Measurement of Bidirectional Reflectance Distribution Function with Linear Light Source

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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 a Bidirectional Reflectance Distribution Function (BRDF) at each point on objects accurately to properly preserve reflectance properties such as colors, diffuse albedo, specularity and roughness. Much research has been devoted to BRDF measurements [1, 2]. In the research, a number of the image acquisitions of the object illuminated under various light conditions are necessary to obtain the specularity at all points on the objects. To reduce the number of the acquisitions, reflectance properties are interpolated from sparsely measured ones. It is useful for objects which have uniform reflectance properties. However, the interpolation cannot reproduce specially-varying reflectance properties, and cause the degradation of the image quality. Not only the capturing problem of the specially-varying reflectance properties, but the problem of measurement spaces and devises must be addressed in the BRDF measurement. In conventional method, a parallel light is used to illuminate objects to make the incident direction and the radiance of the light constant. To collimate the light source, it is required to use huge measurement spaces and devises. For a practical application, it is necessary to construct a simple and compact BRDF measurement system.

In this paper, we present an efficient BRDF measurement system for 3D objects with a linear light source. A comparison between the conventional and our measurement systems is shown in Fig. 1. By the linear light source, we can capture the specularity at more points than by the parallel light in one measurement as shown in Fig. 2. Furthermore, moving and positioning the linear light source on only one direction, we can capture the specularity at almost all points on the object. To estimate reflectance properties from the captured images, we measure a light field of the linear light source to determine incident direction and radiance from the light source to points on the objects. Because we know how rays from the light source come into the object, we can illuminate the objects at short distance as shown in Fig. 1.

Nishita et al. rendered objects illuminated by a point light source with a radiance distribution and by a linear light source emitting constant radiance rays [3]. Poulin and Amanatides proposed a rendering method for objects illuminated by a general linear light source with integral approximations [4]. Gardner *et al.* [5] measured a BRDF of flat and non-flat surfaces with a linear light source, and estimated the BRDF based on Poulin and Amanatides' method. Although our measurement system is similar to that of Gardner *et al.*, we measure a BRDF of 3D objects instead of flat objects. In their method, they created a virtual version of a linear light source and used it to simulate the appearance of flat surfaces which have various reflectance properties. The appearance was tabulated to estimate reflectance properties of a real flat surface. However they could not estimate reflectance properties when geometry of the linear light source and a measured object are different from that in the numerical simulation. From this reason, it was difficult to reproduce 3D objects with their method. In our method, we measure a light field of an actual linear light source, which represents radiance distribution from the light source. Because radiance and incident direction from the linear light source to each point on 3D objects are obtained from the light field, we can estimate the reflectance properties of the objects.

In the modeling of a light source, Verbeck *et al.* [6] and Ngai [7] modeled a light source as a point light source or an array of point light sources. The light field of the light source was described by a goniometric diagram which is a two dimensional angular representation of the directional distribution. Ashdown modeled the light field as a four dimensional function which describes radiances to directions (θ, ϕ) from positions (u, v) on a virtual sphere surrounding a light source [8]. Ashdown also measured the light field by a digital camera observing a light source from many positions on the virtual surrounding sphere. Furthermore, recently Goesele *et al.* [10], Unger *et al.* [11] and Takase *et al.* [12] measured the light field of a light source more accurately with some devises (e.g. a mirrored ball). In this paper, we model the linear light source as a series of point light sources by Verbeck *et al.* and Ngai's method, and simply measure its light field with Ashdown's measurement system.

Much work has been done to analytically model reflectance properties of real objects. Torrance and Sparrow derived a reflectance model where the surface of an object is composed of a collection of mirror like microfacets [13]. Ward proposed an empirical reflectance model which is simple and accurate for most objects [14]. Oren and Nayar proposed a diffuse reflectance model for rough surfaces instead of the Lambert reflectance model [15]. In this paper, we use the Lambert and the Torrance-Sparrow reflectance models to estimate diffuse and specular reflectance properties of an object, respectively.

