Continuous imaging space in three-dimensional integral imaging*

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(Received 22 August 2012; revised manuscript received 4 November 2012)

We report an integral imaging method with continuous imaging space. This method simultaneously reconstructs real and virtual images in the virtual mode, with a minimum gap that separates the entire imaging space into real and virtual space. Experimental results show that the gap is reduced to 45% of that in a conventional integral imaging system with the same parameters.

Keywords: three-dimensional integral imaging, imaging space

PACS: 42.30.–d, 42.30.Va **DOI:** 10.1088/1674-1056/22/5/054202

1. Introduction

Integral imaging (II)[1,2] is a novel display technology which satisfies the requirement of application.[3–6] II is a three-dimensional (3D) display technology that has many positive characteristics, such as full parallax, quasi-continuous view points, and depth perception with relatively low eye fatigue.[7–14] An integral imaging system uses a lens array and an elemental image display device to reconstruct a 3D image. Many papers reported methods to enhance the depth of field, viewing angle, and other parameters, because of animated technology in 3D display.[7–14] However, the range of imaging space is an important parameter to II display systems. An imaging space is where 3D images can be integrated, which decides the range of space where a 3D image can be displayed in the II systems. In a conventional real image mode (see Fig. 1(a)), both the elemental images and the reconstructed 3D image are real, and the range of the imaging space only encompasses the real imaging space in front of the lens array.[7–12] In a virtual image mode (see Fig. 1(b)), both elemental images and reconstructed 3D image are virtual images, comprising the virtual imaging space at the back of the lens array. It was noted that the real and virtual modes waste nearly half of the entire imaging space.[7–12] The imaging space in the focus mode (see Fig. 1(c))[13] or real and virtual modes (see Fig. 1(d))[14] has been presented to increase the effectiveness of the imaging space. Although in these modes, the imaging space can be nearly completely filled, a gap that divides the continuous space into real and virtual spaces remains. This gap breaks the continuity of a reconstructed 3D image and reduces the efficiency of the whole imaging space.

In this paper, we propose an II method to reduce the gap between the real and virtual imaging spaces. In the method, real and virtual images can be simultaneously integrated in the virtual mode by a projection-type II system that does not need a diffuser. The gap between two regions of space is reduced to a minimum. The optical results confirm the feasibility of the method. It enables diverse applications in the new generation of 3D display technologies.

2. Integral imaging method

The ranges of the imaging space of the four modes are shown in Fig. 1. The reconstructed 3D image is integrated by the rays from adjacent lenses. Therefore, the marginal imaging plane (MIP) is the marginal plane of the imaging space in which the reconstructed 3D images can be displayed and determined by the space where adjacent lenses overlap. The central imaging plane (CIP) is given by the image plane of the elemental image plane, where g is the distance between the elemental images and the lens array, f denotes the focal length of the lens, P pertains to the points on the elemental images, I refers to the image points of P imaged by the lens array, and R represents the reconstructed points integrated by the lens array.

As shown in Fig. 1, the two basic image modes (real and virtual) converts just under half of the entire imaging space. The imaging range of the focus mode is nearly the entire imaging space. However, a gap separates the imaging space into two isolated parts and breaks the continuity. The range of imaging space for different II modes are analyzed and shown in Table 1.

Constrained by the Gaussian imaging formula, the minimum gap between the two imaging regions is $2f$. To reduce the gap between the two parts, we develop a method for simultaneously reconstructing the real and virtual 3D images in the virtual mode. The principle is depicted in Fig. 2, where the

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distance from elemental images to the lens array is g, which is smaller than f. The points at the elemental images are denoted as P. To satisfy the Gaussian imaging formula, I is established as the representation of the imaged points of P as a virtual image. The reconstructed 3D images are integrated into the virtual image, which is referred to as the virtual images in virtual mode (VIVM, see Fig. 2(a)). With the same parameters, the real reconstructed 3D images can be integrated by adjusting the elemental images. Each adjusted point in the elemental images is imaged to virtual points in the CIP, but the integrating points are integrated into the real space. We call this reconstruction process the real image in virtual mode (RIVM, see Fig. 2(b)).

