Measuring Light Field of Light Source with High Directional Resolution using Mirrored Ball and Pinhole Camera

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Abstract

This paper presents a method of measuring a light field of a light source with high directional resolution using a mirrored ball and a pinhole camera. The light field describes a spatial and directional distribution of radiances from the light source. The directional distribution is expanded by a reflection on the mirrored ball, and the radiances are measured by a charge-coupled device (CCD) camera with a pinhole lens. The light source is laterally moved by a robot arm to measure the directionally expanded light field, and each pixel on a CCD can obtain the radiances from the light source through the pinhole lens with high directional resolution. The light field is estimated from the pixel value and the position of each pixel using a ray tracing technique. The light field of a krypton lamp was experimentally measured by the proposed method, and the accuracy of the measurement was evaluated against the irradiances measured by a spectro-radiometer at sample points.

Key words: light field, light source, directional resolution, mirrored ball, pinhole camera, ray tracing

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1. Introduction

A digital archiving system has been used in museums with development of a digital imaging system. Collections in the museums are preserved by the digital archiving system and exhibited by digital display technology. For this archiving, it is necessary to record the Bidirectional Reflectance Distribution Function (BRDF) of objects to accurately preserve their reflectance property. Much research has been devoted to BRDF measurements [1-3] in which a light source is assumed to radiate a parallel light as shown in Fig. 1(a). It simplifies the estimation for the reflectance property of a target object because each point of the object is illuminated from a constant direction with constant radiance. Collimating the light source requires use of huge measurement space and devices. For practical application, it is necessary to construct a simple and compact BRDF measurement system. When the target object is illuminated at a short distance by the light source, each point of the target object is illuminated from various directions with different radiances simultaneously as shown in Fig. 1(b). For accurate BRDF measurements, therefore, it is necessary to consider a light field of the light source which describes a spatial and directional distribution of radiances from the light source.

Measurements for the light field are classified into *far field photometry* and *near field photometry*. In the former, Verbeck *et al.* and Ngai modeled a light source as a point light source or an array of point light sources. [4, 5] In their method, the light field is described by a goniometric diagram which is a two-dimensional angular representation of the directional distribution. The light field in *far field photometry* is only a faithful approximation of an emitted light source when it is sufficiently distant from the object to be illuminated. The distance between the light source and the object is at least five times the maximum width of the light source. [6] *Near field photometry,* in contrast to *far field photometry*, was presented by Ashdown. [6, 7] In his work, the light field is assumed to be composed of radiances to directions (θ, ϕ) from positions (u, v) on a virtual sphere surrounding a light source. Therefore, the light field is described as four-dimensional function in *near field photometry*. In *near field photometry*, a digital camera mounted on a robot arm observes a light source from many positions on the virtual surrounding sphere. Both Rykowski and Wooley, and Jenkins and Monch employed a similar measurement setup to acquire the light field, [8, 9] while Siegel and Stock replaced the camera lens with a pinhole lens. [10] For image-based rendering of objects, Levoy and Hanrahan, [11] and Gortler *et al.* [12] used the light field as the flow of radiances through unobstructed space with a two-dimensional array of images. They could represent the light field without considering the geometry of rendered objects.

Recently several advanced methods were proposed for measurement of the light field. Goesele *et al.* measured the light field using a diffuse reflector. [13] In their method, the light field through an optical filter from a light source is reflected by a diffuse reflector and measured by a digital camera. However, it is difficult to measure a wide directional distribution of radiances due to limitation of the movement for the camera and the diffuse reflector. Accuracy of the measurement by their methods is also highly influenced by noise, since radiances from the light source are reduced by the diffuse reflector. Unger *et al.* measured spatially and directionally varying illumination by two methods. [14] Firstly, mirrored ball arrays are used for reflecting radiances from light sources. This method is similar to our method which is described later, however, inter-reflection of radiances between mirrored balls should be considered for an estimation of the light field. Furthermore, the spatial and directional resolution is low, because the mirrored balls cannot be located at arbitrary positions. Therefore, they proposed the second method by a moving camera with a fisheye lens to measure the light field with high spatial and directional resolution. Their directional resolution, however, is still lower than that by our method which uses a pinhole camera, because a pixel in the camera with an ordinary lens integrates radiances in various directions from the light source due to the wide aperture of the ordinary lens.

