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Simultaneous Measurement of BRDF and Surface Curvature by using Pattern Illumination

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Abstract

In this study, we propose the simultaneous measurement method of the bidirectional reflection distribution function (BRDF) and the radius of curvature by using pattern illumination. For non-planar objects, the angle of reflection light changes according to the surface normal angle of curved object. Therefore, it is necessary to consider the effects of curved surfaces when measuring the BRDF on non-planar surfaces. We suppose a convex surface that can be represented by a constant radius of curvature. The pattern of illumination was generated by placing the illumination mask with pattern apertures in the incident light path of the BRDF measurement apparatus in which the incident light is collimated light. We developed the measurement apparatus. We measured four types of sample with different BRDFs on three different radiuses of curvature. The results showed that the BRDF and the radius of curvature can be measured simultaneously by using the pattern illumination.

1. Introduction

Gloss, an important property of materials, affects product texture and thus appearance. In a dichromatic reflection model, the intensity of the reflected light is the sum of the diffuse reflection and the specular reflection. As shown in Fig. 1, part of the incident light is absorbed, scattered, and widely reflected in all directions. This is called diffuse reflection. The printed image is observed as a diffuse reflection phenomenon. Specular reflection is the mirror-like reflection of the light source from a surface. Specular reflection is a much more directional reflection. Gloss is a specular reflection phenomenon.

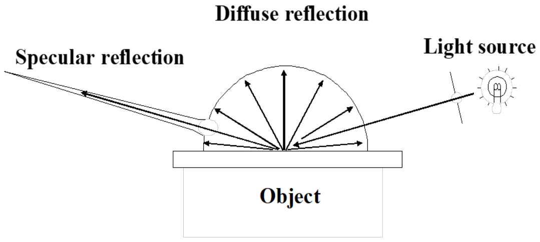


Figure 1. Schematic diagram of a dichromatic reflection model.

The characteristics of specular reflection can be represented by the bidirectional reflection distribution function (BRDF). The BRDF represents how much light is reflected in each direction when light enters from a certain direction at a certain point on the reflecting surface. These reflectances at the deviation angle can be measured using a goniophotometer for example [1]. As shown in Fig. 2, a goniophotometer has a movable detector for measuring the reflectance at various angles for a given angle of incident light.

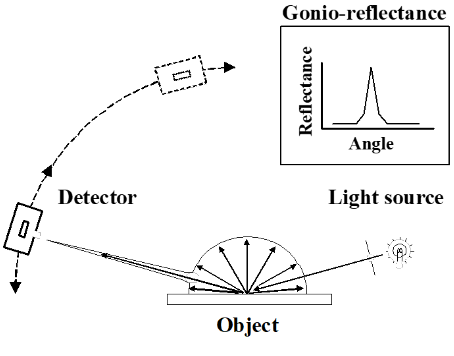


Figure 2. Schematic diagram of goniophotometer and gonio-reflectance.

Measurement techniques for BRDFs have been proposed for various lighting environments and observation conditions [2-6]. Many BRDF measurements assume that the sample surface is planar.

On the other hand, these measurement targets are not limited to planar surfaces. The BRDF is used for quality control as a physical property of industrial materials. The BRDF is also used in computer graphics as the material's reflective properties. There may be already molded products or artworks. The surface of these objects is not always flat.

We suppose a convex surface that can be represented by a constant radius of curvature. For non-planar objects, the angle of reflection light changes according to the surface normal angle. As shown in Fig. 3, if the object surface has an angle, incident light is reflected in certain direction at the point. The reflection angle by this surface is measured in addition to the BRDF of the material. In the actual BRDF measurement, the area irradiated by the incident light is not a point but an area. Therefore, if the object to be measured is not a planar surface, the reflection angle will change at each position of the measurement area and accurate measurement will not be possible.

