Depth extraction method with high accuracy in integral imaging based on moving array lenslet technique*

WANG Yao-yao (王尧尧)[1], **ZHANG Juan** (张娟)[1], **ZHAO Xue-wei** (赵雪微)[1], **SONG Li-pei** (宋丽培)[1], **ZHANG Bo** (张勃)[1], **and ZHAO Xing** (赵星)[1,2]**

1. Key Laboratory of Optical Information Science and Technology, Ministry of Education of China, Institute of Modern Optics, Nankai University, Tianjin 300350, China

2. Tianjin Key Laboratory of Optoelectronic Sensor and Sensing Network Technology, Nankai University, Tianjin 300350, China

(Received 25 October 2017; Revised 14 December 2017)

In order to improve depth extraction accuracy, a method using moving array lenslet technique (MALT) in pickup stage is proposed, which can decrease the depth interval caused by pixelation. In this method, the lenslet array is moved along the horizontal and vertical directions simultaneously for N times in a pitch to get N sets of elemental images. Computational integral imaging reconstruction method for MALT is taken to obtain the slice images of the 3D scene, and the sum modulus (SMD) blur metric is taken on these slice images to achieve the depth information of the 3D scene. Simulation and optical experiments are carried out to verify the feasibility of this method.

Document code: A **Article ID:** 1673-1905(2018)02-0148-4

DOI https://doi.org/10.1007/s11801-018-7230-y

Integral imaging has unique advantages of simple system structure and color images, which makes it possible to extract depth information by recording the 3D object from different perspectives[1-4]. Therefore, various researches for depth extraction method based on integral imaging have been performed[5-9]. All of these methods can implement the depth extraction of the 3D scene. However, because of the pixelation effect of the elemental images conducted by all these recording systems, the accuracy of these depth extraction methods is limited. Therefore, in order to improve the accuracy of depth extraction, it is necessary to degrade the pixelation effect. The moving array lenslet technique (MALT) was proposed to overcome the Nyquist upper limit by increasing the sampling rate[10-15], and it can also get sub-pixel information by taking advantage of the sub-pixel displacement. Therefore, MALT was taken to improve the resolution of the 3D object sensing and recognition by increasing the number of elemental images in the depth estimation stage, which can improve the longitudinal distance estimation quantization error[13]. So, in terms of depth extraction, the MALT is expected to be effective to degrade the pixelation effect.

In this letter, we present a method to improve depth extraction accuracy by using MALT in pickup stage to decrease the depth interval caused by pixelation. Then the computational integral imaging reconstruction method is used to obtain the slice images of the 3D object, and the sum modulus (SMD) blur metric is taken on these slice images to achieve the depth information of the 3D scene.

In the conventional pickup process, the elemental images of the 3D scene can be obtained by the recording system. Owing to the limited size of the pixel of the recording device, the pixels containing the corresponding image points in each elemental image, referred as the corresponding pixels, overlap in the image space and lead to a depth interval in which the energy distribution is indistinguishable. As shown in Fig.1(a), the point A in the 3D object is recorded on the elemental images as a pixel. In Fig.1(b), all of these corresponding pixels in each elemental image are projected to the image space and overlap in an interval, where z_1 and z_2 are the endpoints of it. The overlapped interval size is decided by the projection of the corresponding pixel in the marginal elemental image on the z axis[16]. The distance between the center of the marginal lens and the axis is h. L is the distance from the lower edge of the corresponding pixel to the axis. z_1 and z_2 can be calculated by Eqs.(1) and (2) based on geometric relationship

$$z_1 = \frac{g\times h}{L-h-\delta}, \tag{1}$$

$$z_2 = \frac{g\times h}{L-h}, \tag{2}$$

* This work has been supported by the National Natural Science Foundation of China (Nos.11474169 and 61675100), and the Tianjin Natural Science Foundation (No.15JCYBJC16900).

** E-mail: zhaoxingtjnk@nankai.edu.cn

where g is the gap between the elemental images and the lenslet array. From Eqs.(1) and (2) the depth interval size can be calculated. Then the accuracy of the depth extraction is limited by the depth interval. Therefore, in order to improve the accuracy, it is necessary to reduce the interval size. In our proposed method, the lenslet array is moved along the horizontal and vertical directions simultaneously for N times in a pitch to get N sets of elemental images. Computational integral imaging reconstruction method for MALT[14] is taken to obtain the slice images of the 3D scene. The analysis of decreasing the depth interval by MALT is shown in Fig.2.

