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Integral Imaging System using Locally Controllable Point Light Source Array

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Abstract

An integral imaging system can be utilized for many three-dimensional (3D) imaging applications. However, improvement in display performance, such as resolution and viewing angle, is generally difficult because a large amount of image information is required. Therefore, we propose an integral imaging system using a locally controllable point light source array. In this system, point light sources with the desired light distribution angle, light direction, and light-diffusing states are generated as a local backlight through the projection of a predetermined image pattern. An integral 3D image with an enhanced viewing angle can be reproduced by controlling the light distribution of each point light source in time division and displaying the corresponding elemental images on a liquid-crystal display (LCD). Moreover, a high-resolution two-dimensional (2D) image can be reproduced on the entire or partial region of the display screen by generating diffused light in predetermined areas. In this study, a prototype display system was developed and experimentally evaluated to demonstrate the enhancement of the horizontal viewing angle from 14.2° to 28.0°. Furthermore, we confirmed the possibility of partially switching between 3D and 2D images.

Introduction

Integral imaging is an autostereoscopic method based on "integral photography," which was invented by Lippmann in 1908 [1]. This method has a wide variety of three-dimensional (3D) imaging applications, such as 3D television, because it can reproduce 3D images with smooth motion parallaxes in both horizontal and vertical directions without special glasses. Several studies investigated the techniques for displaying and capturing 3D images [2, 3].

In a typical integral imaging system, a lens array comprising many small lenses is placed in front of a display device. A 3D image can be reproduced by displaying the corresponding elemental images on the display device. However, it is difficult to enhance the image quality using a single display device. A large amount of image information is required to improve the display performance, such as resolution, viewing angle, and depth range. Presently, methods for enhancing image quality, such as using multiple display devices [4, 5] or controlling the added mask layer in time division [6, 7], are reported in many studies. However, the display system becomes too large or complex, which is a common limitation of these methods.

An integral imaging system using a point light source array was reported as a potential method to resolve this problem [8-15]. In this method, a point light source array was placed at the back of a liquid-crystal display (LCD) as a backlight. The advantage of this method is that techniques, such as the time division display or 3D/2D switching display, can be easily implemented to enhance the display performance because the display characteristics can be changed depending on the state of the backlight. For example, several methods are reported involving switching of light distribution and lighting position of point light sources to enhance the resolution or viewing angle [8, 9]. Moreover, several methods have also been reported involving the implementation of a polymer dispersed liquid crystal or diffusion plate in the display system to generate diffused light for switching between 3D and two-dimensional (2D) images [10, 11]. However, in these approaches, the light distribution of point light sources is fundamentally static and the dynamic enhancement of the display characteristics is limited. Furthermore, the light-diffusing state of the backlight is switchable only over the entire region of the display screen; thus, the partial reproduction of a 2D image is difficult. If the light distribution and light-diffusing states of point light sources can be locally controlled, the display performance can be enhanced more flexibly.

Therefore, in this study, we propose an integral imaging system using a locally controllable point light source array. In the proposed method, point light sources with the desired light distribution angle, light direction, and light-diffusing states are generated as a local backlight through the projection of a predetermined image pattern. The viewing angle characteristics of an integral 3D image can then be enhanced by switching the light distribution of each point light source in time division and displaying the corresponding elemental images on an LCD. Additionally, switching between 3D and 2D images on a partial region of the display screen becomes possible by locally controlling the light-diffusing state. The principle of the proposed method and the experimental results with a prototype display system are presented.

Integral Imaging System using Point Light Source Array

This section discusses the basic principle of an integral imaging system using a point light source array. The display system configuration is shown in Fig. 1. A point light source array is composed of point light sources with minute light emission area, placed towards the back of an LCD as the backlight. When elemental images are displayed on the LCD, light rays emitted from

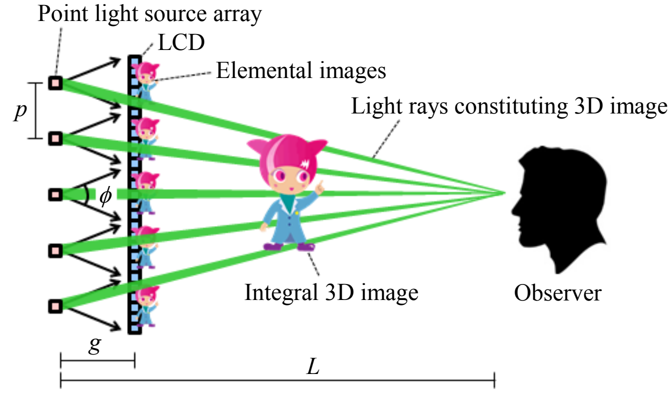

Figure 1. Principle of integral imaging system using point light source array.