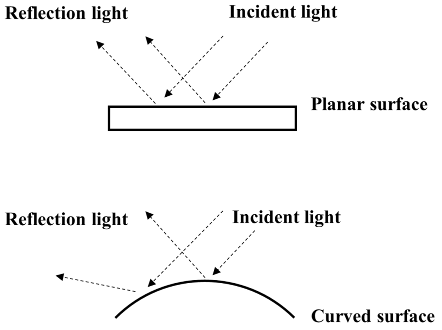


Figure 3. Schematic diagram of reflection on a curved surface.

Image-based BRDF measurement methods were reported [7-9]. These measurement objects were a convex solid, and had a curved surface. This method, however, is complicated because it requires moving the light source at each measurement angle.

In this study, we introduce measurement method for the simultaneous measurement of the BRDF and radius of curvature. For this purpose, we used collimator optical system and pattern illumination. This method is a simple one that can be measured with one shot of camera. We developed a measurement apparatus. It is shown the measurement results of four types of sample with different BRDF on three different radiuses of curvature. We discuss how to estimate the BRDF and the radius of curvature simultaneously.

2. Theory

2.1 Pattern illumination method

In this study, we try the simultaneous measurement of BRDF and surface curvature. Assume a BRDF measuring apparatus that can measure the angle of reflected light. It is considered that the BRDF can be measured at two positions by dividing the incident light into two positions within the measurement area. For this purpose, a mask with two holes is installed on the incident light pass. It is assumed that the curvature of the object surface is a curved surface that can be represented by a constant radius of curvature within a small area. The radius of curvature can be estimated by knowing the two positions on this surface and the normal angle difference. In this paper, we propose this method as the pattern illumination method.

We use a collimator optical system for the measurement of the BRDF and radius of curvature. Figure 4 shows a diagram of apparatus for measuring BRDF based on the pattern illumination method. This BRDF measuring apparatus is based on the gonio-reflectance distribution measurement method reported by the authors [2]. It has been modified for the addition of an illumination mask with pattern apertures and for 45 degrees measurements.

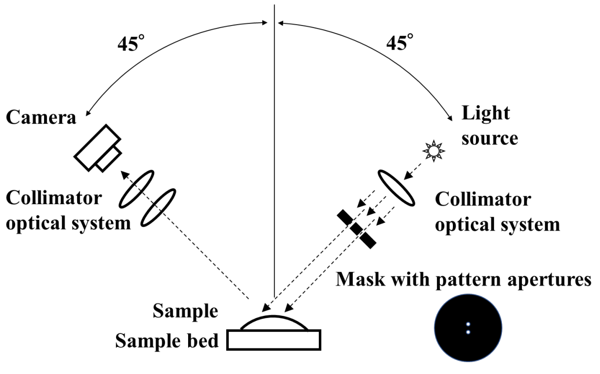


Figure 4. Diagram of apparatus for measuring BRDF based on the pattern illumination method.

2.2 Measurement for reflection angle by using collimator optical system

We use a collimator optical system for the measurement. This background is the gonio-reflectance distribution measurement method reported by the authors [2]. In the collimator optical system, a focal position is determined by the angle of the input light. The collimator optical system has a focus on one side of the lens, and the other side is parallel light. The focal position is determined by the angle of parallel light, which is calculated by the position of the focal plane. The schematic diagram of a collimator optical system is shown in Fig. 5. The distance from the center, d, is calculated with the incident light angle, Δθ, and the focal length, f, in Eq. (1).

$$d = f \cdot \sin(\Delta\theta) \qquad \text{--(1)}$$

This feature of the collimator optical system was used to measure the reflection angle distribution and surface normal angle.

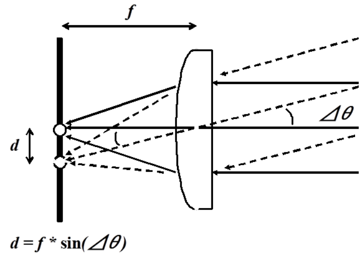


Figure 5. Schematic diagram of collimator optical system. Focal point distance, d, can be calculated from focal length, f, and incident light angle, Δθ.

