Abstract: We propose a display for stereoscopically representing an arbitrary object that is responsive to an arbitrary physical illumination source in the display environment. Our scheme is based on the eight-dimensional reflectance field, which contains angular and spatial information of incoming and outgoing light rays of an object, and is also known as the bidirectional scattering surface reflectance distribution function (BSSRDF). This system is composed of an integral photography unit, an integral display unit, and a processor connecting these units. The concept was demonstrated experimentally. In the demonstrations, a stereoscopically represented object responded to changes in physical illumination coming toward the display.

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1. Introduction

Conventional displays typically reproduce a two-dimensional light distribution by using a light source array. Recently, displays that can represent an object stereoscopically without the use of special glasses have become popular [1, 2]. These displays reproduce outgoing light rays from an object. The rays are expressed by a four-dimensional function called the light field [3].

The light field, $L_{\text{out}}(u, v, s, t)$, is typically determined by using two parallel planes indicating the angle and spatial position of a ray, as shown in Fig. 1, where $u, v$ and $s, t$ are called the angular and spatial coordinates in this paper, respectively. The light field was originally applied to an information acquisition technique called integral photography (IP). IP uses a camera array or a lens array to observe the angles and the spatial positions of the rays [1–6]. The captured light field has been used for depth imaging, creating arbitrary perspective views, refocusing, etc.

To display the outgoing light field (OLF) of an object, various systems have been proposed based on the concept of integral display (ID), in which a lens array, a lenticular lens, or a projector array is used to reproduce the light rays [1, 2, 7, 8]. These ID systems represent the object stereoscopically by reproducing the OLF with these optics.

Some displays that can respond to changes in the physical illumination (illumination-responsive displays) have been proposed [9, 10]. In these displays, a camera was used to measure the two-dimensional spatial position of an illumination source in the display environment, and an output image was calculated computationally using the measured position. Displays that change the displayed object in response to the incoming light rays to an object also have been proposed [11, 12]. The incoming light field (ILF) generated by a physical illumination source is $L_{\text{in}}(u', v', s', t')$ in Fig. 1, where $u', v'$ and $s', t'$ are the angular and spatial coordinates of

![Fig. 1. Incoming and outgoing light field of an object.](image_url)
the ILF, respectively. These ILF-responsive displays use passive optics such as a multi-layered lens array or a liquid surface in order to change the represented object image in response to the ILF from a physical illumination source in the display environment. However, displays that reproduce the OLF in response to the ILF toward the display have not been realized yet.

IP and ID are well-known methods of observing and reproducing the light field [13]. They have been combined to realize display systems that capture and reproduce the OLF [14–16]. In these systems, an object is illuminated by a fixed light source, and only the OLF, not the ILF, of the object is captured by an IP unit and is reproduced by an ID unit. Furthermore, ID systems using computer graphics to generate an input integral image have been demonstrated for high-quality displays [17–19]. In these systems, an IP unit is implemented virtually by computer graphics. In a virtual world, the IP unit observes the OLF of a virtually illuminated object, and the ID unit physically reproduces the OLF. A represented object in the systems mentioned in this paragraph is unresponsive to the physical illumination in the display environment.

Here, we present a display that represents stereoscopically an arbitrary object that is responsive to an arbitrary physical illumination source in the display environment; that is, our display reproduces an OLF that changes in response to the ILF of the object. This display system is based on the reflectance field, which contains both the OLF and the ILF [20]. The eight-dimensional reflectance field function \( R(u,v,s,t,u',v',s',t') \) is written as

\[
R(u,v,s,t,u',v',s',t') = \frac{\partial L_{\text{out}}(u,v,s,t)}{\partial L_{\text{in}}(u',v',s',t')},
\]

where \( d \) shows an infinitesimal quantity. This function is also known as the bidirectional scattering surface reflectance distribution function (BSSRDF), which has been used to express translucent materials in computer renderings [21,22]. The reflectance field \( R \) can be interpreted as a response OLF \( L_{\text{out}} \) to an impulse ILF \( L_{\text{in}} \). The reflectance field enables us to perform image-based rendering of an object with an arbitrary camera and illumination. Capturing the eight-dimensional reflectance field generally requires a long observation time, but some fast methods have been proposed [23,24]. In this paper, we experimentally demonstrate the proposed concept, in which a represented object is stereoscopic and its appearance changes in response to changes of physical light rays coming toward the display, using a computer-generated reflectance field.

## 2. Proposed display system

As shown in Fig. 2, our proposed system is composed of an IP unit for observing the ILF, an ID unit for reproducing the OLF, and a processor for calculating the OLF from the ILF. The IP unit consists of a camera and a lens array, and the ID unit has a projector and a lens array. The ID lens array can also serve as the IP lens array, as shown in Fig. 2. The camera and the projector focus on the focal plane of the lens array. The processor connects these IP and ID units.

Before operating the display system, the reflectance field \( R(u,v,s,t,u',v',s',t') \) of an object is captured by a reflectance field observation system or is generated computationally, and this is stored in the processor. The angular and spatial coordinates \( u,v,s,t \) of the OLF are on the focal plane of the lens array, as shown in Fig. 2, and the angular and spatial coordinates \( u',v',s',t' \) of the ILF are also on this focal plane.

The proposed display is a time-division system composed of three steps, as shown in Fig. 3. First, the ILF \( L_{\text{in}} \) from the physical illumination source in the display environment is observed by the IP unit, as shown in Fig. 3(a). Pixels of the image captured by the IP unit are rearranged directly to generate pixels of the ILF \( L_{\text{in}} \), as shown in Fig. 2 [13]. Next, the observed ILF \( L_{\text{in}} \) is sent to the processor, which calculates the OLF \( L_{\text{out}} \) with the ILF \( L_{\text{in}} \) and the stored reflectance.
Fig. 2. Schematic diagram of the computational reflectance field display system, where ILF is the incoming light field observed by the integral photography unit, and OLF is the outgoing light field reproduced by the integral display unit.