The remainder of this paper is organized as follows. In the next section, we describe the light field of a linear light source is described as a three dimensional function, and perform the measurement of the light field. Using the linear light source, a BRDF of a 3D object is measured in section 3. In this section, a shape and surface normal of the object are also measured by a 3D digitizer. In section 4, the BRDF of the object is estimated with the Lambert and the Torrance-Sparrow reflectance models, and is rendered in real time using a graphic hardware. From a comparison among an actual image and rendered images in conventional and proposed methods, we validate the accuracy of the estimation by the proposed method. Finally, a conclusion and a discussion of future work are presented in section 5.

2. Measuring Light Field of Linear Light Source

2.1 Light field of linear light source

In this paper, we model a linear light source as a series of point light sources with a radiance distribution as shown in Fig. 3. The point light sources are arranged on a center of the linear light source, and emit rays to various directions with different radiances. The radiance distribution of the linear light source is composed of the radiance distribution of each point light source, which is called a light field [11, 16, 17]. The light field describes radiance I of a ray toward a direction (ϕ, θ) from a position u of a point light source as $I(u, \phi, \theta)$. Although the light field is originally defined as a four dimensional function, it is described as a three dimensional function in this paper.

2.2 Measurement of light field of linear light source

We measure a light field of a linear light source (Xe lamp, FX) by Ashdown's method [6] and use it to capture images of an object for a BRDF measurement in the next section. The linear light source is with 33.0 cm in length and 1.0 cm in diameter. In this paper, we divide the linear light source into 101 point light sources and assume the radiance distribution of each point light source in the linear light source is the same, and apply a measured radiance distribution of a point light source to a radiance distribution of the others. Therefore we only measured the radiance distribution of one point light source. Let us explain the experimental setup of the measurement in Fig. 3 and Fig. 4. Because the back side of the linear light source is covered by a reflector, we define that a surface normal is the center of the uncovered face as shown in Fig. 4 (a), and perpendicular to the U axis in Fig. 3. A digital camera (D1X, Nikon) observed radiance from the point light source, and was moved around the point light source on two ways. One is the way around the U axis (Fig. 4 (a)) and the other is the way on the plane composed of the U axis and the surface normal (Fig. 4 (b)). As the direction of the surface normal is zero degrees, the digital camera was positioned from -75.0 to 75.0 degrees at 5.0 degrees intervals on the both way. The measured radiances are shown as dashed lines in the upper side of Fig. 4. In this figure, radiance of each outgoing angle is normalized by radiance at zero degrees. Some spiky peaks are shown in the measured radiances. The peaks are caused by a flicker of radiance of the light source. From another experiment which is not shown in this paper, it is found that this linear light source has three-percent radiance variation against its max radiance at one outgoing angle, although the light source is connected to an electric ballast. Another linear light source without the electric ballast has 10-percent radiance variation in the same experiment. From the results, we consider that it is permitted to use the linear light source with the electric ballast.

To obtain continuous radiance distribution, the measured sparse radiance distribution is approximated by a polynomial. The approximated radiance distributions are shown as solid lines in Fig. 4, and used for the BRDF measurement in the next section.

3. Measurement of Bidirectional Reflectance Distribution Function with Linear Light Source

3.1 Experimental setups and acquired images

We measured a BRDF of an 3D object illuminated at short distance by the linear light source whose the light field was measured in the last section. Figure 5 and 6 show geometry of the measurement. The linear light source was moved along the X axis and positioned at 36 points from -28.0 cm through 28.0 cm by a robot arm (RV-2A, Mitsubishi). The object and a digital camera (D1X, Nikon) were located at $(0.0, 5.0)$ and $(0.0, -160.0)$ [cm], respectively. For evaluation of efficiency and accuracy of the measurement by the proposed method, we also measured the same object by a conventional method. In the conventional method, the object was illuminated by a parallel lightfrom 36 directions. To collimate the light, the object and the light source were separated at intervals of one meter.

The difference between radiances of diffuse and specular reflection was too wide to obtain them simultaneously. To measure reflected radiances accurately, the object was captured as high dynamic range (HDR) images by the method of Debevec and Malik [18]. In our measurement, the light field was captured three times with different shutter speeds at each light position. As the result of the image acquisition, the HDR images at several light positions are shown in Fig. 7.

