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Magnified augmented reality 3D display based on integral imaging

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ABSTRACT

In this paper, we propose a magnified augmented reality (AR) 3D display based on integral imaging (II). A micro II display unit reconstructs a micro 3D image, and then the mciro-3D image is magnified by a convex lens. The lateral and depth distortions of the magnified 3D image are analyzed and resolved by the pitch scaling and depth scaling processes. The magnified 3D image and real 3D scene are overlapped by using a half-mirror to realize AR 3D display. In the experiments, a prototype of magnified AR 3D display based on II is developed, and it shows good AR 3D visualization with high fidelity.

1. Introduction

Augmented reality (AR) display allows the overlaying of virtual two-dimensional (2D) or three-dimensional (3D) images on viewer's real world view so that the 2D or 3D images seamlessly blend into the real 3D scene [1–3]. AR display can greatly enhance the viewer's perception of reality, so it has been widely used in many fields, such as medicine [4,5], architecture [6], military and even daily life [7,8]. For example in the oral surgery, the overlay of a wisdom tooth (real 3D scene), tooth roots and nerve channels (virtual 2D or 3D images) are presented to the surgeon through the AR display system. Surgeons could perform operations safely by avoiding damage to the tooth roots and nerve channels with the help of the in situ image overlay. In the war, AR display may allow the soldiers to receive the military instruction and battlefield maps which blend into the live battlefield environment. In a car, the driver can see the navigation information while driving.

The monocular AR displays, such as Google Glass, only can superimpose 2D images on real 3D scene, in which images cannot be displayed with the same depth as real objects. Binocular stereoscopic AR displays can superimpose 3D images on real 3D scene, but the accommodation-convergence discrepancy causes visual fatigue. Integral imaging (II) which can reconstruct 3D image which is the same as the original 3D object without visual fatigue is a good candidate for AR display. Recently, several optical see-through AR 3D displays based on II have been developed [5,9–12]. An integral floating AR display system in which a convex half mirror effectively reduces the pixel pitch of the display panel and extends the expressible range of the 3D image is proposed [13]. However, to implement the compact AR 3D display, the II display unit should be miniaturized. However, the 3D image reconstructed by the miniature II display unit is too small to be suitable for overlapping with the real 3D scene. An optical see-through head-mounted display is proposed by combining the emerging freeform optical technology and microscopic integral imaging [14]. Though the micro II 3D image is magnified by the wedge-shape freeform prism, the 3D image distortion remains to be investigated. Especially for surgical navigation application, the 3D image is expected to have the same geometric shape as the original organ. An approach to achieve magnified AR 3D display based on II with high geometric fidelity is investigated in this paper.

2. Principle of the proposed magnified AR 3D display

In this paper, we propose a magnified AR 3D display based on II with high geometric fidelity. It includes a micro II display unit, a convex lens and a half-mirror, as shown in Fig. 1. The micro II display unit contains a micro-EIA and a micro-MLA, and creates a micro 3D image. The micro II display unit locates within the focal length of the convex lens, so the micro 3D image is magnified by the convex lens. The rays from the magnified 3D image are reflected into the viewer's eye by the half-mirror while the rays from the real 3D scene are transmitted through the half-mirror. So the magnified 3D image overlaps with the real 3D scene in viewer's eyes, and the AR 3D perception is achieved.

The distortions of the magnified 3D image include the lateral distortion and the depth distortion. Fig. 2 shows the generation of the lateral distortion. Here, we ignore the half-mirror because the half-mirror doesn't cause distortion. The micro-EIA, the micro-MLA and the micro 3D image are all within the focal length of the magnifying

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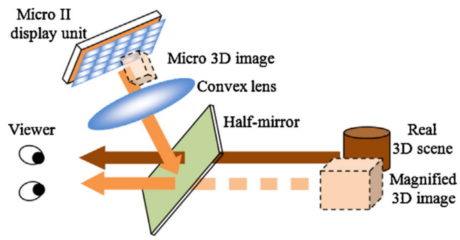

Fig. 1. Schematic diagram of the proposed AR 3D display based on II.

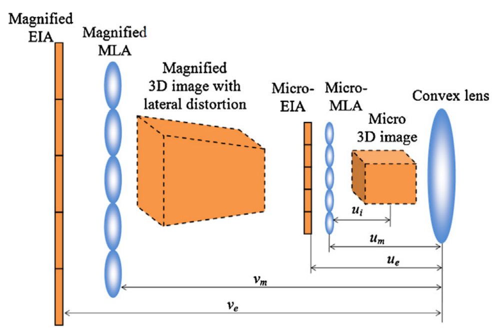

Fig. 2. Generation of the lateral distortion.

lens. Based on the Gauss image formula, the lateral magnification of the *i*th depth plane of the micro 3D image can be deduced as

$$M = \left|\frac{F}{F - u_i}\right|, \tag{1}$$

where | | denotes the absolute value, u_i is the distance between the *i*th depth plane of the micro 3D image and the convex lens, and F is the focal length of the convex lens. From Eq. (1) we can see that different depth planes of the micro 3D image has different lateral magnifications, and the depth plane which is closer to the focal plane has larger lateral magnification. So the lateral size of the magnified 3D image is distorted, as shown in Fig. 2.