2.3 Estimating radius of curvature

It is shown that the schematic diagram for radius of curvature in Fig. 6. The radius of curvature can be estimated by knowing the two positions on the surface and the normal. The distance of positions, Δx, is the distance of incident light.

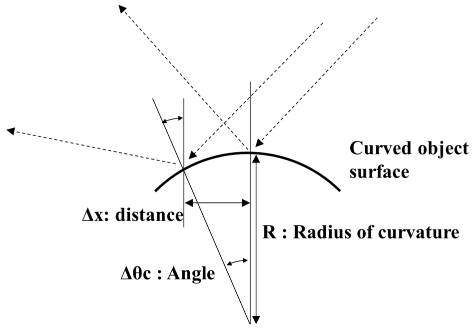


Figure 6. Schematic diagram of geometry of curved surface. The radius of curvature, R, can be calculated from position distance, Δx, and the normal angle difference, Δθc.

The radius of curvature, R, is calculated with the normal angle, Δθc, and the distance of positions, Δx in Eq. (2). The normal angle is measured from the reflection angle distribution of each BRDF . Here, the measured reflection angle is twice the normal angle.

$$R = \Delta x / \sin(\Delta\theta c) \qquad \text{--(2)}$$

2.4 Estimating BRDF

This apparatus is based on the gonio-reflectance distribution measurement method reported by the authors [2]. The apparatus functions as a goniophotometer within a narrow solid angle. Therefore, the measured reflectance distribution is BRDF.

3. Experiments

3.1 Apparatus

We developed a BRDF measurement apparatus based on the pattern illumination method. Figures 4 and 7 show the apparatus used to measure the BRDF and surface curvature in this study. The light source and the observation angles are set to 45°. The light from the light source is collimated by the collimator optical system. The camera captures the reflection light that has passed through the collimator optical system. The focal length, f, (shown in Fig. 5) is 50.1 mm in the collimator optical system. The magnification at the camera image is 0.7. The image resolution of the CCD camera is 1960×1200 pixels, and it has a 12-bit output level per pixel. The size of one pixel corresponds to 0.00586 mm. The output values can be used as the light intensity because the linearity between the output values and the light intensity was confirmed in advance. The sample is set on the sample bed, and the measurement was done in a darkroom. There were 3 sample beds, a flat sample bed, a curved sample bed (R = 125 mm in Fig. 7) and a cylindrical curved sample bed (R = 62.5 mm). We prepared and measured a black glass whose refractive index is 1.567 to perform the calibration process for the measured values. The relative magnification of this experiment is 1.0 for black glass.

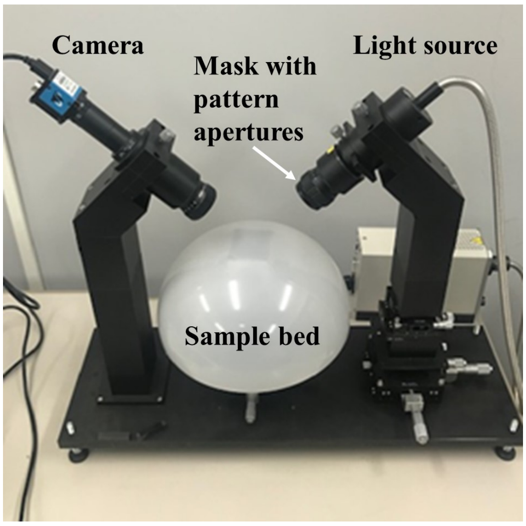
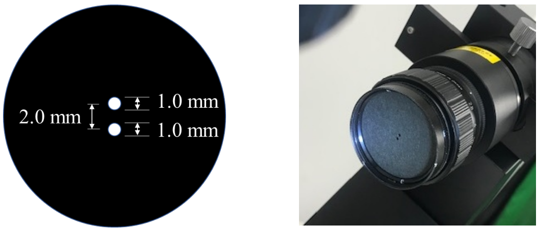


Figure 7. *Photograph of the measurement apparatus.*

The pattern of illumination was generated by placing the illumination mask with pattern apertures in the incident light path in Fig.7. Figure 8 shows the mask in this study. There were two holes of 1.0 mm and the distance between the holes were 2 mm, was this center to center of the holes.



