Double depth-enhanced 3D integral imaging in projection-type system without diffuser*

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Integral imaging is a three dimensional (3D) display technology without any additional equipment. A new system is proposed in this paper which consists of the elemental images of real images in real mode (RIRM) and the ones of virtual images in real mode (VIRM). The real images in real mode are the same as the conventional integral images. The virtual images in real mode are obtained by changing the coordinates of the corresponding points in elemental images which can be reconstructed by the lens array in virtual space. In order to reduce the spot size of the reconstructed images, the diffuser in conventional integral imaging is given up in the proposed method. Then the spot size is nearly 1/20 of that in the conventional system. And an optical integral imaging system is constructed to confirm that our proposed method opens a new way for the application of the passive 3D display technology.

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Compared with other three-dimensional (3D) display technologies of parallax and holograph, integral imaging has many positive characteristics, such as full parallax, quasi-continuous view points, and depth perception with relatively low eye fatigue [1,2]. An integral imaging system often uses a lens array and corresponding elemental images to reconstruct a 3D image, and the elemental images are displayed by flat panel display devices or projectors. Limited by the aperture of the lens array and the resolution of elemental images shown by display devices, viewing-angle and depth-of-field (DOF) of the integrated images are not very good[1,2]. From the principle of the integral imaging, the reconstructed 3D object is around the central depth plane (CDP)[1]. However, the DOF is very small, and many methods are reported to enhance it[3-12]. In recent years, multi-layer is a useful method to enhance the DOF. J. Hong[5] enhanced the image depth of integral imaging by doubling the number of central depth planes by using optical path control. Then multiple display devices are used to enhance DOF[6,7]. They elevated the expressible depth by increasing the number of display devices in a projector-type system or a flat panel display, which is a useful way to enhance DOF in the integral imaging system, but the refresh frequency in the method must be up to the flicker fusion frequency of the human eye (approximately 50 Hz). Another method to enhance DOF is virtual and real mode. Original method is the focus mode of integral imaging. But the spot size of the image point is the pitch of the elemental lens[2]. Y. Kim[9] achieved real and virtual modes on integral imaging simultaneously by the DOF of the single projector, but the parameters in the system must be designed carefully to satisfy the requirement.

In this paper, we propose a double depth-enhanced integral imaging method in a projection-type integral imaging system without a diffuser only by elemental images processing[13,14]. The 3D image is reconstructed in real and virtual images simultaneously in real mode. The real 3D image is reconstructed where the lens array works as an image device, and the virtual 3D image is reconstructed where the lens array works as a refraction device. The principle is also explained in the paper. A special requirement of this proposed method is that the elemental images should be projected by a projector without diffuser to reduce the spot size of the 3D reconstructed virtual image. This double-DOF enhancement is demonstrated by optical experiment. And our proposed method is easy to expand on video of 3D integral imaging system.

In real mode integral imaging system, the distance between elemental images plane and the lens array is g, which is longer than the focus length of the lens array. Limited by the lens law, the reconstructed 3D image is a real image as shown in Fig.1(a), and we call this condition as the real image in real mode (RIRM). Then in the same g, the elemental images are calculated by the computer where the images are reconstructed by the lens

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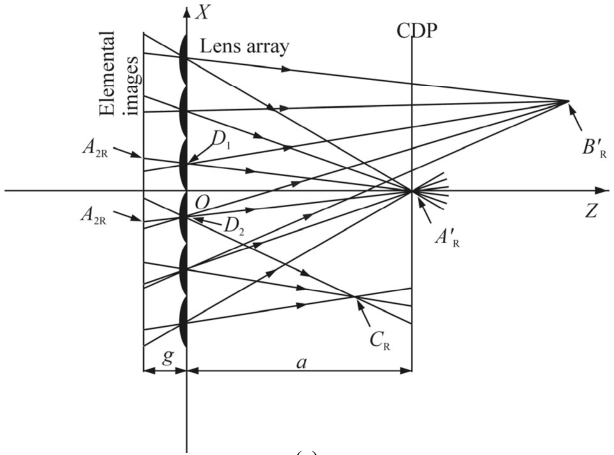
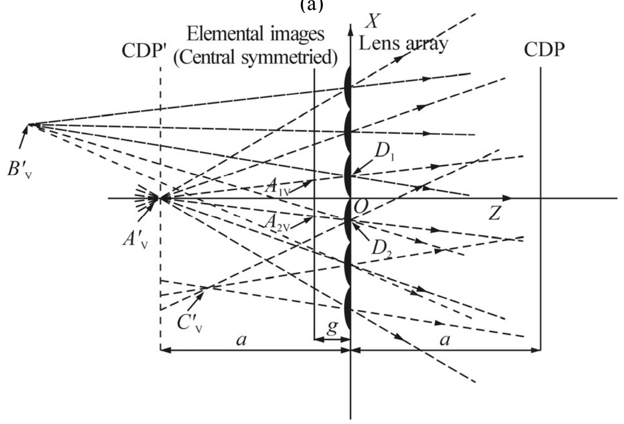
array images in the virtual image space. In this condition, the lens array is used to change the direction of the ray of the corresponding points in the elemental images. In this paper, we call this condition as the virtual image in real mode (VIRM), which is shown in Fig.1(b).