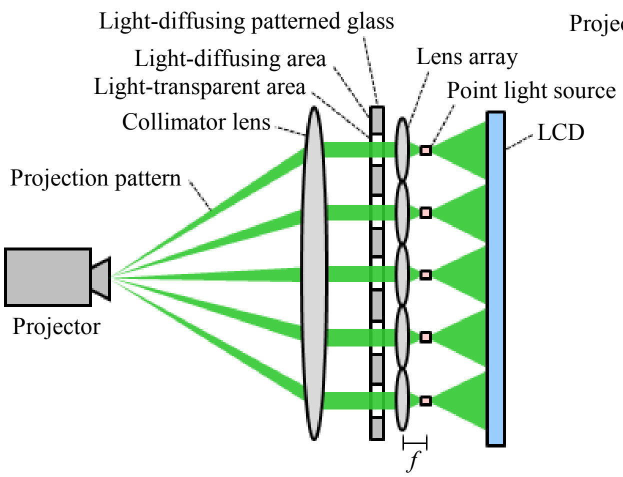

Figure 2. Basic configuration of the proposed method.

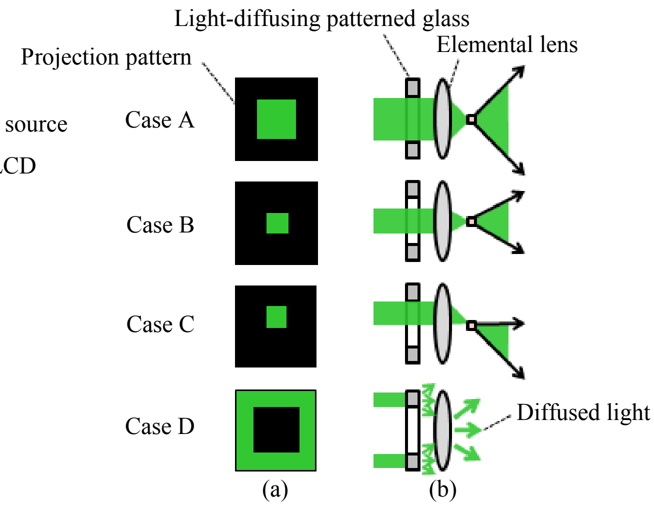

Figure 3. Example of projection pattern corresponding to elemental lens: (a) projection pattern, (b) path of light rays.

each point light source are incident on a different pixel in the LCD, and the luminance of each light ray is modulated. The light rays form optical images, and an integral 3D image is reproduced.

We examined the resolution characteristics of a 3D image. In this system, as shown in Fig. 1, discrete light rays, which are sampled by each point light source, reach the observer. Given that these light rays eventually form the individual pixels that constitute the 3D image, the resolution of the imaging system is equal to the number of point light sources. The maximum spatial frequency of the 3D image β_{max} is given as follows:

$$\beta_{max} = \frac{L}{2p} \tag{1}$$

where L is the viewing distance and p is the pitch between the point light sources. This equation shows that a higher density of point light sources leads to, higher resolution characteristics.

We then considered the viewing characteristics of a 3D image. The viewing angle of a 3D image is determined from the arrangement and distribution angle ϕ of the point light sources. The viewing angle θ is given as follows:

$$\theta = \min\left\{2 \cdot \tan^{-1}\left(\frac{p}{2g}\right),\ \phi\right\} \tag{2}$$

where g is the distance between the point light source array and the LCD. When the light distribution angle ϕ is small, the viewing angle θ becomes smaller and is equal to ϕ. Conversely, when ϕ is larger than θ, the light rays emitted from the point light sources are incident on the neighboring elemental images, and crosstalk occurs. Therefore, a display system design where ϕ is equal to θ is desirable. This is the basic principle of an integral imaging system using a point light source array.

