Measuring Bidirectional Reflectance Distribution Function Out of the Laboratory: Modeling a Light Source

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Abstract

This paper presents a method for sampling a ray from a distribution of rays leaving a light source to illuminate objects for measurements of bidirectional reflectance distribution function (BRDF). The BRDF measurements of real objects are required to preserve and reproduce the objects in Internet museum, telemedicine, E-commerce and so on. In conventional methods for BRDF measurements, huge measurement space is required to collimate rays from a light source to target objects. In this paper, we sample a ray from a distribution of rays leaving a light source by using a mirrored ball and a pinhole camera, and use the light source to illuminate objects from a short distance for BRDF measurements. By using a mirrored ball, the proposed method can expand a directional distribution of original rays leaving a light source. Based on this expansion, rays leaving a light source are captured at each pixel in images taken by a pinhole camera with high directional resolution. Radiant intensity and a direction of a ray from a distribution of rays leaving a light source are estimated from the taken images by using a ray tracing technique. The accuracy of the estimation in the proposed method was evaluated by a numerical simulation and the result showed an effectiveness of the proposed method. As a preliminary experiment, we measured BRDF of a real object illuminated from a short distance by the light source whose rays was sampled by the proposed method. From the measured data, we estimated diffuse reflectance of the object more accurately than conventional methods.

Introduction

With the development of a digital imaging system, a digital archiving system has been used in museums to preserve collections and exhibit them by a digital display technology. For this archiving, bidirectional reflectance distribution function (BRDF) of objects must be recorded accurately to preserve the reflectance property of the objects. Many works have been done for BRDF measurements. In those works, rays leaving a light source are assumed to be collimated in BRDF measurements for the ease of processing.[1] Huge measurement space and devices, however, are required to collimate rays leaving a light source to the target object.[2] It is expected to construct a simple and compact BRDF measurement system for a practical application. A concept of BRDF measurements is shown in Fig. 1. In the system, the object is illuminated from arbitrary directions by a light source which is positioned by hand. The distance between the light source and the object is very short. Therefore the measurements can be performed out of laboratory. In this case, it is necessary to sample a ray from a distribution of rays leaving a light source for accurate BRDF measurements.

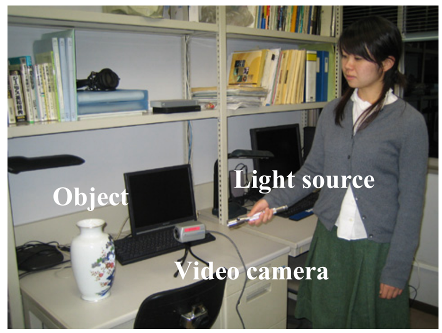


Figure 1. Simple and compact BRDF measurement system

Goesele et al. sampled a ray from a distribution of rays leaving a light source by using a diffuse reflector.[3] In their method, reflected rays by a diffuse reflector from a light source are captured by a digital camera. However, it is very difficult to capture all rays leaving a light source by the limitation of a camera movement and a diffuse reflector. Their method is also highly influenced by noise, since radiant intensity of rays is reduced by the reflection at a diffuse reflector. Unger at el. measured spatially and directionally varying illumination by a moving camera with a fisheye lens to capture the wide directional distribution of rays.[3] However, directional resolution is reduced, since the environmental scene is imaged on a rectangle area of CCD array.

In this paper, we sample a ray from a distribution of rays leaving a light source with high directional resolution by using a mirrored ball and a pinhole camera, and use the light source to measure diffuse reflectance of a real object. By using a mirrored ball, the proposed method can expand a directional distribution of original rays leaving a light source. Based on this expansion, rays leaving a light source are captured at each pixel in images taken by a pinhole camera with high directional resolution. Radiant intensity and a direction of a ray from a distribution of rays leaving a light source are estimated from the taken images by using a ray tracing technique.