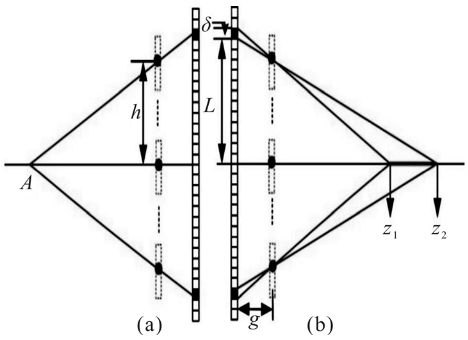


Fig.1 Principle of the generation for depth interval: (a) Pickup stage; (b) Process of reconstruction

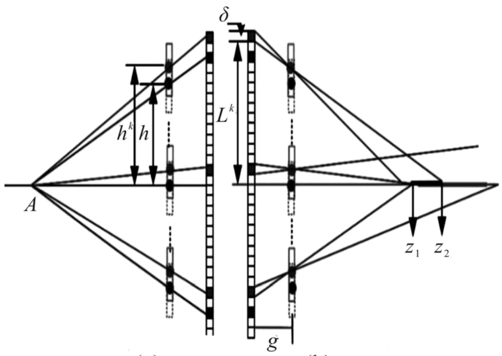


Fig.2 Principle of MALT to improve the depth accuracy: (a) Pickup stage; (b) Process of reconstruction

For the k-th movement, the distance between the marginal lens and the z axis becomes h^k, and L also changes to L^k. From Fig.2(b) we can see that the k-th depth interval is not consistent with the original one, therefore the final interval is determined by the overlapped part. The coordinates of the endpoints of the k-th interval can be calculated by

$$z_1^k = \frac{g \times h^k}{L - h^k - \delta}, \tag{3}$$

$$z_2^k = \frac{g \times h^k}{L - h^k}. \tag{4}$$

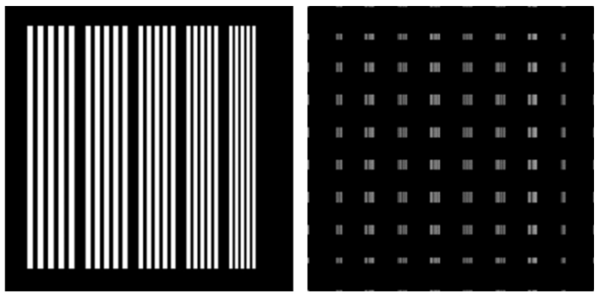
The final depth interval is the overlapped part of N intervals, and the coordinates of z_1 and z_2 are represented by

$$z_1 = \max(z_1^k), \quad z_2 = \min(z_2^k). \tag{5}$$

According to the previous discussion, MALT can decrease the depth interval caused by pixelation of the recording system. Then, the SMD evaluation method is taken to extract the depth of the object. The SMD measurement which is a gray variance function is based on the smoothing effect of blur on edges and consequently attempts to measure the spread of edges[10,11]. We take this method on each slice image. The value of SMD always varies with the depth, and the maximum appears in the original position of the 3D object. The value of SMD for one image can be calculated by Eq.(6), where $f(x, y)$ is the gray value of the pixel at the position of (x, y) on the reconstructed slice images:

$$\text{SMD} = \sum_y \sum_x (|f(x,y) - f(x,y-1)|) + (|f(x,y) - f(x+1,y)|). \tag{6}$$

In the simulation, the object is a resolution target as shown in Fig.3(a). A set of elemental images are obtained by moving the lenslet array. One of the elemental images is shown in Fig.3(b). The parameters of this experiment are shown in Tab.1.



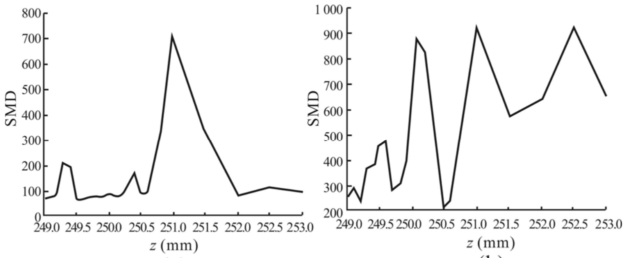
(a) (b)

