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Passive lighting responsive three-dimensional integral imaging

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ABSTRACT

A three dimensional (3D) integral imaging (II) technique with a real-time passive lighting responsive ability and vivid 3D performance has been proposed and demonstrated. Some novel lighting responsive phenomena, including light-activated 3D imaging, and light-controlled 3D image scaling and translation, have been realized optically without updating images. By switching the on/off state of a point light source illuminated on the proposed II system, the 3D images can show/hide independent of the diffused illumination background. By changing the position or illumination direction of the point light source, the position and magnification of the 3D image can be modulated in real time. The lighting responsive mechanism of the 3D II system is deduced analytically and verified experimentally. A flexible thin film lighting responsive II system with a 0.4 mm thickness was fabricated. This technique gives some additional degrees of freedom in order to design the II system and enable the virtual 3D image to interact with the real illumination environment in real time.

1. Introduction

The interaction between virtual 3D images and the real world is critical for 3D display technology. Lighting responsive imaging techniques play a role in bridging virtual 3D images and the real illumination environment. To display lighting responsive images, Nayar et al. used a camera to detect the user defined 2D illumination information first, then rendered and output a corresponding 2D image in real time [1]. Later, to improve the reality of the image, a lens array was used to measure a 4D illumination light field first and then the relit 3D image was displayed using integral photography [2,3]. An 8D reflectance field display system was also demonstrated to display illumination responsive scenes [4]. Unlike these active lighting responsive display techniques, a passive lighting responsive display system uses optical setups to control the reflection of environmental light. Thus, passive lighting display systems are independent of illumination sensors and rendering engines, which makes it not only energy-efficient, but also portable. Holographic and non-holographic systems are two widely used passive lighting responsive display systems. Holographic systems use a holographic stereogram or a volume hologram to record and reproduce the light field from multiple illumination directions [5–9]. Non-holographic systems use a bidirectional reflectance distribution function (BRDF) to render lighting responsive images [10–12]. There are two types of non-holographic systems. One is a micro-structure based lighting responsive image; the other is an integral imaging inspired lighting responsive image. Micro-structure based images use micro-facets or high resolution micro-patterns to make a custom BRDF and to obtain a desired surface [13,14]. Integral imaging inspired images use multi-layer structures to display a predefined image or mimic the object's physical surface [15,16].

In this work, a type of passive lighting responsive 3D II system, with novel lighting responsive phenomena, has been designed and demonstrated. As the on/off state, position, direction or the number of light sources is varied, the corresponding transformed 3D images appear immediately. The lighting responsive mechanism of the 3D II system was deduced analytically and verified experimentally. The advantages of these lighting responsive 3D II systems include the following: (i) The 3D performance can be used to adapt or augment a real environment; (ii) The illumination environment and 3D performance can be predesigned interactively; (iii) The 3D transform process is optical and in real time; (iv) The system is free from electronic devices and is economical and saves energy.

2. Principle

2.1. Structures of conventional II and proposed II systems

The typical structure of a conventional II system consists of a lens array, elemental image array and diffused backlight. The elemental image array is set near the focal plane of the lens array [17,18], as shown

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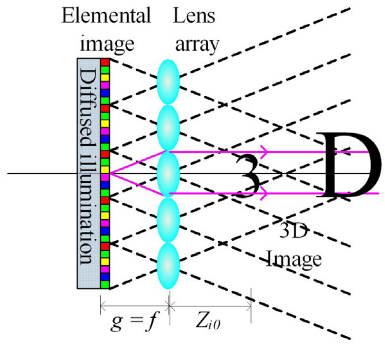

Fig. 1. Schematic of the conventional 3D II system.

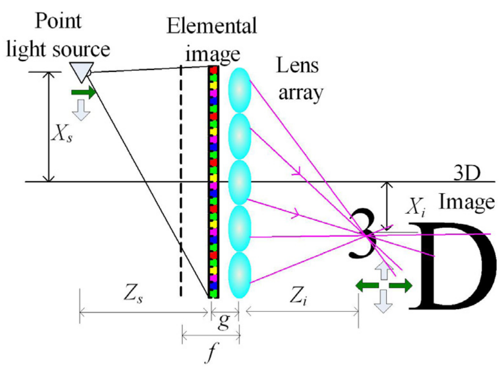

Fig. 2. Schematic of the proposed lighting responsive II system.

in Fig. 1. The diffused backlight is used to illuminate the elemental image array. Light rays from the backlight go through the pixels of the elemental image array and then are focused by the lens array. These light rays from one pixel will become a collimated beam with a specific angle. These beams will synthesize a 3D image in the space, as the characters marked '3D' in Fig. 1. In such a system, the 3D images cannot be updated until the elemental image array is refreshed. Furthermore, if the elemental image array is out of the focus of the lens array, the 3D images will defocus and disappear.