In this paper, we measure the wide directional distribution of the light field with high directional resolution using a mirrored ball and a pinhole camera. By a reflection on the mirrored ball, the proposed method can expand the directional distribution of the original light field. Each pixel on a CCD can sample the directionally expanded light field through a pinhole lens with high directional resolution. The light field is estimated from the pixel value and the position of each pixel using a ray tracing technique. [15, 16] In this proposed method, the accuracy of the measurement is less influenced by noise than that by Goesele's method, since radiances from the light source are reflected by a specular object.

The remainder of this paper is organized as follows. In the next section, the light field is described as a four-dimensional function, and we propose the method of measuring the light field with high directional resolution using a mirrored ball and a pinhole camera. The light field of a krypton lamp is measured by the proposed method and the measured directional distributions are shown in §3. To evaluate the accuracy of the measurement, irradiances estimated at sample points from the measured light field are compared with those experimentally measured by the spectro-radiometer. Finally, a conclusion and a discussion of future work are presented in §4.

2. Measuring Light Field of Light Source using Mirrored Ball and Pinhole Camera

2.1 Definition of light field of light source

In this paper, the light field defined by Unger *et al.* [14] is applied to a spatial and directional distribution of radiances from a light source. At first, the definition of the light field is described in this section. A light source radiates in various directions from its surface. In the definition of the light field, a light plane is located in front of the light source as shown in Fig. 2, and the light source is assumed to radiate through the plane as if the light plane itself radiated. The light field is described as a distribution of radiances in various directions from various positions on the light plane. In this paper, the light plane is spatially sampled as (u,v) and the distribution of radiances from the plane is directionally sampled as (ϕ,θ), then the sampled radiance in the direction (ϕ,θ) from the position (u,v) on the light plane is defined as a ray $I(u,v,\phi,\theta)$.

2.2 Measurement for light field of light source

Figure 3 shows geometry for measurement of the light field using a mirrored ball and a pinhole camera. In this figure, we describe the camera system as if a CCD was placed in front of the camera, since a pinhole lens is attached to the camera. [17] The distance between the pinhole lens and the CCD is the focal length *f*. The directional distribution of the light field is expanded by a reflection on the mirrored ball, and radiances in a part of the light field are measured by each pixel on the CCD. In Fig. 3, a ray **V** describes the radiance measured through the pinhole lens by a pixel (x,y) on the CCD, and the ray **V** is originally emitted as a ray **R** from the position **p** on the light plane. To measure radiances in various parts of the light field, the light source is laterally moved along the YZ plane by a robot arm.

The proposed method can measure the light field with high directional resolution using the mirrored ball. Figure 4 shows how a ray from the light plane is reflected on the ball. Let us explain the detail of the reflection in 2D space instead of 3D space for ease of explanation. The ray from a light plane to the outgoing angle θ_o is reflected on the surface of the mirrored ball and comes into the CCD with the incident angle θ_i. Figure 5 shows an example of the relation between the outgoing angle θ_o and the incident angle θ_i of a ray, when the light source is located at (X, Y, Z) = (6.0, 0.0, -7.0) [cm] in Fig. 3 and other devices are in the same geometry in the measurement in section 3.1. In Fig. 5, the horizontal and the vertical axes indicate outgoing and incident angles of rays, respectively. From the diagonal line in this figure, it is found that the range of the outgoing angle from 20.0 through 60.0 degrees becomes from -59.9 through 70.0 degrees, and that the reflection on the mirrored ball expands the directional distribution of the light field. By this expansion, since the directional distribution per pixel on the CCD becomes small, the proposed method can measure the light field with high directional resolution. Furthermore, the pinhole camera is used to improve the directional resolution. Figure 6 shows the comparison between the pinhole and ordinary cameras in the measurement of the light field. In this figure, one pixel integrates a part of the radiances described by an oblique line. From the oblique line, it is found that the wide directional distribution of radiances is measured by the ordinary camera, because an ordinary lens is wider than a pinhole lens. Therefore, the ordinary camera measures the light field with low directional resolution since each pixel in this camera integrates radiances from the directionally wide part of the light field.

2.3 Estimation for light field of light source

In this subsection, the light field is estimated by a ray tracing technique from a measured pixel value and the position of each pixel on the CCD in the pinhole camera. In Fig. 3, the ray **R** from the position **p** on the light plane is reflected on the mirrored ball and measured by the pinhole camera as the ray **V** as described above. When the ray **V** is measured at (x, y) on the CCD, the ray is expressed as follows,

$$\mathbf{V} = -normalize([x - x_o, y - y_o, f]^T), \tag{1}$$

where (x_o, y_o) is the center of the CCD, and the function "*normalize*()" indicates the normalizing operator that the length of a vector is unit length. From the ray **V,** the position $\mathbf{p}_r$ on the mirrored ball is calculated using a ray tracing technique since the position $\mathbf{p}_o$ and the radius of the mirrored ball are known parameters. Since the mirrored ball is a sphere, the surface normal **N** of the position $\mathbf{p}_r$ is determined as follows,