In the next section, we define a ray leaving a light source and propose the method for sampling it. From the sampled data, we estimate radiant intensity and a direction of a ray from a distribution of rays leaving a light source. In section 3, the accuracy of the estimation in the proposed method is evaluated by a numerical simulation. A ray from a distribution of rays leaving a real light source is also sampled by the proposed method. As a preliminary experiment, in section 4, we measure BRDF of a real object by using the light source whose rays are sampled. From the measured data, we estimate diffuse reflectance of the object.

Method for Sampling a Ray from a Distribution of Rays Leaving a Light Source

Definition of a Ray from a Distribution of Rays Leaving a Light Source

In a practical case, a light source can not be assumed to be an ideal point light source, because distance between a light source and illuminated objects is not usually long enough and a size for a light plane of a light source is not infinitely small. In this paper, we assume that a light source is composed of an array of point light sources on a light plane, and each point light source has own radiant intensity and directional distribution of rays leaving it. The light plane is located just in front of the light source. The light plane and the point light sources are defined as Unger et al.,[3] although they defined an incident light field which describes incident lights toward an object.

Figure 2 shows the point light sources on a light plane, and an outgoing ray leaving a point light source. Radiant intensity I of the outgoing ray toward the direction (θ,ϕ) is defined as $I(u,v,\theta,\phi)$. The position of a point light source is defined as (u,v). Incident radiant intensity at a position $\boldsymbol{r}$ in 3D space is described as summation of radiant intensity of outgoing rays leaving each point light source on the light plane as follows:

$$D(\boldsymbol{r}) = \sum_{u}\sum_{v} \frac{I(u,v,\theta,\phi)}{(\boldsymbol{r} - \boldsymbol{p}(u,v))^2}, \tag{1}$$

where $\boldsymbol{p}(u,v)$ is a position of a point light source on a light plane in 3D space.

Sampling a Ray from a Distribution of Rays Leaving a Light Source Using a Mirrored Ball and a Pinhole Camera

Figure 3 shows geometry for sampling a ray from a distribution of rays leaving a light source using a mirrored ball and a pinhole camera. In this figure, a ray reflected by the mirrored ball is captured by the pinhole camera. Figure 4 shows how a ray leaving the light source is reflected by the mirrored ball. Let us explain the detail of the reflection in 2D space instead of the 3D space for simplicity. A ray from a light plane to the outgoing angle θ_o is reflected to the angle θ_r on the surface of the mirrored ball. We only consider the case that reflected rays go to the left side of the mirrored ball in Fig. 4. The range of reflected angle is then described as $0 \le \theta_r \le \pi \; (-\pi/2 \le \theta_o \le \pi/2)$. Figure 5 shows an example of relation between θ_o and θ_r of a ray at the decided position of the light source. In this figure, the horizontal axis indicates an outgoing angle θ_o of rays leaving a light source and the vertical axis indicates a reflected angle θ_r of rays by the mirrored ball. From the ruler in this figure, it is found that a range of a reflected angle is five times wider than that of outgoing angle. The reflection on the mirrored ball can expand an outgoing angle of rays. By this expansion, we can capture rays with high angle resolution for an outgoing angle of them.

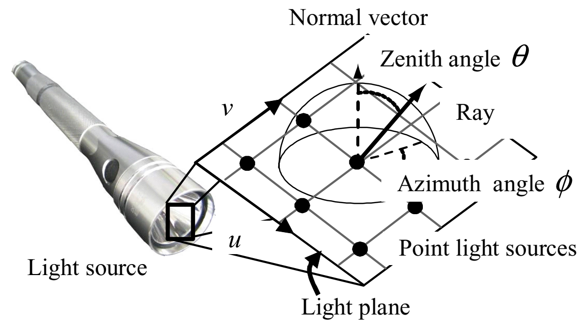


Figure 2. Ray leaving a point light source on a light plane

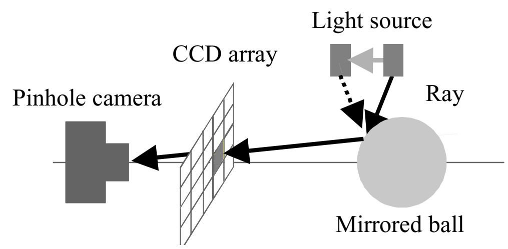


Figure 3. Geometry for sampling a ray from a distribution of rays leaving a light source

