Kim, I.-K. Lee, Encrypting 2D/3D image using improved lensless integral imaging in Fresnel domain, Opt. Commun. 381 (2016) 260–270.
20. B. Javidi, Computational Reconstruction of Three-Dimensional Integral Imaging by Rearrangement of Elemental Image Pixels, J. Disp. Technol. 5 (2009) 61–65.
21. R. Martínez-Cuenca, G. Saavedra, and A. Pons, Facet braiding: a fundamental problem in integral imaging, Opt. Lett. 32 (2007) 1078–1080.
22. Héctor Navarro, Raúl Martínez-Cuenca, Ainhoa Molina-Martín, Manuel Martínez-Corral, Genaro Saavedra, and Bahram Javidi, Fellow, IEEE, Method to Remedy Image Degradations Due to Facet Braiding in 3D Integral-Imaging Monitors, J. Disp. Technol. 6(2010) 404–411.
23. Cheol-Joong Kim, Minh Chang, Muyoung Lee, Junoh Kim, and Yong Hyub Won*, Depth plane adaptive integral imaging using a varifocal liquid lens array, Appl. Opt. 54(2015) 2565–2571.