(a) (b)

Figure 8. *The mask with pattern apertures in this study. There were two holes of 1.0 mm and the distance was 2 mm. (a) is the schematic diagram and (b) is the photograph.*

3.2 Samples and captured images

Four types of sample were measured. The plastic plate which was like mirror surface was used. (denoted as Plastic). Three types of photo-like Inkjet paper, namely high gloss (denoted as IJ-HG), medium gloss (denoted as IJ-MG), and low gloss (denoted as IJ-LG), were used. They were measured on the three sample beds. The samples were bent in the direction of the optical path because they were sheet style. Therefore, the data was analyzed at vertical center line of image in this study. The captured images by the camera on the apparatus are shown in Fig. 9. The authors reported that the distribution of this reflected light is BRDF [2].

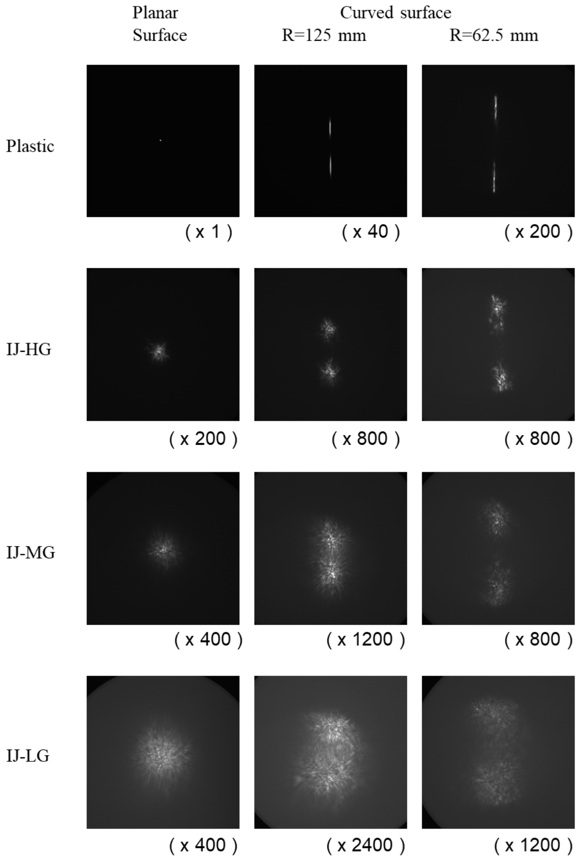


Figure 9. *Captured images measured by patterned incident light method. The intensity (image brightness) is the relative intensity and the axes (x and y) are in the range of reflection angle of 8 degrees. The relative magnification at the time of measurement is shown in parentheses.*

3.3 Estimate the radius of curvature

Figures 10-12 show the profile of the reflection light intensity in the direction of the incident light center. Here, the vertical axis is the relative intensity and the horizontal axis is the deviation of the reflection angle.

In the planar surface, the reflected light is measured with one distribution in Fig. 10. These distributions are the BRDFs of each sample. Even if illuminated by two incident lights, the BRDF at each position is the same, so the angular distribution of the reflected light is measured the same.