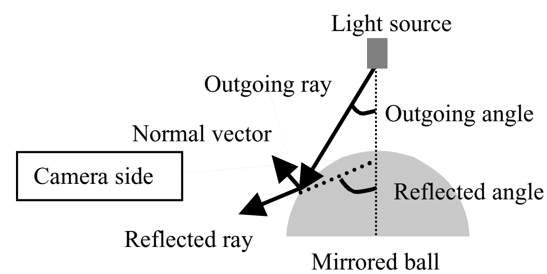


Figure 4. Reflection of a ray leaving a light source

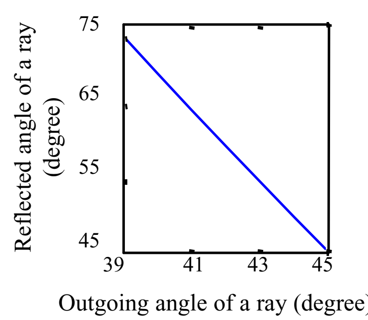


Figure 5. Example of relation between an outgoing angle and a reflected angle of a ray

A part of rays leaving point light sources on the light plane is captured by the pinhole camera at the decided position of the light source. Therefore the position of the light source is moved as shown in Fig. 3 to sample every ray from other point light sources to other directions. Images are taken at each position of a light source. The pinhole camera is used to improve the directional resolution for incoming rays to each pixel on CCD. Without a pinhole camera, rays coming from different directions go into the same pixel.

Dynamic range is usually wide in radiant intensity of rays leaving a light source. To measure the radiant intensity precisely, rays are captured as high dynamic range (HDR) images by the method of Debevec[5] in the proposed method.

Estimation for Radiant Intensity and a Direction of a Ray from a Distribution of Rays Leaving a Light Source

Radiant intensity and a direction of a ray from a distribution of rays leaving a light source are estimated from many HDR images of rays taken in the measurement. They are estimated by a ray tracing technique from a pixel of CCD array in the pinhole camera to point light sources.

For this estimation, it is required to capture images of every ray leaving the light source. However, the number of the images becomes a quite large in this case. In this paper, discrete radiant intensity of sampled rays which go toward other direction is fitted to a Gaussian distribution or a polynomial to estimate continuous values for radiant intensity of rays leaving the light source.

Evaluation of the Proposed Method

Evaluation of the Proposed Method by a Numerical Simulation

We evaluated the accuracy of the estimation in the proposed method by a numeral simulation. In the evaluation, a light source is simulated as composed by five point light sources on a light plane as shown in Fig. 6.

These point light sources have different isotropic radiant intensity distribution of rays leaving them each other. The radiant intensity distribution is calculated with a Gaussian distribution and is shown as a solid line in Fig. 6. In this figure, the radius indicates radiant intensity and the angle indicates outgoing zenith angle of rays leaving a point light source on a light plane. In the simulation, we set a diameter of a pinhole lens at 0.2 millimeters based on the pinhole lens used in the experiment in the next sub-section.

Estimated radiant intensity of rays leaving each point light source is also shown as a broken line in Fig. 6. From this figure, we can see that radiant intensity of rays leaving a light source is estimated accurately by the proposed method.