3.2 Measurement and result of shape acquisition

In the BRDF measurement, three dimensional shape and surface normal of the object were measured by a laser range scanner (Vivid910, Konica Minolta). From this measurement, 156,458 polygons and surface normal were obtained and are shown in Fig. 7. In this figure, the number of polygons of the object is reduced for the visualization. For an alignment between the polygons and the HDR images acquired in the last subsection, a projection matrix from points composing the polygons to pixels in the images was calculated from corresponding points and pixels which were manually selected. A root mean square error between positions of corresponding pixels was less than a few pixels, and it is considered that the error of the projection does not cause serious error of the BRDF estimation.

4. Reflectance Model Fitting and Reproduction of Object

4.1 Dichromatic reflection model

Before the estimation of the reflectance properties of the object, we separate the measured pixel values at each point to diffuse and specular reflectance components based on a dichromatic reflection model [19]. A reflection $f_r(\omega_o, \omega_i)$ at a surface point p is composed of the diffuse color $C_o(p)$ and the reflection components as follows.

$$f_r(p, \omega_o, \omega_i) = C_o(p) f_{rd} + C_l f_{rs}(\omega_o, \omega_i) \tag{1}$$

where (ω_o, ω_i) denotes a pair of directions from a surface point p to a light source and a viewer, respectively, f_{rd} and f_{rs} are the diffuse and the specular reflection, and C_i are color of the light source. Sato *et al.* performed the separation with RGB pixel values and a direction of an incident light to an object [20]. In our case, many lights come into an object simultaneously and only one pixel value is obtained at one light position. Therefore we cannot separate them in the same manner. From the reason, we separate a diffuse color, the diffuse and the specular reflection components from color information of the light source as Tonsho *et al.* [21]. Figure 8 shows the obtained diffuse colors of the object in the conventional and proposed methods.

4.2 Estimating parameters of reflectance model

To obtain reflectance properties of the object, we use the Lambert and the Torrance-Sparrow reflectance models to fit them into the diffuse and the specular reflection components obtained in the last subsection, respectively. These reflectance models are described as follows:

$$f_{rd} = \frac{\rho_d}{\pi}, \tag{2}$$

$$f_{rs}(\mathrm{p}, \omega_o, \omega_i) = \rho_s \frac{D(\omega_h) G(\omega_o, \omega_i) F(\omega_o)}{4 \cos\theta_o \cos\theta_i}, \tag{3}$$

where ρ_d and ρ_s represent the diffuse and the specular parameters, respectively, and (θ_o, θ_i) shows a pair of angles between a surface normal and ω_o, a surface normal and ω_i, respectively.

In the Torrance-Sparrow reflectance model, D, G and F denote a microfacet distribution, a geometric attenuation term and Fresnel reflection, respectively. D and G are shown as,

$$D = \frac{\sigma + 2}{2\pi}(\omega_h \cdot \mathbf{n})^{\sigma}, \tag{4}$$

$$G = \min\left\{1, \frac{2(\mathbf{n}\cdot\omega_h)(\mathbf{n}\cdot\omega_o)}{(\omega_o\cdot\omega_h)}, \frac{2(\mathbf{n}\cdot\omega_h)(\mathbf{n}\cdot\omega_i)}{(\omega_o\cdot\omega_h)}\right\}, \tag{5}$$

where $\mathbf{n}$ represents a surface normal, ω_h is a half vector between ω_o and ω_i and σ represents a standard deviation of a micro facet slope.

The parameters (ρ_d, ρ_s, σ) were estimated at each pixel on the acquired image by a least square fitting operation. In the estimation of the parameters, the linear light source was assumed to be composed of 101 point light sources to determine ω_i and radiance I to surface points of the object. As examples of the result of the estimation, fitted diffuse and specular reflection components, and maps of each parameter are shown in Fig. 9 and Fig. 10, respectively. In the former figure, reflection components are normalized for visibility. From the upper side of this figure, it is found that the estimation was performed accurately at each reflection component. However the estimation is failed when the direction ω_i is not correct, which is caused by a sampling rate of the linear light source. As we discuss the problem of the sampling rate in section 5, the rate should be considered carefully. From Fig. 10, a part of the specular reflectance and surface roughness parameters in the conventional method could not be estimated, although the part was estimated in the proposed method. This is because specular reflection could not be measured in the part in the conventional method. In the proposed method, lights from more directions than in the conventionalmethod come into the object due to the shape of the linear light source. Therefore specularity in the the part could be measured in the proposed method. From this result, we can see that the efficient measurement is performed in the proposed method.