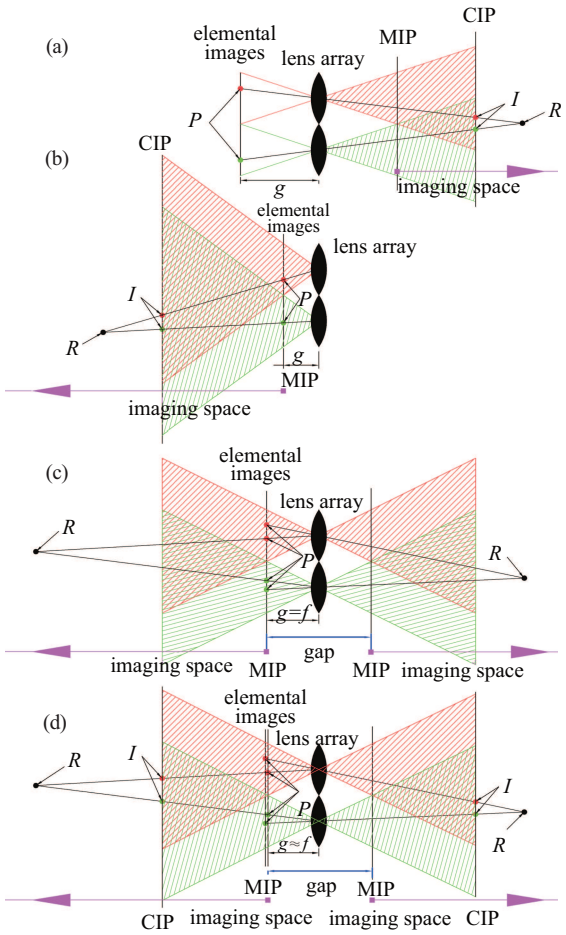


Fig. 1. (color online) Imaging space of different II modes: (a) real mode, (b) virtual mode, (c) focus mode, and (d) real and virtual modes. P denotes the points on elemental images; I denotes the image point of P imaged by the elemental lens; R denotes the integral point of I integrated by len arrays.

Table 1. Imaging ranges of different II Modes.

	Imaging range	Gap
Real mode	$(g, +\infty)$	-
Virtual mode	$(-\infty, -g)$	-
Focus mode	$(-\infty, -f)\cup(f, +\infty)$	$2f$
Real and virtual mode	$(-\infty, -f)\cup(f, +\infty)$	$\approx 2f$

The distance between the integrated point and the lens array is given by

$$l_{\mathrm{R}} = \frac{g\Delta D}{\Delta P - \Delta D}, \tag{1}$$

where ΔD is the pitch between two adjacent lenses, and ΔP is the distance between two adjacent points on elemental images. In this condition, the location of the integrated image depends on ΔP, which can be adjusted in our proposed method. If $\Delta P > \Delta D$, l_{R} is bigger than zero, then the integrated image is displayed as a real image. When $\Delta P < \Delta D$, l_{R} is smaller than zero, then the integrated image is displayed as a virtual image.

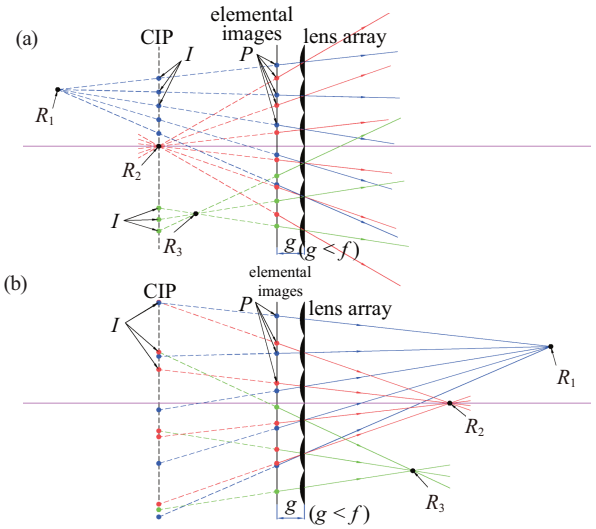


Fig. 2. (color online) Principle of (a) VIVM and (b) RIVM.

In the proposed method, the elemental images for VIVM and RIVM can be combined to obtain real and virtual images simultaneously. The gap generated by the proposed method is depicted in Fig. 3.

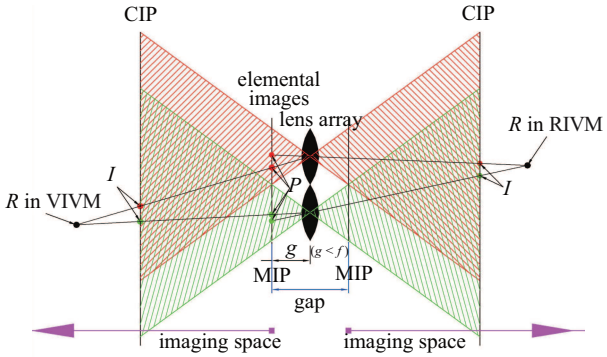


Fig. 3. (color online) Imaging range of our proposed II system.