Experiment for Sampling Radiant Intensity of a Ray from a Distribution of Rays Leaving a Real Light Source

We sampled a ray from a distribution of rays leaving a real light source. Geometry for the experiment is shown in Fig. 7. In the experiment, the light source was a flashlight (DOP-10SL: ASAHI ELECTRIC CORPORATION), a pinhole lens was PINHOLE LENS02 (KENKO), a digital camera was D1x (NIKON), and robot arm (RV-1A: MITSUBISHI) was used for positioning the light source. The distances between the light and the mirrored ball, and the camera and the mirrored ball were 10 and 20 centimeters, respectively. We positioned and moved the light source along a straight line between the camera and the mirrored ball at intervals of 0.25 centimeters. HDR image of rays leaving the light source was taken at each position. We took 66 HDR images in this experiment.

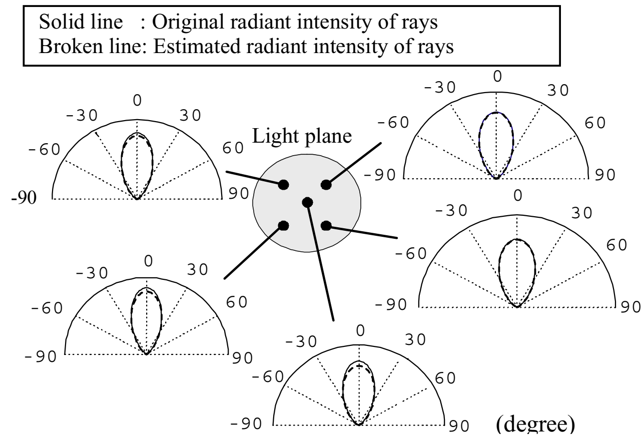


Figure 6. Estimation for radiant intensity of rays leaving a light source

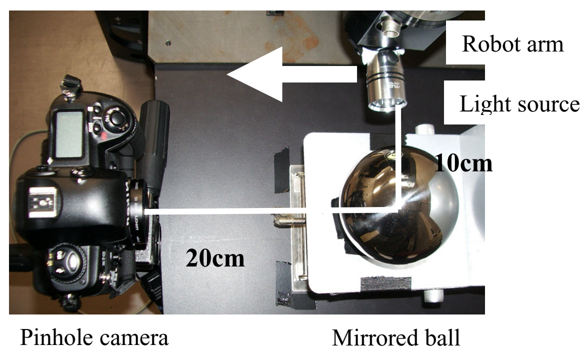


Figure 7. Geometry for sampling a radiant intensity of rays leaving a light source by using a mirrored ball and a pinhole camera

Figure 8 shows an example of estimated radiant intensity of rays leaving a point light source on a light plane by dots. In this figure, the horizontal axis indicates an outgoing zenith angle of a ray leaving a point light source, and the vertical axis indicates relative radiant intensity of a ray which is normalized by the maximal radiant intensity of sampled rays. The estimated radiant intensity of rays leaving a point light source is discrete because it was estimated from the 66 HDR images. We fitted the discrete radiant intensity of rays to a polynomial to estimate the continuous values for radiant intensity of rays. The fitted radiant intensity of rays leaving the point right source is also shown by a solid line in Fig. 8.

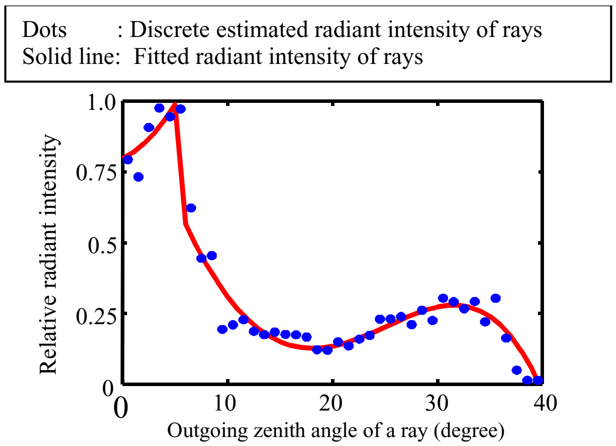


Figure 8. Example of estimated and fitted radiant intensity of rays leaving a point light source on a light plane

