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Performance analysis of three-dimensional integral imaging systems based on human vision

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ABSTRACT

In order to improve the assessment accuracy in three-dimensional integral imaging (3DII) in terms of avoiding misjudgments and facilitating choice-making, we propose a method to analyze performance of the 3DII systems based on human visual characters. The contrastive parameters are defined by calculating ratios of resolution and depth of the optical systems to those of the human vision respectively, which can present distinguishable visual difference between the 3DII systems with equivalent optical performance. Our analysis results indicate that the size of the lens array is closely related to the contrastive parameter of resolution. Furthermore, we also carry out experiments to verify consistency and reliability of the results for two different sets of 3DII systems as proposed in the study.

1. Introduction

Three-dimensional display is classified into two types: stereoscopic and autostereoscopic 3D display [1]. Compared with the stereoscopic 3D display that special glasses required, the autostereoscopic technique is for naked eye 3D display without visual fatigue or headache, which is also called true 3D display. As one of the promising state-of-the-art 3D display technologies, integral imaging (II) could provide many practical advantages: full parallax and continuous viewing points; no coherent or special illumination required; compact system configuration and simple implementation [2,3].

These unique advantages of integral imaging technology attract great attentions in the past decades. For the purpose of improving resolutions [4,5] and depth of field [6,7] of the 3DII display, many ways and methods were proposed. However, compared with great improvement of image quality, there is no specific standard or assessment for the 3DII technology up to date, resulting in difficulties in evaluation and choice-making. Though some methods were reported to evaluate 3D image reconstructed by 3DII systems, such as Mean Square Error (MSE) [8], Mean Structural Similarity Index (MSSIM) [9,10] and the Peak-Signal to Noise Ratio (PSNR) [11], they only focus on the performance of optical systems, which may be different from the real visual performance. In this case, people have to face the situation sometimes that there is no obvious difference in the resolution or depth of two 3DII systems, according to the parameters of optical systems, while the differences in practical visual performance are great. Such a problem may lead to misjudgments, which are made by considering optical system parameters only. Since human eyes are the real final detectors of the three-dimensional images, performance analysis of 3DII systems based on human visual characters is crucial to establish an effective and objective standard or assessment for different applications, which is needed urgently by the researchers and industry. Unfortunately, this problem received little attention in literature in the past years.

In this paper, we propose a method to analyze the performance of different three-dimensional integral imaging systems based on human visual characters. By comparing the resolution and depth of three dimensional integral images with those of human eyes, noticeable differences of two 3DII systems are distinguished. Experimental results verify the efficiency and the feasibility of this analysis method.

2. Performance of the three-dimensional integral imaging optical system

The technology of integral imaging uses elemental images to record 3D object information from different perspectives by a lens array or camera array. When reconstructed, according to the reversible principle of light, the lens array is positioned in front of the elemental images which are shown on the display device, and then the 3D image is replayed in the original position as shown in Fig. 1 [12].

No matter optical or computational techniques are implemented in II systems, resolution and depth are two important parameters to characterize the performance of 3DII systems. These parameters are illustrated in Fig. 2, where p is the lens aperture size, g the distance between the display device and reconstructed

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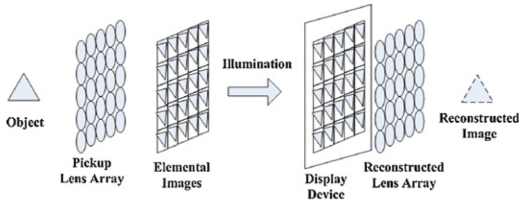

Fig. 1. Principle of 3DII.

lens array, a the distance between the reconstructed lens array and reconstructed image, D the depth of field, L viewing distance and δ_i is the pixel size of the image.