$$\mathbf{N} = normalize(\mathbf{p}_r - \mathbf{p}_o). \tag{2}$$

From **V** and **N**, the outgoing ray **R** from the light plane is calculated by the following equation:

$$\mathbf{R} = \mathbf{V} - 2(\mathbf{V} \cdot \mathbf{N})\mathbf{N}. \tag{3}$$

The position **p** where the ray **R** is emitted on the light plane is also calculated using a ray tracing technique. Since the light plane is along the YZ plane, the position **p** is described on the coordinate system of the light plane as

$$(u, v) = [y_{\mathbf{p}} - y_{\mathbf{p}_c}, z_{\mathbf{p}} - z_{\mathbf{p}_c}]^T, \tag{4}$$

where $(y_{\mathbf{p}}, z_{\mathbf{p}})$ and $(y_{\mathbf{p}_c}, z_{\mathbf{p}_c})$ are the YZ coordinates of **p** and $\mathbf{p}_c$, respectively, and $\mathbf{p}_c$ is the origin of the light plane. As the surface normal of the light plane is along the X axis, the zenith angle θ and the azimuth ϕ of the ray **R** are calculated as follows,

$$\theta = \arccos\left([-1,0,0]^T \cdot \mathbf{R}\right),\ \phi = \arctan\left(\frac{z_{\mathbf{R}}}{y_{\mathbf{R}}}\right), \tag{5}$$

where $(y_{\mathbf{R}}, z_{\mathbf{R}})$ is the YZ coordinates of **R**. Radiance L of the ray **R** on the light plane is estimated as follows,

$$L = \frac{p(x,y)\left(D_{pr} + D_r\right)^2}{F_r(\theta_r)\cos\theta_i \cos\theta}, \tag{6}$$

where $p(x,y)$ is a pixel value at (x,y) on the CCD, D_{pr}, and D_r are the distances between the pixel and the position $\mathbf{p}_r$, and the position $\mathbf{p}_r$, and the position $\mathbf{p}$, respectively, θ_r and θ_i are the angles between the ray **V** and the surface normal **N**, and the ray **V** and the surface normal of the CCD, respectively, and $F_r(\theta_r)$ is a function of the Fresnel reflection for the angle θ_r.

For the estimation of the whole light field, many images are required to be taken in the measurement. In this paper, to reduce the time of the measurement, the light field is interpolated from measured rays which were sampled radiances from the light plane.

3. Measurement and Evaluation of Proposed Method

3.1 Experimental setups

We measured the light field of a light source in geometry which is shown in Fig. 7. In the experiment, the light source was a krypton lamp (LDS110V36WWK: National), a pinhole lens (PINHOLE LENS02: Kenko) was attached to a digital camera D1X (Nikon), a robot arm (RV-1A: Mitsubishi) was used for moving and positioning the light source, and a mirrored ball with a 5 cm radius was made of chromium. Let us explain the experimental geometry as shown in Fig. 3. The position of the pinhole lens was $(0.0, 0.0, -25.5)$ [cm], and the light source was laterally moved by the robot arm on the YZ plane of which the X coordinate was 6 cm. The light source was positioned at 3,530 points on the plane of which the ranges of the Y and Z coordinates were $-10.0 \le y \le 10.0$, $-1.0 \le z \le 12.0$ [cm], respectively.

Dynamic range was wide in radiances from the light source. To measure radiances accurately, the light field was captured as high dynamic range (HDR) images by the method of Debevec and Malik [18)]. In our measurement, the light field was captured twice with different shutter speeds at each position.

3.2 Results of measurement

Figure 8 shows the directional distributions of radiances measured by the proposed method. Twelve polar charts are shown at the positions corresponding to $u = 0.15, 0.75, 1.35$ and $v = 0.00, 0.15, 0.75, 1.35$ [cm] in the (*u, v*) coordinates on the light plane as described in Fig. 2. In Fig. 8, radius and angle of the polar coordinate system indicate relative radiances and azimuth angles ϕ of the distribution, respectively. The radiances are normalized by the maximum radiance at the position (*u, v*) = (0.00, 0.15). Each chart has four directional distributions of different colors. The color of each distribution shows its zenith angle θ. As the caption shows, red, green, blue and cyan indicate that the zenith angles are 10, 20, 30 and 40 degrees, respectively. From this figure, it is found that the radiance toward the radial direction from the origin is stronger than that to other directions in each chart. Furthermore, when radiances in each distribution are compared in each chart, the zenith angle of the distribution which has the maximum radiance is large as the distance between the origin and the position of the chart is long. These results are explained by the filament emitting radiances being placed beneath the origin of the light plane. These results reflect the structure of the measured lamp.