Fig. 3. Flow of the computational reflectance field display system. (a) ILF observation, (b) computational process, and (c) OLF reproduction.

field \( R \) as shown in Fig. 3(b). The computational process is simply written as

\[
L_{\text{out}}(u,v,s,t) = \sum_{u'} \sum_{v'} \sum_{s'} \sum_{t'} R(u,v,s,t,u',v',s',t') \times L_{\text{in}}(u',v',s',t'). \tag{2}
\]

The angle and the spatial position of the physical illumination source are not calculated in this system. Therefore, the scheme is robust against variations in the illumination and the object. The calculated OLF \( L_{\text{out}} \) is sent to the ID unit. Finally, the OLF \( L_{\text{out}} \) is physically reproduced in the display environment by the ID unit, as shown in Fig. 3(c). Pixels of the OLF \( L_{\text{out}} \) are also rearranged directly to generate pixels of the projected image in the ID unit. Eventually, these three steps will be executed in real-time, but in the following experimental demonstration, they were executed separately to show a proof of concept. This computational reflectance field display can reproduce an OLF \( L_{\text{out}} \) that changes in response to the physical ILF \( L_{\text{in}} \) in the display environment. Our scheme is image-based and is useful for photorealistic expression [3].

3. Experimental verification

The proposed concept was demonstrated experimentally with a computer-generated reflectance field. A camera (Digital SLR: D200 manufactured by Nikon) and a projector (3-LCD pro-
Fig. 4. Object and illumination. (a) Front and (b) top views.

Fig. 5. Reproduced object. Views from (a) the center and (b) the left under illumination from the right of the observer. Views from (c) the center and (d) the left under illumination from the left of the observer.
jector: EH-TW400 manufactured by Epson) were arranged as shown in Fig. 2. A lenticular lens (pitch: 20 LPI, focal length: 3 mm, material: acrylic) was used instead of a lens array for simplicity. A diffuser was placed on the focal plane of the lenticular lens to increase the incoming and outgoing angles of the rays through the lenticular lens.

A teapot shown in Fig. 4(a) was used as the object. The surface was assumed to be a diffuse and specular material. The reflectance field \( R \) of the teapot was computationally generated by OpenGL with scanning of the lateral position of the camera capturing the response and the angle and lateral position of a spotlight stimulating the impulse based on Eq. (1). The size of the reflectance field \( R \) was \( 4 \times 1 \times 128 \times 128 \times 4 \times 1 \times 32 \times 32 \) pixels, where the variables are \( u, v, s, t, u', v', s', \) and \( t' \), respectively, as shown in Eq. (1). The angular resolutions (along the \( u, v, u', \) and \( v' \)-axes) were calculated from the lens pitch of the lenticular lens and the projector’s resolution on the focal plane of the lenticular lens. The spatial resolutions (along the \( s, t, s', \) and \( t' \)-axes) were determined by the number of lenses of the lenticular lens. The spatial resolution of the ILF was assumed to be lower than that of the OLF because the spot produced by the illumination source was larger than a single pixel of the object. The center of the teapot was assumed to be located at the center of the lenticular lens, as shown in Fig. 4(b).

A laser pointer was used as the physical illumination source in the display environment, and it illuminated a white square area on the lenticular lens, as indicated in Fig. 4(a), with two different incoming angles, from the right and left of the observer. These incoming light beams and the actually illuminated location on the lenticular lens are shown by arrows in Fig. 4(b). Two images with the two incoming angles were captured by the camera. The captured images were resized and reshaped to \( 4 \times 1 \times 32 \times 32 \) pixels to generate the ILFs \( L_{in} \). The OLFs \( L_{out} \) were calculated with the ILFs \( L_{in} \) and the reflectance field \( R \) based on Eq. (2). Finally, the two calculated OLFs \( L_{out} \), whose sizes were \( 4 \times 1 \times 128 \times 128 \) pixels, were projected individually onto the lenticular lens by the projector.

The results are shown in Fig. 5. The reproduced object under physical illumination from the right is shown in Figs. 5(a) and 5(b), which are views from the center and the left, respectively. The parallax between them was well-reproduced. The reproduced object under physical illumination from the left is shown in Figs. 5(c) and 5(d), which are views from the center and the left, respectively. The response effect for the physical ILF in the display environment, namely, the varying bright area due to the changing angle of the incoming physical light from the laser pointer, was demonstrated successfully, as can be seen by comparing Figs. 5(a) and 5(c), and also Figs. 5(b) and 5(d).

4. Conclusions

In this paper, we proposed a computational eight-dimensional reflectance field display system. It observes the four-dimensional physical ILF in the display environment and reproduces the four-dimensional OLF, that changes in response to the observed ILF, in the environment. The system is composed of an IP unit for observing the ILF, an ID unit for reproducing the OLF, and a processor for calculating the OLF from the ILF. The concept was experimentally verified with a computer-generated reflectance field. In the experiments, a lenticular lens was used instead of the lens array in Fig. 2 for simplicity. This simplification eliminated the vertical parallax of the proposed display, but the parallax can be readily implemented by using a lens array. A display representing the reflectance field, in other words, the BSSRDF, of an object was demonstrated successfully. In the experiments, an object was represented stereoscopically and it was responsive to the angles and spatial positions of incoming light rays toward the display from a physical illumination source.