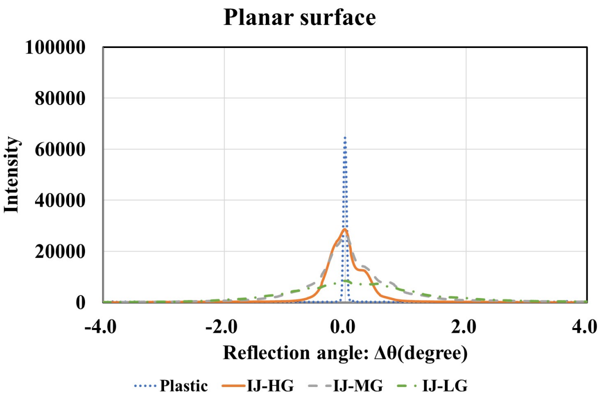


Figure 10. *The measured BRDFs on the planar surface.*

On curved surfaces, the reflected light was measured in two distributions. In the case of a curved surface, the BRDF at each position is measured by shifting by that angle because there is an inclination on the surface where the two incident lights illuminate.

Figure 11 shows the profile of the reflection light intensity in the curved surface which is the radius of curvature 125 mm.

The radius of curvature, R, is calculated with the normal angle difference, $\Delta\theta c$, and the distance of positions, Δx in Eq. (2). The distance of positions, Δx is 2x1.4142 mm in this experiment. The reflection angle difference, $\Delta\theta$, was 2.2 degree in the peak to peak difference of IJ-HG for example. The normal angle difference, $\Delta\theta c$, was 1.1 degree. In this case, the estimated R was 147.3 mm. This result was bigger than the radius of sample bed. The theoretical value is 2.6 degree in R = 125 mm.

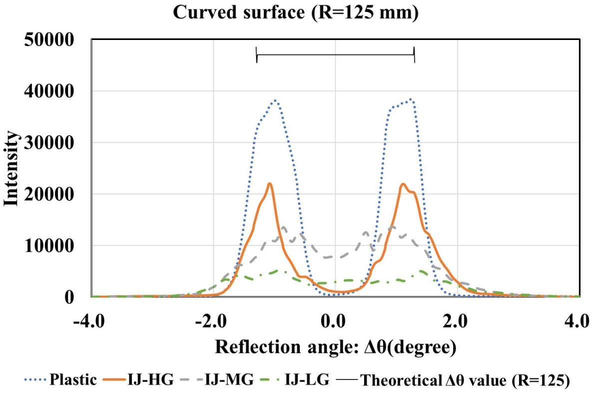


Figure 11. *The measured BRDFs on the curved surface (R=125 mm).*

Figure 12 shows the profile of the reflection light intensity in the curved surface which is the radius of curvature 62.5 mm. The reflection angle difference, $\Delta\theta$, was 4.1 degree in the peak to peak distance of IJ-HG for example. In this case, the estimated R was 79.1 mm. This result was bigger than the radius of sample bed. The theoretical value is 5.2 degree in R = 62.5 mm.

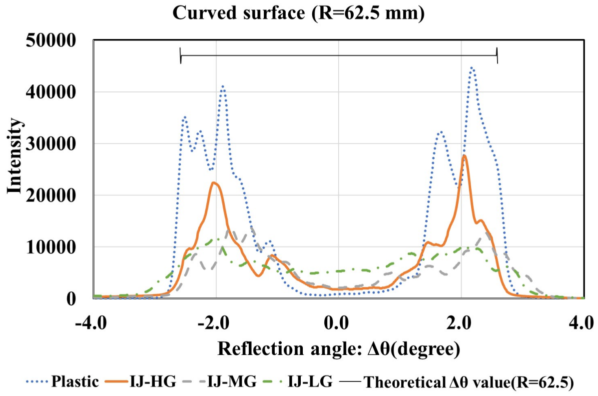


Figure 12. *The measured BRDFs on the curved surface (R=62.5 mm).*

The curvatures of the two objects were both estimated as greater than the actual curvature. The accuracy of curvature prediction needs to be improved. For example, future research will examine the effects of diffraction.