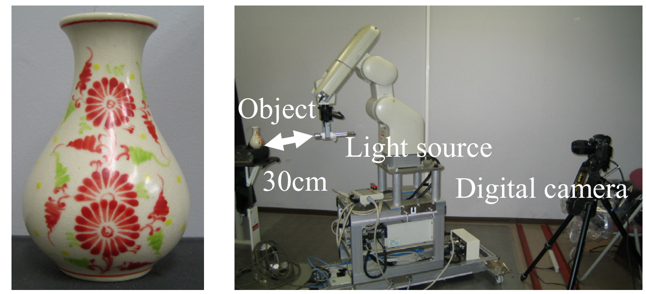
From the estimated radiant intensity of rays, we can see a strong directional distribution for radiant intensity of rays leaving a light source, since it is a LED light source and a head part of a light source reflects rays of a LED light forward. From this measurement, we found that a relative position among the digital camera, the mirrored ball and a light source should be controlled precisely for the accurate measurement. We also found that the optimization for positions of a light source must be considered, because they influence the accuracy of the fitting operation in the estimation for continuous values of radiant intensity of rays leaving a light source.

Estimation for Diffuse Reflectance of a Real Object Illuminated from a Short Distance by a Light Source

Measurement for BRDF of a Real Object Illuminated from a Short Distance

As a preliminary experiment, we measured BRDF of a real object illuminated from a short distance by the light source whose rays were sampled by the proposed method in the last section. In this experiment, we estimated diffuse reflectance of the measured object from the taken images in the measurement. The measured object is shown in Fig. 9(a). The whole part of the measured object has almost similar reflectance property, although some parts of the measured object are painted. Therefore estimated diffuse reflectance should be similar in the whole part of the measured object. From the estimated diffuse reflectance, we show the effectiveness of the proposed method.

We set the distance between the light source and the measured object at 30 centimeters as shown in Fig. 9(b). Figure 10 shows a diagram of the measurement. We illuminated the object from the angle. The angle was from 10 degrees though 50 degrees at intervals of 10 degrees. In the measurement, 3D shape of the object was measured by 3D digitizer Vivid910 (KONICA MINOLTA) and images of the object illuminated from arbitrary directions were captured by D1x (NIKON). From 3D shape of the object and the captured images, diffuse reflectance of the object was estimated by the method of Tonsho et al.[6]



(a) Measured object (b) Geometry for BRDF measurement

Figure 9. Measured object and geometry for BRDF measurement

We estimated diffuse reflectance of the measured object by three methods: two conventional methods and the proposed method where the radiant intensity of rays leaving the light source is considered. In conventional method #1, incident light to the object is assumed as a collimated light, although the distance between the measured object and a light source was 30 centimeters as described above. In conventional method #2, the light source was assumed as a point light source whose rays have a constant radiant intensity for outgoing direction. In the proposed method, the radiant intensity of rays sampled in the last section was used for the diffuse reflectance estimation. Lower part of Fig. 11 illustrates incident rays assumed in each method. The estimated diffuse reflectance of the measured object by the three methods is shown in upper part of Fig. 11.

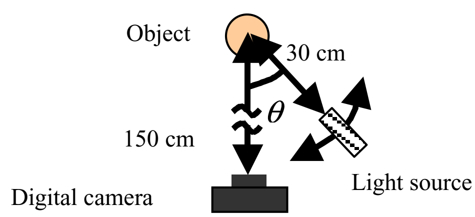


Figure 10. Diagram of BRDF measurement

In conventional method #1, radiant intensity and a direction of incident rays to all part of the measured object is assumed to be the same. In the actual case, however, the radiant intensity of incident rays to the center parts of the measured objects is stronger than that to the other parts of it, since the light source has a radiant intensity distribution of rays and the distance between the light source and the center parts of the measured object is shorter than the distance between the light source and the other parts of the measured objects. Furthermore, the assumption for a direction of incident rays is not correct, because the distance between the light source and the measured object is only 30 centimeters. These mistaken assumptions cause the error for the estimation of diffuse reflectance. That's why diffuse reflectance for the upper and the lower parts of the measured object was estimated to be lower.