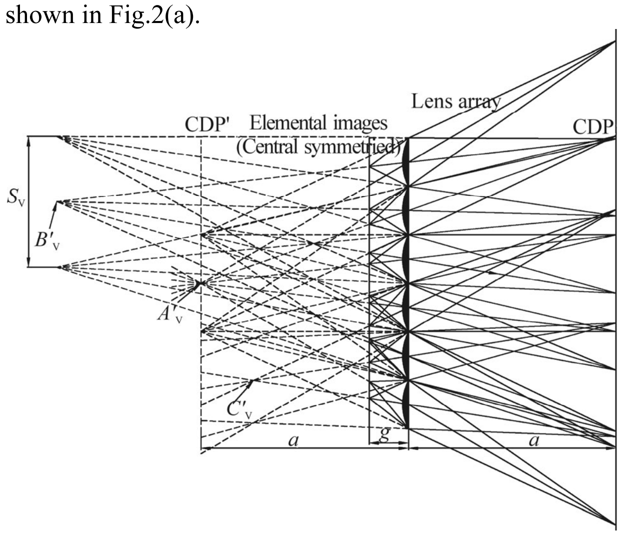
(a)



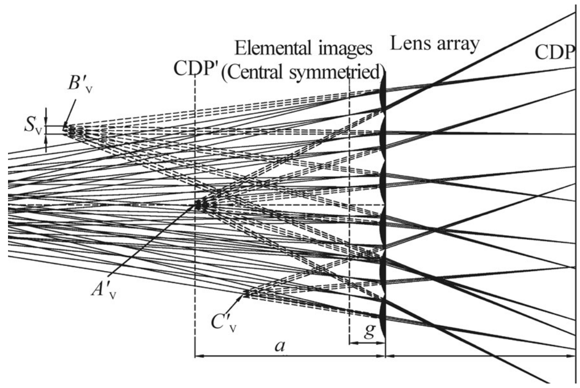
(b)

Fig.1 (a) Real image in real mode and (b) virtual image in real mode

In conventional projection-type integral imaging system, a diffuser is used to display the elemental images. But the diffuser is a disadvantage for the VIRM, which is shown in Fig.2(a).



(a)



(b)

Fig.2 Spot sizes in VIRM (a) with diffuser and (b) without diffuser

In the VIRM with diffuser, the spot size can be calculated as

$$S_v = \frac{p}{a}(l_v + a), \tag{1}$$

where S_v is the spot size of the image point, and l_v is the distance from the image point to the lens array. The spot size is $2p$ on the mirror plane of the CDP in RIRM, and this is too large for application. To solve this problem, the diffuser is removed out as shown in Fig.2(b). And p in Eq.(1) is changed to be

$$p' = \frac{g}{l_p} p_p, \tag{2}$$

where l_p is the distance from projector to elemental images plane, and p_p is the pupil of the projector.

In the projection-type mode without diffuser, the spot size of image point in VIRM can be controlled by l_p and p_p to satisfy the limitation of the system. In the optical experiment, l_p is much longer than g, so p' is much smaller than p. The spot of image point in VIRM in projection-type integral image system without diffuser is nearly 1/20 of that in the conventional system with diffuser as shown in Fig.3.