Proposed Method

Figures 2 and 3 show the concept of the proposed method. Figure 2 shows a display system comprising a projector, collimator lens, light-diffusing patterned glass, lens array, and LCD. The light-diffusing patterned glass is an optical glass with light-transparent areas that correspond to the central region of the elemental lenses, and the light-diffusing areas correspond to the peripheral part of the elemental lenses. In the proposed method, the light distribution angle and light direction of point light sources can be locally controlled, which correspond to the projection of a predetermined image pattern from the projector. Additionally, light-diffusing states of the backlight can be partially switched. For example, in case A of Fig. 3, when an image pattern that illuminates the central part of an elemental lens is projected, collimated light rays pass through a light-transparent area of the light-diffusing patterned glass, and a point light source is generated at focal length f of the elemental lens. In case B of Fig. 3, when the illuminated area is reduced, the light distribution angle of the point light source becomes smaller. Furthermore, as shown in case C of Fig. 3, when the upper portion of the elemental lens is illuminated, the light direction is directed downwards. By using these point light sources as a backlight and displaying the corresponding elemental images on the LCD, an integral 3D image with the desired viewing angle characteristics can be reproduced. On the other hand, as shown in case D of Fig. 3, when an image pattern illuminates the peripheral part of the elemental lens, collimated light rays illuminate the light-diffusing areas of the light-diffusing pattern, and diffused light is generated. By using this diffused light as backlight, a 2D image can be displayed.

Figure 4 shows an example of enhancing the horizontal viewing angle by twofold using time division. Figure 4(a) shows the projection pattern when the time division display is not used. The same number of point light sources as elemental lenses is generated. Light rays emitted from each point light source illuminate the LCD without non-irradiation areas. Figure 4(b) shows the projection pattern when using the time division display. In the first frame, as shown in the upper image of Fig. 4(b), an image pattern consisting of multiple rectangles illuminates every other elemental lens to generate point light sources with horizontal viewing angles enhanced by twofold. The resolution of the 3D image expressed in Eq. (1) is decreased by half because the pitch between the point light sources p is doubled. On the contrary, the viewing angle of the 3D image θ, as expressed in Eq. (2), is doubled because the distribution angle ϕ is also doubled. In the next frame, as shown in the lower image of Fig. 4(b), the other point light sources are generated. By switching between these frames at high speed while synchronously displaying the corresponding elemental images on the LCD, the horizontal viewing angle of the 3D image can be enhanced by twofold, while the resolution is maintained by the afterimage effect. Similarly, the vertical viewing angle can be enhanced and the 3D

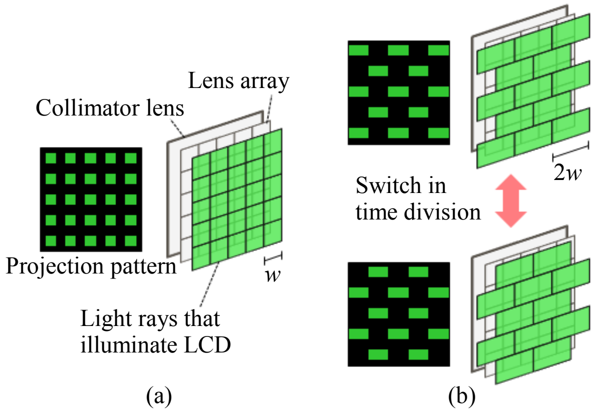

Figure 4. Examples of projection pattern to reproduce 3D image: (a) without time division, (b) with time division to enhance the horizontal viewing angle by twofold.

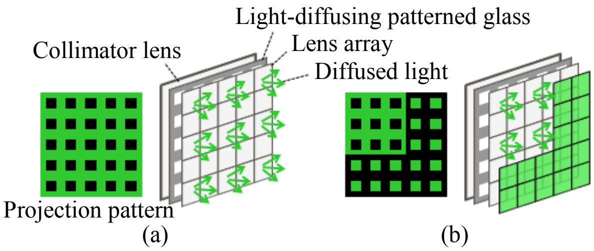

Figure 5. Examples of projection pattern to reproduce 2D image on: (a) entire display screen, (b) partial region of the display screen.

images with different viewing angle characteristics corresponding to the subdivided display areas can be displayed. The light-diffusing patterned glass is excluded in this example.