In conventional method #2, a direction of incident rays is approximated to be that of the real incident rays as shown in Fig. 11. However, intensity of incident rays is stronger than that of real radiant rays because the light source has a radiant intensity distribution of rays. Therefore estimated diffuse reflectance by conventional method #2 is similar to the result of the conventional method #1. On the other hand, the estimated diffuse reflectance by the proposed method has similar reflectance property in the whole part of the measured object. From these comparisons, we can see that BRDF of objects can be estimated by the proposed method, when the objects are illuminated from a short distance.

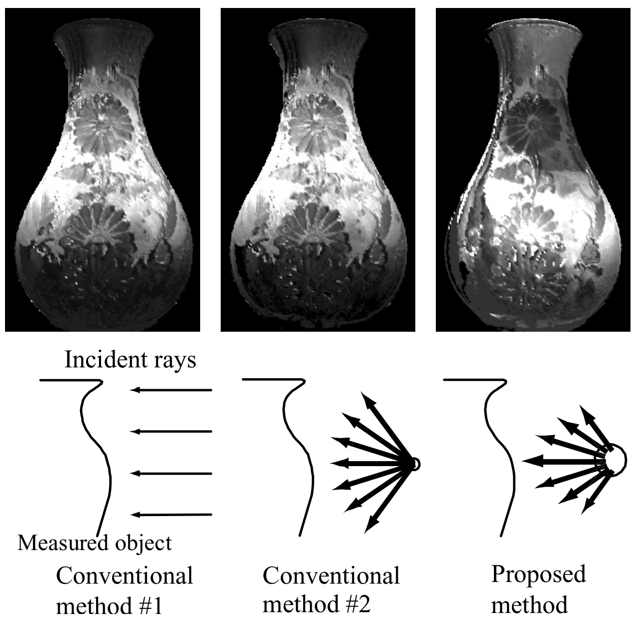


Figure 11. Estimated diffuse reflectance of the measured object by three methods and illustrations of incident rays assumed in each method

Conclusion

We proposed the method for sampling a ray from a distribution of rays leaving a light source, and used the sampled light source to illuminate a real object for BRDF measurements. The accuracy of the estimation in the proposed method was evaluated by a numerical simulation. By using the proposed method, we also sampled a ray from a distribution of rays leaving a real light source. In the measurement, we found that a relative position among a digital camera, a mirrored ball and a light source should be controlled precisely for the accurate measurement.

As a preliminary experiment, we measured BRDF of a real object illuminated from a short distance by the light source whose rays were sampled by using the proposed method. In the experiment, we could see that the proposed method estimated the diffuse reflectance of the measured object better than the conventional methods, although their experimental set-ups were not appropriate. From the comparison, we found that the accuracy of the BRDF estimation highly depends on radiant intensity and a direction of a ray from a distribution of rays leaving a light source in the case that measured objects are illuminated from a short distance. For the accurate BRDF estimation, we should sample a ray from a distribution of rays leaving a light source precisely.

For a practical application, we will construct a simple and compact BRDF measurement system as shown in Fig. 1. The proposed method becomes the first step of the BRDF measurement system. In the future system, we are expected to measure BRDF of objects out of the laboratory.

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Author Biography

Koichi Takase was born in Ishikawa, Japan, on Jan. 31 1980. He received his B.E. and M.E. degrees in department of information and image science, and computer science from Chiba University in 2002 and 2004, respectively. Now he is a PhD candidate in Chiba University. He got the Optics Prize for Young Scientists (The Optical Society of Japan) in 2005. His research interests include image-based rendering, image analysis and GPGPU.