Fig.3 (a) The resolution target and (b) one of the elemental images

Tab.1 Parameters of simulation

Parameters	Values
Lenslet number	10×10
Lenslet pitch (mm)	0.48
Pixel number of elemental image	160×160
Moving times	5
Moving gap (mm)	0.09
Recording distance (mm)	42

All of these elemental images are carried out to obtain the reconstruction results with 0.1 mm depth interval. The curves of the SMD value varying with the depth z are shown in Fig.4. For comparison, the SMD evaluation method is also taken on the reconstruction results of the conventional recording method and the curve is shown in Fig.4(b). From the results, the SMD value of the MALT has a sharp peak and dramatic changes with the depth. Specifically speaking, when the depth increases or decreases by 0.1 mm around the peak position, the SMD value of the MALT method will decrease rapidly. However, the values for conventional method oscillate within a certain range and make it difficult to get the exact depth information. In other words, the depth extraction accuracy of the conventional method can't reach 0.1 mm. This comparison demonstrates that the depth extraction accuracy is really improved by MALT.



(a) (b)

Fig.4 Curves of the SMD varying with depth: (a) Evaluation result with MALT; (b) Evaluation result with conventional pickup method

From the evaluation results, we can get the depth of the object which is 251 mm. The reconstruction result with MALT at the position of 251 mm is shown in Fig.5(a). Fig.5(b) is the reconstruction result of the conventional pickup method. From the comparison we can see that not only the depth extraction accuracy has been improved but also the image quality has become better.

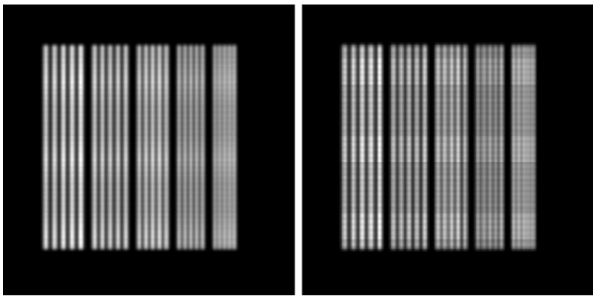

(a) (b)

Fig.5 The reconstruction results of two pickup methods: (a) MALT; (b) Conventional pickup method

The optical experiment is also conducted to test the method. The 3D scene is a cube with question mark and a warning board in different depths. One of the elemental images is shown in Fig.6. The parameters of this experiment are listed in Tab.2.

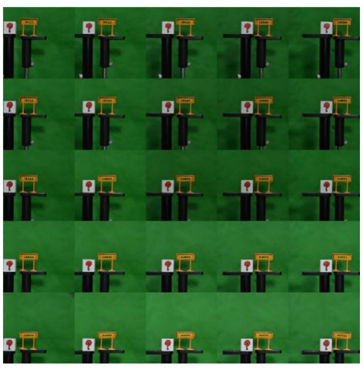


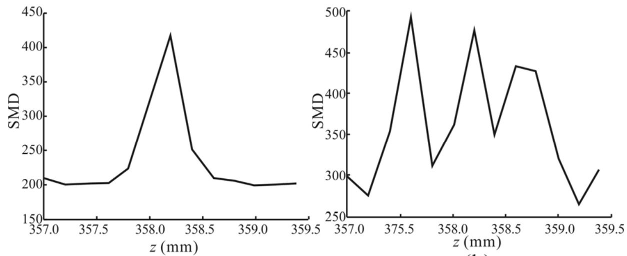
Fig.6 One of the sequence elemental images

Tab.2 Parameters of the optical experiment

Parameters	Values
Lenslet number	5×5
Lenslet pitch (mm)	5.5
Pixel number of elemental image	1 100 ×1 100
Moving times	5
Moving gap (mm)	1.1
Recording distance (mm)	35

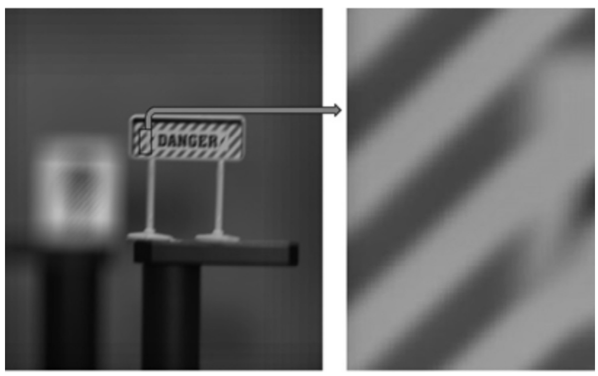
We use all of these elemental images to get the slice images of the 3D scene with 0.2 mm depth interval. In order to get the depth of the warning board, SMD evaluation is carried out and the result is shown in Fig.7. The depth of the warning board can be clearly confirmed at 358.2 mm from Fig.7(a). When the depth varies around the peak value of 358.2 mm, the SMD value will decrease rapidly. It demonstrates that the depth extraction accuracy of the MALT method can reach 0.2 mm. For comparison, the depth is hard to extract by conventional recording method as shown in Fig.7(b). The SMD values for conventional method oscillate within a certain range which means the depth extraction accuracy can't reach 0.2 mm.