In contrast to the conventional II system, a point light source is used in the proposed lighting responsive II system, as shown in Fig. 2. The point light source can be configured as a part of the II system or a part of a user defined illumination environment. The elemental image array is set at a distance g from the lens array, which is out of the focal plane of the lens array. These different configurations not only give some additional degrees of freedom to the design of the II system, but also enable the II system to respond to the illumination environment automatically. When the point light source is turned on, a 3D image appears in the space. When the point light source is turned off, the 3D image disappears even under bright diffused illumination conditions. When the position and direction of the point light source are changed, the 3D image is scaled and translated in real time. If multiple light sources are lit up, multiple copies of transformed 3D images are displayed simultaneously.

2.2. *Lighting responsive mechanism of the proposed II system*

To simplify the system, one point light source is used to illuminate the II system. The relations among the point light source, II system, and 3D image are illustrated in Fig. 2. The point light source is set to Z_S axially away from the lens array and X_S transverse from the axis. The II system shows a scaled and translated 3D image at the coordinates of (X_i, Z_i), although the elemental image array is the same as that used in a conventional II system that synthesizes a 3D image at a distance, Z_{i0}, away from the lens array, as shown in Fig. 1. If we change parameter Z_S of the point light source, the 3D image will be scaled. In the same way, if we change the parameter X_S, the 3D image will be translated. According to the geometrical relationship between the light source and 3D image, the relation between parameters Z_S and Z_i is given by

$$Z_i = \frac{f}{1 - \frac{Z_{i0}\left(1+\frac{g+f}{Z_s}\right)}{(Z_{i0}+f)\left(1+\frac{g}{Z_s}\right)^2}}, \tag{1}$$

where f is the focal length of the lens array. The transverse magnification, M, of the 3D image relative to that generated by the conventional II system is given by

$$M = \frac{f}{Z_{i0} - \frac{Z_{i0}^2\left(1+\frac{g+f}{Z_s}\right)}{(Z_{i0}+f)\left(1+\frac{g}{Z_s}\right)^2}}. \tag{2}$$

The relationship between X_s and X_i is given by

$$X_i = \left(\frac{f+Z_i}{Z_S+g} - \frac{gZ_i}{Z_S f}\right) \cdot X_s, \tag{3}$$

where g is the distance between the elemental image array and lens array. In most II systems, the value of g is the same of the order as the focal length of the lens array. Parameters Z_S and Z_i satisfy $Z_S \gg g$ and $|Z_i| \gg g$. According to Eq. (3), when $Z_S \gg g$ or Z_S trends to infinity, the equation can be simplified as

$$X_i = \left(f + Z_i - \frac{gZ_i}{f}\right) \cdot \tan(\theta), \tag{4}$$

where θ is the illumination acute angle between the axis and the line connecting the point light source and the center of the lens array.

Eqs. (1) and (2) show that both the axial position and magnification of the 3D image are functions of the illumination parameter, Zs, when parameters, g, f and Z_{i0}, are fixed. That is to say, the size and axial position of the 3D image in the proposed II system respond to the axial position of the illumination light source automatically. In practice, parameter Zs can be easily changed by selectively activating light sources, such as LEDs arranged in different axial positions.

According to Eq. (1), there is a singularity where the denominator in the right hand side (r.h.s.) of the equation tends to zero and Z_i approaches infinity. In the singularity, the value of the axial parameter, Zs, is defined as Zs_0. The singularity divides parameter Zs into two parts: when $Zs > Zs_0$, and image distance $Z_i > 0$, there will be a real 3D image in front of the lens array; when $Zs < Zs_0$, and the image distance $Z_i < 0$, there will be a virtual 3D image at the back of the lens array. This means that a real/virtual 3D image will be transformed into a virtual/real 3D image when the axial position of the light source crosses the singularity. In addition, the 3D image's axial direction of motion is the same as that of the light source. According to Eq. (2), when the elemental image array sits on the focal plane of the lens array, i.e., $g = f$, and the II system meets the conditions $Z_S \gg g$ and $|Z_i| \gg g$, the value of M is fixed to 1. This is why, in conventional II systems, the 3D image cannot respond to the axial position of the illumination light source.

Eqs. (3) and (4) show that the transverse position of a 3D image is a function of the illumination parameter, X_S or θ, when parameters, g, f and Z_i, are fixed. This means that the transverse position of the 3D image responds to the point light source's transverse position or the illumination angle. In practice, parameters X_S or θ can be tuned by moving a LED transversely or selectively lighting up LEDs in different transverse positions. The illumination angle, θ, can also be tuned by sunlight, the illumination angle of which varies as time goes by. This means that the proposed II system can respond to a user defined or natural illumination environment.

According to Eq. (3), when the elemental image array sits on the focal plane of the lens array, i.e., $g = f$, and the II system meets