It is also found that the spatially-varying diffuse and specular reflectance properties were obtained without their interpolations by moving the linear light source in only one direction. Furthermore, we can see small differences of reflectance properties on the same materials.

4.3 Reproduction of object

In this section, we render the object with graphic hardware from the reflectance properties measured by the conventional and the proposed methods. By comparing the rendering results and an actual image, we compare the accuracy of the estimation by the conventional and the proposed methods. In the conventional method, reflectance properties of the object were estimated in the same manner of the proposed method. The rendered images are shown in Fig. 11. Diffuse colors of the real and the conventional images are the same because the measurements were performed with the same light source. A difference of the diffuse color between in the conventional and the proposed methods is due to the difference of the light sources. In the case of the diffuse and the specular reflections, the appearances are the almost same. We can see this reason from the estimated parameters in Fig. 10. The estimated parameters are the almost same except the part where the parameters could not be estimated.

5. Conclusion and Discussion

This paper presented an efficient BRDF measurement system with a small measurement space using a linear light source. Moving the linear light source on only one direction, we can measure diffuse and specular reflectance properties of 3D objects. In the BRDF measurement, its HDR images were acquired by illuminating an object from a short distance. Due to the short distance measurement, a parallel light cannot be assumed in this measurement. To know how alight comes into the measured object, therefore, a light field of a linear light source was measured by observing the light source from many directions with a digital camera by Ashdown' method. From the obtained HDR images and the light field of the light source, we estimated BRDF parameters of each point on the object. An interpolation of the parameters was not necessary in the proposed system, because diffuse and specular reflection components were densely obtained using the linear light source. We performed a real-time rendering of the object with the parameters estimated by the conventionaland proposed methods, and compared the results to validate the effectiveness of the estimation. From the comparison, we could see that the BRDF parameters were measured at more points on the object, and the same accuracy of the estimation was obtained, although the measurement space of the proposed method was quite smaller than that of the conventional method.

In the measurement of the BRDF, the linear light source was simply moved in one direction. For an efficient measurement of a specular reflection component, we could find that moving the linear light source around the object can reduce the measurement time. It is because a specular reflection component at almost the same points is only acquired when the linear light source is distant from the object. To illuminate the object from a short distance, a light field of a linear light source was measured by Ashdown's method in section 2.

In the BRDF estimation, the linear light source was specially sampled and was assumed to be composed of 101 point light sources. The location of the point light sources especially influences accuracy of the estimation of a specular reflectance parameter. The sampling rate of the linear light source should be optimized for the accurate BRDF estimation. Although a result of the accurate estimation will be obtained with many point light sources, the time of the estimation is increased significantly. In this case, it is useful for the reduction of the duration time to use a fast estimation method [22] of reflectance function.

Polygons and surface normals measured by a 3D digitizer were projected to the HDR images captured at a various light positions. To calculate the projection matrix, we selected corresponding polygons and pixels manually. It takes much time and causes an alignment error. Using Nehab et al.'s estimation method [23] for a shape and surface normals, it will be unnecessary to align polygons and pixels, because we can obtain the shape, the surface normal and the images by the same camera. This method is expected to reduce the time and error of the estimation in our system.

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Figure captions

Figure 1. Comparison between BRDF measurements. (a) Measurement with a distant light source. (b) Measurement with a linear light source from a short distance.

Figure 2. Comparison of specular reflection caused by different illuminants (a) Object illuminated by a parallel light. (b) Object illuminated by a linear light source.

Figure. Flow diagram of a proposed method.

Figure 3. Light field of a linear light source.

Figure 4. Measured light field of a linear light source. (a) Side view parallel to U axis. (b) Side view perpendicular to U axis.

Figure 5. Geometry of a BRDF measurement.

Figure 6. Illustration of geometry of a BRDF measurement.

Figure 7. Flow diagram of a proposed method

Figure 8. Estimated diffuse color of an object. (a) conventional method. (b) proposed method.

Figure 9. Measured and estimated reflections at a sample point. (a) Diffuse reflection. (b) Specular reflection.

Figure 10. Estimated model parameters. (a) Parameters estimated by conventional method. (b) Parameters estimated by proposed method.

Figure 11. Comparison of real and rendered objects. (a) Real image. (b) Conventional method. (c) Proposed method.