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Analysis on pixel number of elemental image in integral imaging 3D display

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ABSTRACT

We analyze the effect of pixel number of elemental image on the resolution and depth of focus in depth-priority integral imaging display. By modeling the pupil as a thin lens, we simulate the retinal image received by an observer's one eye in four situations according to the principle of geometrical optics. A subject test is carried out to find the minimal pixel number to maintain the resolution and depth of focus of 3D images. The experimental results show how the resolution and depth of focus are degraded as the decreasing of pixel number of elemental image. When the pixel number of elemental image is 36 × 36 or higher, high-quality 3D images could be produced by the integral imaging 3D display.

1. Introduction

Integral imaging (II) is one of the most attractive and convenient methods in three-dimensional (3D) display field, because it does not require any special glasses and can provide 3D images that have full color and both horizontal and vertical parallaxes [1]. However, since II was brought out by Lippmann in 1908 [2], it suffered from several drawbacks such as the resolution and depth of focus of the reconstructed 3D images. Several attempts have been made to obtain higher quality 3D images [3–10]· The resolution of II is the resolution of the reconstructed 3D image. The maximum viewing spatial frequency is treated as the resolution of II [11]; the resolution of II is defined as the reciprocal of the spot size on the central depth plane [12]. The depth of focus of II is defined as the thickness of the reconstructed 3D image around the central depth plane (CDP). The 3D image is increasingly broken and distorted as it is located farther from the central depth plane.

The reconstructed 3D images are sampled by a micro-lens array (MLA), so the number of micro-lenses (MLs) determines the upper limit of resolution [13]. The number of pixels in each elemental image (EI) affects the resolution of 3D images away from the MLA. If there are only a few pixels per EI, it becomes difficult to reconstruct a 3D image with depth [14]. However, the total number of pixels that the display device requires is the product of the number of EIs and the pixel number of EI horizontally or vertically. Thus, extremely high resolution is required for displaying. The effects of the finite number of pixels in EIs on the resolution and depth of focus of 3D images is discussed, and theoretically derived the minimal pixel number of EI to maintain the depth of focus of reconstructed 3D images [15].

However, the resolution that we derived has been used as the resolution of II, it does not indicate the resolution of the image that the observer actually views [11]. In this paper, we analyze the effect of pixel number of EI on the resolution and depth of focus in a depth-priority II by simulating the retinal image according to the principle of geometrical optics. Then, we

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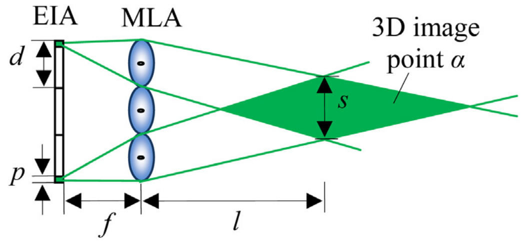

Fig. 1. Reconstruction of a 3D image point.

carry out a subject test to derive the minimal pixel number of EI to maintain the resolution and depth of focus of 3D images. To simplify the mathematical expressions, we assume one-dimensional II. The results obtained can be easily expanded to two-dimensional II.

2. Principle of the proposed method

2.1. Resolution and depth of focus of 3D images

The depth-priority II is accomplished by setting the distance between the MLA and the elemental image array (EIA) being equal to the focal length f of ML, and it is assumed that the CDP is located on the MLA. The pixel pitch of the display device is p, and the pitches of the ML and EI are both d. So the pixel number r of EI can be expressed as:

$$r = \frac{d}{p} \tag{1}$$

Then, we confirm the spot size of the 3D image point. As shown in Fig. 1, the two pixels in two different EIs are homonymous pixels. The light rays emitted from the two homonymous pixels are refracted by their corresponding MLs, then they reconstruct a 3D image point α, and the spot size s is [15]:

$$s = \frac{lp}{f} + d \tag{2}$$

where l is the depth of the 3D image point. The resolution R_I of the 3D image is the reciprocal of s:

$$R_I = \frac{f}{lp + fd} \tag{3}$$

From Eq. (3), we can see that the 3D images which are closer to the CDP will have higher resolution while they are increasingly blurred as they are located farther from the CDP [16].

For the depth-priority II, the depth of focus $\triangle z_m$ is expressed as [12]:

$$\Delta z_m = \frac{2fd}{p} \tag{4}$$

Assuming the pitch d and the focal length f of ML to be fixed values, the resolution R_I and depth of focus $\triangle z_m$ of 3D images increase as the decreasing of pixel pitch p of the display device. In other words, the large number of pixels in EI increases the resolution and depth of focus of 3D images.

2.2. Analysis of retinal images

We discuss the effect of pixel number on the resolution and depth of focus of 3D images by simulating the retinal image according to the principle of geometrical optics. For simplicity, we assume that the II 3D display contains only one EI and one ML. The pupil is modeled as a thin lens with an aperture and the retina is modeled as a flat plane [17], as shown in Fig. 2. The light rays emitted from a pixel are refracted by its corresponding ML and spread in space. At the standard viewing distance, the rays are received by an observer's one eye. Generally speaking, the standard viewing distance L is six times the height of the display device. As shown in Fig. 2, based on the retinal image received by the observer's eye at the standard viewing distance, we simulate the retinal image of 3D image point in four situations: (1) $s = e$, (2) $s < e$, (3) $s > e$, (4) $s \geq E$, where e is the pupil diameter and E is the interpupillary distance. Typically, the pupil diameter e of the eye is about 3 mm, and the interpupillary distance E is about 65 mm. We analyze the four situations in detail.

In situation (1), the observer's eye just receives one pixel's information from each EI, as shown in Fig. 2(a). This situation only happens under the condition that the pitches of the EI and ML are less than the pupil diameter. We obtain the pixel number r_o of EI and the pixel pitch p_o as follows:

$$r_o = \frac{dL}{f(e-d)} \tag{5}$$