In the proposed AR display, the micro-MLA and micro-EIA are also magnified by the convex lens, and the magnified MLA and magnified EIA form the magnified II display. Since the magnified 3D image can be considered to be reconstructed by the magnified II display, we analyze the lateral magnifications M_m and M_e of the magnified MLA and magnified EIA, which are

$$M_m = \left|\frac{F}{F - u_m}\right|, \tag{2}$$

$$M_e = \left|\frac{F}{F - u_e}\right|, \tag{3}$$

where u_m and u_e are the object distances of the micro-MLA and micro-EIA, respectively, and $u_m < u_e < F$. So the pitches of the magnified MLA $p_m{}'$ and magnified EIA $p_e{}'$ can be expressed as

$$p'_m = M_m p_m, \tag{4}$$

$$p'_e = M_e p_e, \tag{5}$$

where p_m and p_e are the pitches of the micro-MLA and micro-EIA, respectively. Generally, the pitches of the MLA and EIA are identical in the conventional II display, that is $p_m = p_e$. Since $u_m < u_e$, from Eqs. (4) and (5), we can get $p_m{}' < p_e{}'$. So the magnified EIA is larger than the magnified MLA. We know that when the pitches of the EIA and MLA are different, the lateral distortion exists in the reconstructed 3D image. So we propose the pitch scaling of the micro-EIA in the micro II display unit to resolve the lateral distortion problem. The pitch of the micro-EIA should be scaled by the factor K_e,

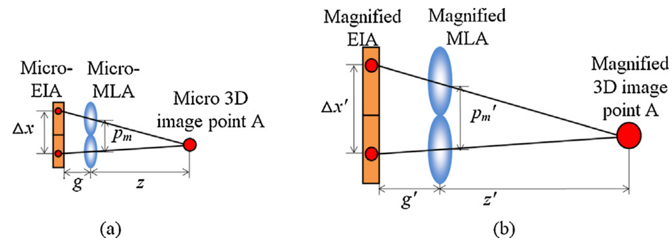

Fig. 3. Depth of the 3D image point. (a) Micro-II display, and (b) magnified II display.

$$K_e = \left|\frac{F - u_e}{F - u_m}\right|. \tag{6}$$

In this way, though the micro-MLA and micro-EIA have different pitches, the magnified EIA and magnified MLA could have the same pitches after the pitch scaling. So each depth plane of the magnified 3D image has the same lateral magnification, and the lateral magnification of the magnified 3D image is equal to the magnification of micro-MLA M_m.

Fig. 3(a) and (b) shows the depths of the 3D image point in the micro II display and magnified II display, respectively. Based on the geometric relationships, the depths of the 3D image point A in micro II display z and magnified II display z' can be expressed as

$$z = \frac{p_m g}{\Delta x - p_m}, \tag{7}$$

$$z' = \frac{p'_m g'}{\Delta x' - p'_m}, \tag{8}$$

where Δx and $\Delta x'$ are the parallax values between two adjacent homologous pixels in the micro-EIA and magnified EIA, g and g' are the distances between the EIA and MLA in micro II display and magnified II display, respectively.

However

$$\Delta x' = K_e M_e \Delta x = M_m \Delta x. \tag{9}$$

Combine Eqs. (4), (7)–(9), we can get

$$z' = \frac{g' z}{g}. \tag{10}$$

So, the longitudinal magnification M_z is

$$M_z = \left|\frac{z'}{z}\right| = \left|\frac{g'}{g}\right| = \left|\frac{v_e - v_m}{u_e - u_m}\right|, \tag{11}$$

where v_m and v_e are the image distances of the magnified MLA and magnified EIA. Since

$$v_m = \frac{u_m F}{u_m - F}, \tag{12}$$

$$v_e = \frac{u_e F}{u_e - F}, \tag{13}$$

Combine Eqs. (11)–(13), we can get

$$M_z = \left|\frac{-F^2}{(u_m - F)(u_e - F)}\right|. \tag{14}$$

Generally, $M_z \neq M_m$. We define the ratio between longitudinal magnification and lateral magnification as the depth distortion factor, denoted as K_z:

$$K_z = \frac{M_z}{M_m} = \left|\frac{F}{u_e - F}\right|. \tag{15}$$