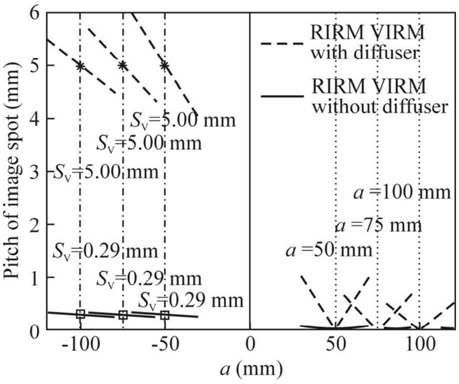


Fig.3 Spot sizes in conventional integral imaging system with diffuser and in direct projected integral imaging system without diffuser

Fig.4 shows the photo of the optical experimental system. A projector and a lens array construct our proposed system. In this experiment, a projector is used to project the elemental images without a diffuser to satisfy the requirement of the VIRM. An additional screen is used to demonstrate that the image of "D_R" is in RIRM mode. The parameters of the experiment are shown in Tab.1.

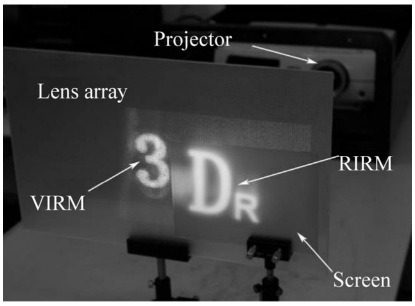
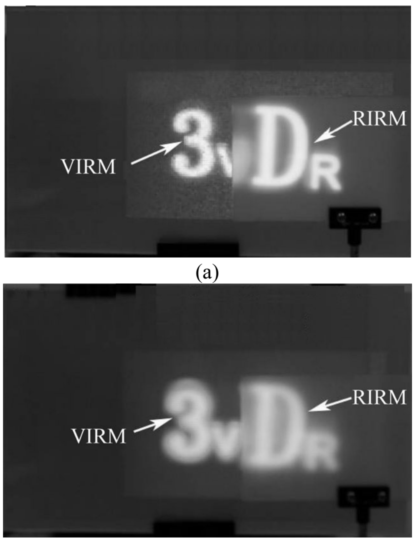


Fig.4 Photo of the optical experimental system

Tab.1 Parameters of the experiment

Parameter	Value
Lens shape	Square
Pitch of element lens	2.5 mm×2.5 mm
Focal length	4 mm
Lens number	128 (H) ×72 (V)
Pixels of element image	15 (H) ×15(V) pixels
p_p	20 mm
l_p	600 mm
g	4.35 mm
a	50 mm

A comparison of VIRM is made between conventional projection-type system with diffuser and the proposed system without diffuser. The result is shown in Fig.5.



(b)

Fig.5 VIRM in (a) proposed integral imaging system without diffuser and (b) conventional integral imaging system with diffuser

The only difference between two systems is the diffuser. As shown in Fig.5, the size of the image point of VIRM in conventional system is much larger than that in the proposed one. The spot size of "3_V" in the conventional system is 5 mm. But in our proposed system without diffuser, the spot size of "3_V" is only 0.29 mm. Multi-viewing point images of the reconstructed 3D object are shown in Fig.6.

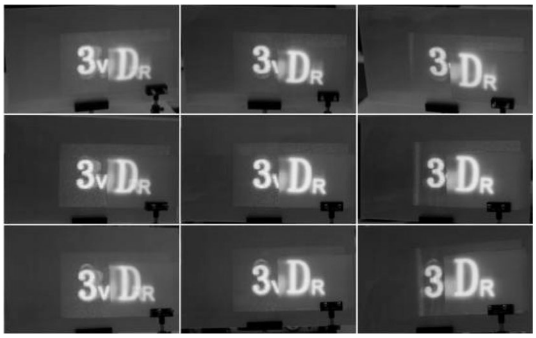


Fig.6 Multi-viewing point images of the reconstructed 3D object by the proposed double depth-enhanced method with VIRM and RIRM

The optical experimental results show that VIRM and RIRM can be used in the projection-type integral imaging system without diffuser. In this mode, the spot size is small enough to enhance the DOF twice. And it can be subjoined to the conventional method, such as a multi-layer (four layers), to enhance the DOF 8 times easily.

In this proposed method, a VIRM and a projection-type integral imaging system without diffuser are formed to enhance the DOF of the integral imaging system. Elemental images for VIRM are central symmetrical with the conventional elemental images. And then the elemental images which are mixed with VIRM and RIRM are projected to the lens array directly. This method can enhance the DOF twice. Corresponding optical experiment is presented to demonstrate the feasibility of the proposed method. And another advantage of this method is that it is easy to be combined with the conventional method, such as a multi-layer, to enhance the efficiency twice.

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