3.3 Evaluation of accuracy of estimation by proposed method

The accuracy of the measurement by the proposed method is evaluated in this subsection. In this evaluation, a diffuse reflector was located at sample points and illuminated by the krypton lamp measured above. Figure 9 shows geometry for the measurement of the irradiances. The diffuse reflector faced the light plane, and was located at each rectangular position which was 10.0 cm apart from the light plane and from 0.0 to 10.0 cm at 0.2 cm intervals from the central axis of the light source. Irradiance at each position was measured by the spectro-radiometer (CS1000: Konica Minolta) and also estimated from the measured light field. A comparison between the measured and the estimated irradiances was used to evaluate the accuracy of the measurement by the proposed method.

Figure 10 shows the measured irradiance at each position by a solid line. The horizontal and the vertical axes indicate the distance between the central axis of the light source and each point, and relative irradiance, respectively. Irradiances are normalized by the irradiance at the sample point on the central axis of the light source.

From the light field measured by the proposed method, irradiance E to each sample point $\mathbf{p_s}$ is estimated as integration of radiance $L(u,v,\phi,\theta)$ on the light plane as follows:

$$E(\boldsymbol{p}_s) = \int_u \int_v \frac{L(u,v,\phi,\theta)\cos\phi}{\| \boldsymbol{p}_s - \boldsymbol{p} \|^2} dv du \,, \tag{7}$$

where $\mathbf{p}$ is a position (u,v) in 3D space, ϕ is the angle between a ray and a surface normal of the diffuse reflector. In this paper, the light plane was discretized into 216 points to calculate the equation for irradiance as a summation of radiances. The estimated irradiance is shown in Fig. 10 by a broken line. From this figure, it is found that the irradiances were estimated precisely. Therefore, we conclude that the proposed method did measure the light field accurately.

4. Conclusion and Discussion

We proposed a method of measuring the light field of a light source with high directional resolution using a mirrored ball and a pinhole camera. The light field of a krypton lamp was measured by the proposed method and radiances from the positions on the light plane of the lamp were shown as polar charts. These charts were used to discuss the directional distribution of the light source, since the proposed method can measure the light field with high directional resolution. To evaluate the accuracy of the estimation by the proposed method, the irradiances estimated at sample points from the measured light field were compared with those experimentally measured by the spectro-radiometer, and this comparison showed it was found that the measurement using the method had been made appropriately.

From the measurement for the light field, we found that a control of relative positions among a pinhole camera, a mirrored ball and a light source is important for an accurate measurement. We also found that we should consider optimizations for lateral positions of a light source in the measurement and for the spatial discretization of the light plane in the estimation, because they influence the accuracy of the measurement and the estimation by the proposed method, and have potential to reduce the number of images taken of the light field.

Acknowledgement

This research was partly supported by Grants-in-Aid for Scientific Research from Japan Society for the Promotion of Science (No. 16760031).

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Captions of figures

Fig.1. Measurement of BRDF of an object. (a) Object illuminated by a parallel light. (b) Object illuminated at a short distance from a light source.

Fig.2. Light field of a light source.

Fig.3. Illustration of measuring a light field using a mirrored ball and a pinhole camera.

Fig.4. Reflection of a ray on a mirrored ball.

Fig.5. Example of relation between outgoing angle θ_o and incident angle θ_i of a ray. Outgoing and incident angles of a ray are illustrated in Fig. 4. When a ray comes into a CCD, the directional distribution of the light field is expanded by a reflection on a mirrored ball. In contrast, outgoing and incident angles are the same when a ray is not reflected by a mirrored ball.

Fig.6. Comparison of measurement for a light field using a pinhole camera and an ordinary camera. (a) Capturing a light field by a pinhole camera. (b) Capturing a light field by an ordinary camera.

Fig.7. Geometry for measurement of a light field of a krypton lamp.

Fig.8. Directional distributions of radiances from each position on a light plane.

Fig.9. Geometry for measurement of irradiance toward a diffuse reflector to evaluate the accuracy of the measurement by the proposed method. A diffuse reflector is located at sample points to measure irradiance there.

Fig.10. Comparison of irradiances measured by a spectro-radiometer and estimated from the light field of a krypton lamp.