Figure 5 shows examples of reproducing a 2D image. Figure 5(a) represents the projection pattern to generate diffused light over the entire display area. A 2D image can be reproduced on the LCD using this diffused light as a backlight. Figure 5(b) shows the projection pattern to generate diffused light in the upper left portion of the display area and to generate point light sources in the other area. The 3D and 2D images can be reproduced partially by displaying the 2D images and elemental images on the LCD, respectively. Thus, the proposed method can reproduce 2D images on the entire or partial region of the display screen.

Prototype Display System

We developed a prototype display system to confirm the effect of the proposed method experimentally. The appearance and specifications of the prototype system are shown in Fig. 6 and Table 1, respectively. We used a twisted nematic LCD with a VGA resolution and a projector with a 4K resolution. Image signals were inputted from the video card mounted on a desktop computer.

In the proposed method, the accurate positional alignment between the projector, lens array, and LCD is extremely important. However, in practice, positional errors of the displayed images occur due to installation errors, projection distortions, and other factors. Therefore, we utilized our technology that was previously developed to accurately reverse-correct the distortion of the projected image using 3D markers [16]. Using this method, the geometrical correction parameters were calculated. The displayed image of the projector and LCD were aligned to the lens array at the subpixel level.

In the 3D/2D switching display experiment, we used a light-diffusing patterned glass with the structure shown in Fig. 7. The

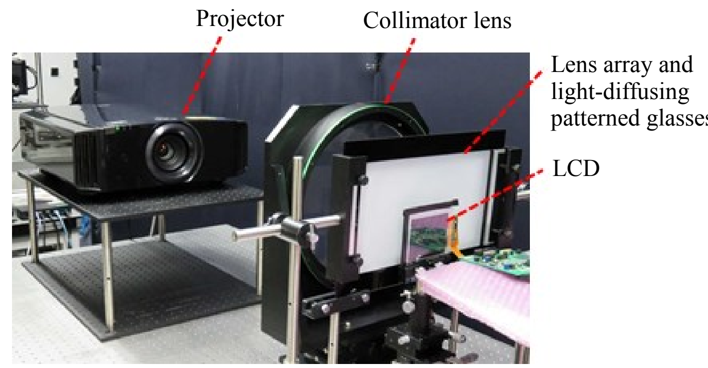

Figure 6. Prototype display system.

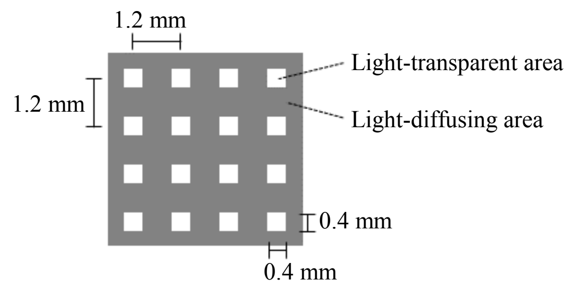

Figure 7. Structure of the light-diffusing patterned glass (partially enlarged).

Table 1. Specification of the prototype display system.

LCD	Resolution	640 × 480
	Pixel pitch	117 μm
	Frame rate	60 Hz
	Molecular alignment	Twisted nematic
Projector	Resolution	3840 × 2160 using wobbling technology
Collimator lens	Focal length	670 mm
Lens array	Pitch	1.2 mm (square lens)
	Focal length	2.4 mm
3D image	Resolution	50 × 40
	Viewing angle	Default: 14.2° (H) × 14.2° (V) Time division mode: 28.0° (H) × 14.2° (V) 3D/2D switching mode: 9.5° (H) × 9.5° (V)

light-transparent areas and light-diffusion areas were patterned corresponding to the arrangement of the lens array. The size of the light-transparent area was set to 0.4 mm, while the pitch between elemental lenses was set to 1.2 mm.