4. Discussion

4.1 Simultaneous measurement of BRDF and surface curvature

In the planar surface, the reflected light was measured with one distribution. On curved surfaces, the reflected light was measured in two distributions. Furthermore, the difference angle of two distributions were dependent on the surface curvature. These distributions are BRDFs. These show that BRDF and surface curvature can be measured simultaneously by the patterned incident light method.

There are limitations to the proposed method. In BRDF with a large spread, the two distributions may not be separated, for example IJ-MG and IJ-LG. In addition, technology that accurately estimates the curvature of the surface is required. It is considered that one of the solutions is to improve the incident light pattern. In this experiment, one-dimensional analysis was performed using two simple holes, but two-dimensional analysis is possible with multiple holes. Furthermore, the shape of the hole is not limited to a circle.

4.2 Difference between BRDF on planar surface and curved surface

The measurement BRDF on a curved surface was spreader than that on a planar surface. Figure 13 shows the BRDFs of the plastic plate. On a planar surface, plastic BRDF had a narrow distribution, like dots. It spread greatly on curved surfaces. Therefore, BRDF measured on a curved surface needs correction. Figure 14 shows the BRDFs of the IJ-HG. The IJ-HG BRDFs had a spread distribution, like Gaussians. They also spread out on curved surfaces. The authors reported a technique for simulating the case of a curved surface using BRDF measured in the planar surface [10]. In future work, it is necessary to consider the development of a technique for estimating the BRDF of a flat surface from the measured BRDF of a curved surface.

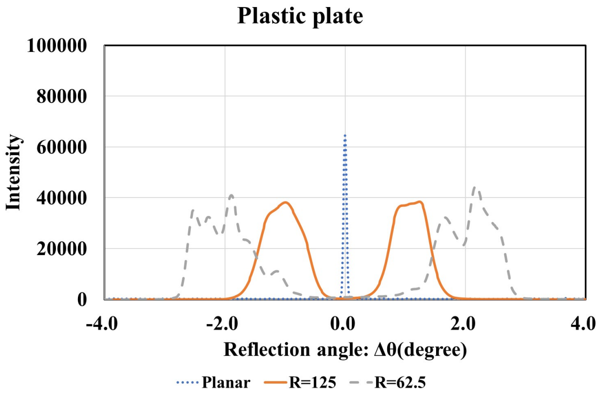


Figure 13. *The measured BRDFs of the plastic plate.*

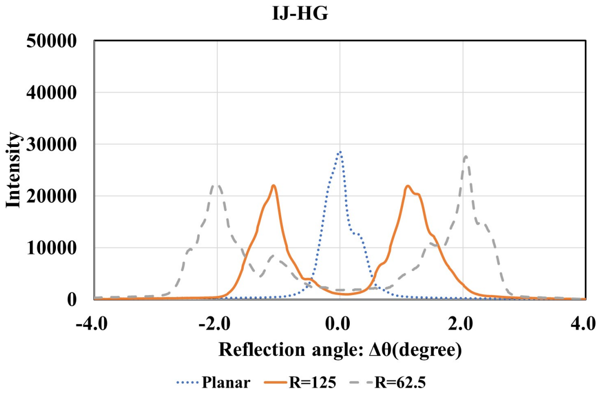


Figure 14. *The measured BRDFs of the IJ-HG.*

5. Conclusion

We proposed the simultaneous measurement for BRDF and surface curvature by pattern illumination method. The pattern of illumination was generated by placing the illumination mask with pattern apertures in the incident light path. The mask with two holes was used in this study. The BRDF at two illuminated positions was measured by using two separated incident lights, and the radius of curvature was estimated from the difference between the two positions. The BRDF spreads on curved surfaces. Therefore, it is important to know the curvature of the surface when the BRDF was measured. In future work, it is necessary to consider the development of a technique for estimating the BRDF of a flat surface from the measured BRDF of a curved surface.

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