2.1. The resolution of 3DII optical system

Ideally, according to the geometric relationships, the ideal resolution R_{i1} is given by [13]

$$R_{i1} = \frac{g}{a\delta} = \frac{g}{a} R_D \tag{1}$$

where δ and R_D represent the pixel size and resolution of the display device respectively. In reality, however, due to diffraction of the elemental lens and other limitations of the lens array and recording device, it is hard to obtain the above ideal performance. Taking the Airy disk and Rayleigh limit [14] into account, the diffraction resolution R_{i2} can be expressed as

$$R_{i2} = \frac{p}{2\lambda a} \tag{2}$$

where λ is the wavelength of light. Like most imaging systems, the resolution of 3DII optical system R_i is determined by both ideal case and diffraction limit, then we can get

$$R_i = \frac{1}{(1/R_{i1}) + (1/R_{i2})} \tag{3}$$

If the physical resolution of display device is higher, R_{i1} is comparable with R_{i2} and R_i is calculated as Eq. (3); while if the physics resolution is relatively low, R_{i1} is far less than R_{i2} and thus R_i is approximately equal to R_{i1}.

2.2. The depth of 3DII optical system

The calculation of depth of field is similar to the resolution's. The ideal depth of field D_{i1} is [13]

$$D_{i1} = 2\frac{a}{p}\delta_i \tag{4}$$

and the diffraction depth of field D_{i2} is [14]

$$D_{i2} = 4\frac{\lambda a^2}{p^2} \tag{5}$$

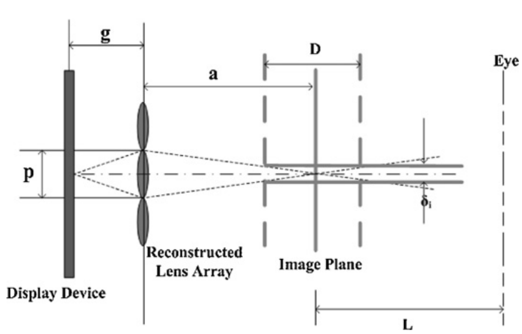

Fig. 2. 3DII system display parameters.

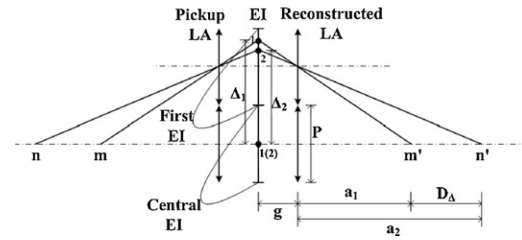

Fig. 3. Principle of the depth of reconstructed image.

The above is the traditional meaning of 3DII depth of field described in the most of literatures. However, what we are more concerned is the depth of two or more images reconstructed by the 3DII system, that is to say, the distance between different reconstructed objects in the image space. Here we call it the depth of reconstructed image denoted as D_Δ in Fig. 3, as well as, m and n represent two points in the object space respectively while their corresponding reconstructed imaging points are m' and n'. The point 1 is the imaging point of m in the adjacent elemental images and the point 2 is the ones of n. The cognominal points spacing means the distance of points imaged by the same object point in different elemental images. Δ_1 and Δ_2 are the cognominal points spacing of m and n between the central elemental image and the first one.

From the Fig. 3 we can get

$$\frac{\Delta_1}{p} = \frac{g + a_1}{a_1} \tag{6}$$

$$\frac{\Delta_2}{p} = \frac{g + a_2}{a_2} \tag{7}$$

Therefore, the depth of reconstructed image D_Δ could be expressed as

$$D_\Delta = a_2 - a_1 = pg\frac{\Delta_1 - \Delta_2}{(\Delta_1 - p)(\Delta_2 - p)} \tag{8}$$

3. Human visual characters

Eqs. (1)–(8) indicate that the performance of 3DII systems correlate to the parameters of elemental lens only and have nothing to do with the size of the whole lens array, especially the resolution R even has no reference to the elemental lens aperture in ideal case. This may lead to the performance of 3DII systems with different size of lens array undistinguishable. However, for the best viewing case, the size of lens array determines the viewing distance which will affect the visual perception, such as viewing resolution and depth. With respect to this point, we should analyze and distinguish the performance difference of 3DII systems based on human visual characters, which are described as follows:

3.1. Visual resolution

According to the diffraction theory, the angle resolution ω of human eyes is given as follow:

$$\omega = \frac{1.22\lambda}{d} \tag{9}$$

where d is the pupil diameter and λ is the wavelength. In good lighting conditions, the angle resolution is about 1′ [15].

Human eyes have higher resolution ability only in the central part of vision scope, which is called resolution view field, whose value is about 15° normally [16]. We can get best viewing effect in aspects of resolution and comfort when the resolution view field is filled with display image. Accordingly, the corresponding best