The gap generated by the proposed method is denoted as $2g$, which is smaller than the gap of the conventional method. The gap can be reduced to zero when g is sufficiently small. This decrease in the gap converts two separate regions into a continuous one. An optical experiment is conducted to test the feasibility of our method. In the experiment, a projection-type II system without a diffuser is used. The distance from

elemental images to the lens array is carefully adjusted to satisfy the requirements for virtual mode operation. The sketch of the optical experiment is shown in Fig. 4. The parameters used in the experiment are chosen: the pitch of element lens is 2.5 mm×2.5 mm, the focal length is 5 mm, the lens number is 128(H) ×72(V), the pixels of element image are 15(H) × 15(V), and $g = 2.26$ mm.

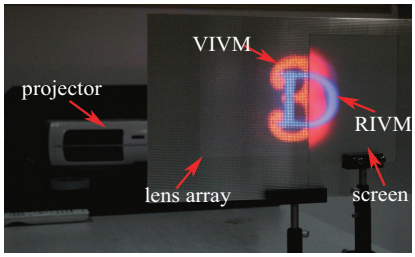


Fig. 4. (color online) Setup of projection-type II system without a diffuser.

In the optical experiment, two characters of "3" and "D" are integrated by our II system. The two characters have different locations as a 3D object crossed the lens array. The character "3" is located behind the lens array, and "D" is located in front of the lens array. The reconstructed "3" is a virtual image in VIVM, indicating that the image cannot be received by a screen. The reconstructed "D" is a real image in RIVM, which means the image can be received by a screen. Figure 5(a) shows the results for the simultaneously reconstructed virtual and real images. The directly observed results for nine viewing points are shown in Fig. 5(b).

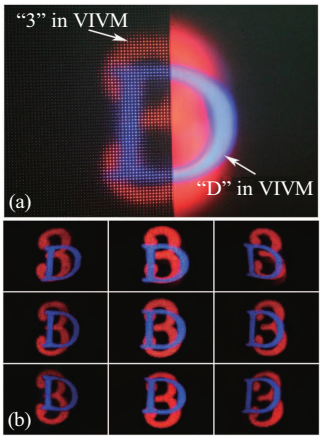


Fig. 5. (color online) Reconstructed (a) 3D image and (b) multi-viewing points .

The number "3", in green color, moves from the virtual imaging space to the real imaging space. The track that the number follows is shown in Fig. 6(a). The elemental images of our proposed method are calculated using a computer. Optical results derived from two methods are shown Fig. 6(b). Figure 6(c) indicates that the wide gap generated by the conventional method breaks continuity and loses information. In our method, the minimal gap brings the separated parts together. This gap is only 45% of that generated by the conventional method.

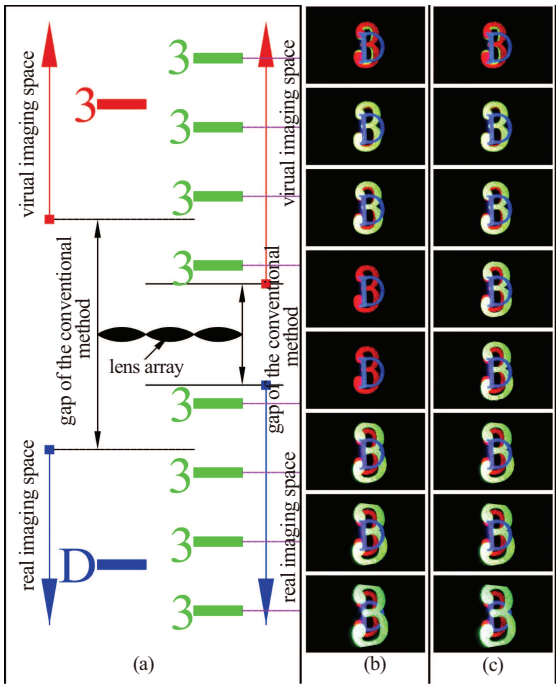


Fig. 6. (color online) (a) Sketch of the optical experiment; (b) images reconstructed by conventional method; (c) images reconstructed by proposed method.

3. Conclusions

In conclusion, we have proposed an II method of reconstructing a continuous imaging space. In contrast to the conventional II system, which has a separated imaging space, the proposed method can simultaneously reconstruct real and virtual images, and reduce the gap between two regions of imaging space to a minimum, linking the divided regions together. When g is 2.26 mm, optical results show that the gap in the II method is reduced to 4.52 mm which is 45% of 10 mm (twice of focus length) that is generated by the conventional approach. The proposed II method effectively enhances the typical imaging space ratio and provides new opportunities for expanding the applications of II technologies for 3D display.

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