The reconstruction results of these two recording methods at the depth of 358.2 mm are shown in Fig.8. From the comparison of two results we can see that not only the depth extraction accuracy has been improved, but also the image quality becomes better.

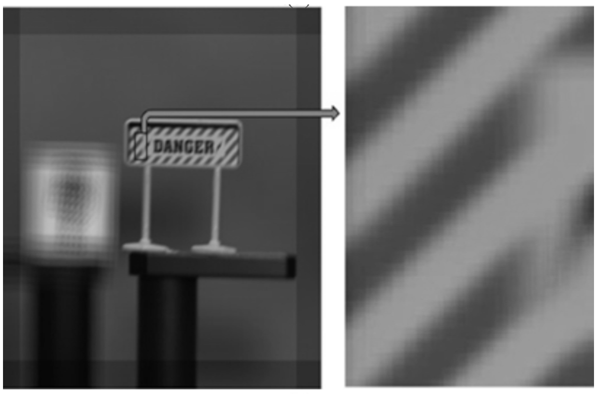


(a) (b)

Fig.7 Curves of SMD varying with depth: (a) Evaluation result with MALT; (b) Evaluation result with conventional recording method



(a)



(b)

Fig.8 The reconstruction results of two pickup methods: (a) MALT; (b) Conventional pickup method

In conclusion, we propose a depth extraction method with high accuracy using MALT in pickup stage, which can decrease the depth interval caused by pixelation of the recording system. From the experimental results we can see that not only the depth extraction accuracy has been improved, but also the image quality of the reconstruction result becomes better by using MALT.

References

[1] J.-H. Park, K. Hong and B. Lee, Appl. Opt. **48**, H77 (2009).

[2] A. Stern and B. Javidi, Proc. IEEE **94**, 591 (2006).

[3] J-H. Park, Y. Kim, J. Kim, S.-W. Min and B. Lee, Opt. Express **12**, 6020 (2004).

[4] D. Shin and B. Javidi, Opt. Lett. **37**, 1394 (2012).

[5] D. C. Hwang, D. H. Shin, S. C. Kim and E. S. Kim, Appl. Opt. **47**, D128 (2008).

[6] J. J. Lee, B. G. Lee and H. Yoo, Appl. Opt. **50**, 5624 (2011).

[7] S. P. Hong, D. Shin, B. G. Lee and E. S. Kim, Opt. Express **20**, 23044 (2012).

[8] J. Y. Jang, J. I. Ser, S. Cha and S. H. Shin, Appl. Opt. **51**, 3279 (2012).

[9] D. C. Hwang, K. J. Lee, S. C. Kim and E. S. Kim, Opt. Express **16**, 3623 (2008).

[10] A. Schwarz, J. Wang, A. Scheme, Z. Zalevsky and B. Javidi, Opt. Lett. **40**, 1814 (2015).

[11] Y. Chen, X. Wang, J. Zhang, S. Yu, Q. Zhang and B. Guo, Opt. Express **22**, 17897 (2014).

[12] T. H. Jen, X. Shen, G. Yao, Y. P. Huang, H. P. D. Shieh and B. Javidi, Opt. Express **23**, 18415 (2015).

[13] S. Kishk and B. Javidi, Opt. Express **11**, 3528 (2003).

[14] J. Wang, X. Xiao, G. Yao, A. Stern and B. Javidi, Journal of Display Technology **23**, 827 (2015).

[15] T. H. Jen, X. Shen, G. Yao, Y. P. Huang, H. P. D. Shieh and B. Javidi, Opt. Express **23**, 18415 (2015).

[16] L. Q. Zhou, X. Zhao, Y. Yang and X. C. Yuan, Opt. Lett. **39**, 2032 (2014).