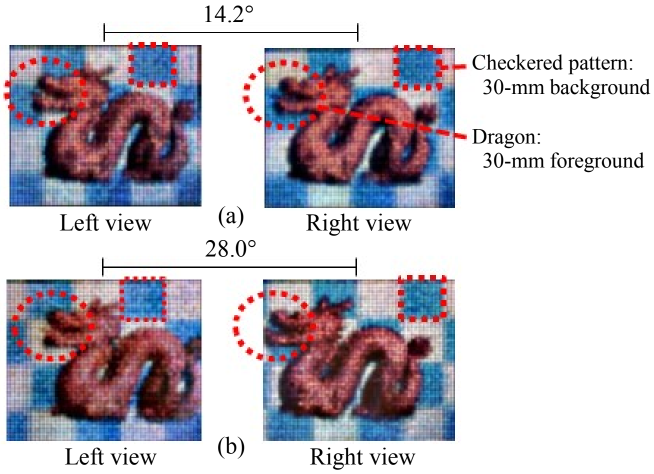

Figure 8. Viewing angle enhanced integral 3D image by time division display: (a) before enhancement, (b) after enhancement.

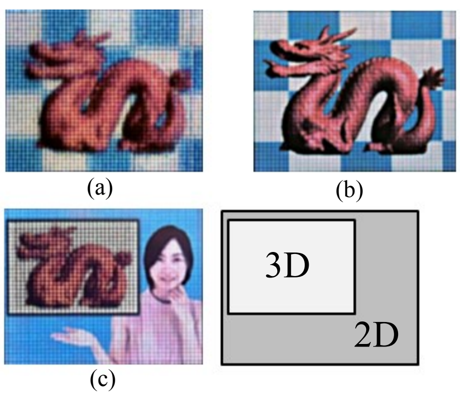

Figure 9. Reproduced images by 3D/2D switching display: (a) 3D image, (b) 2D image, (c) 3D and 2D images on partial regions.

Experimental Results

Viewing Angle Enhancement by Time Division Display

We enhanced the horizontal viewing angle using the same method as that shown in Fig. 4. The reproduced integral 3D images are shown in Fig. 8. The result before and after the enhancement is shown in Fig. 8(a) and Fig. 8(b), respectively. The depth positions of the dragon and checkered pattern were 30 mm foreground and 30 mm background from the point light source array, respectively. When observing the change of the positional relation between the head of the dragon identified by a red circle and the portion of the checkered patterned identified with a red square, motion parallax is confirmed to be larger after the enhancement. The horizontal viewing angles before and after the enhancement were 14.2˚ and 28.0˚, respectively. We confirmed that the viewing angle of a 3D image can be enhanced by approximately twofold with the proposed method. The resolution of the 3D image was low because an LCD with low resolution (VGA resolution) was used.

3D/2D Switching Display

We switched between 3D and 2D images based on the method as shown in Fig. 5. A single light-diffusing patterned glass was placed in the front and back of the lens array to increase the degree of diffusion. Figure 9 shows reproduced images based on this optical arrangement. Figures 9(a) and 9(b) show the results of displaying a 3D and 2D image, respectively. Figure 9(c) shows the result of displaying the dragon as a 3D image and the woman as a 2D image. Thus, we confirmed the possibility of switching between 3D and 2D images in a flexible manner using the proposed method. One of the issues encountered with the prototype display system is the occurrence of uneven granular luminance because of the non-uniform distribution characteristics of the generated diffused light. We will improve the display quality by optimizing the distribution characteristics, structure, and arrangement of the light-diffusing patterned glass in future studies.

Conclusion

We proposed an integral imaging system using a point light source array where the light distribution and light-diffusing states can be locally controlled. Using the proposed method, the display performance can be flexibly enhanced by utilizing a point light source array as a backlight. The prototype display system developed in this study confirmed the possibility of enhancing the viewing angle characteristics using the time division display. Moreover, we confirmed that partial switching between 3D and 2D images could be effectively achieved using the proposed method. We will continue to develop this integral imaging system and improve on the high display performance and thin structure, while also enhancing the display method and prototyping a point light source array composed of small self-emitting display devices.

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