https://doi.org/10.2352/lim.2023.4.1.07

Measuring Method for Gloss Unevenness with Three Directional Lights

Shinichi Inoue*, Yoshinori Igarashi**, Takeyuki Hoshi** and Toshifumi Satoh*

**** Faculty of Engineering, Tokyo Polytechnic University Kanagawa, Japan***

***** CHUO PRECISION INDUSTRIAL CO., LTD., Fukushima, Japan***

Abstract

In this paper, we introduce the analysis for gloss unevenness by using developed multiple directional incident lights optics. Gloss unevenness is strongly related to recognition of material texture. However, it looks different depending on the angles, so it has been difficult to measure quantitatively. The gloss unevenness caused by surface roughness is able to analyze by the distribution of normal on the surface. We have developed the optical system that simultaneously illuminates with light from three different directions, angles, and captures images of gloss unevenness in one shot. We confirmed that the normal distribution of the surface can be estimated by analyzing the image. This proposed method can not only measure the gloss unevenness image, but also estimate the shape of the surface. As an application of this gloss unevenness observation technology, it is also possible to detect of scratches and coating unevenness in industrial quality control.

1. Introduction

Gloss is an important phenomenon that gives a sense of the texture of a material. When an object is observed under a light source, gloss is observed in addition to the appearance of the object's surface. We humans read further information about the texture of the material from the gloss unevenness. Gloss is physically the specular reflection phenomenon, as shown in Figure 1. From a macroscopic viewpoint, even though the gloss is constant, the appearance of gloss unevenness changes with the direction of incident light. The main cause of gloss unevenness is the mesoscopic undulations of the object surface. The gloss unevenness is caused by differences in reflection on the object surface. Therefore, the pattern of gloss unevenness, the image, will vary depending on the position of the light source. For this reason, gloss unevenness, while important in recording texture, have been difficult to record and analyze quantitatively.

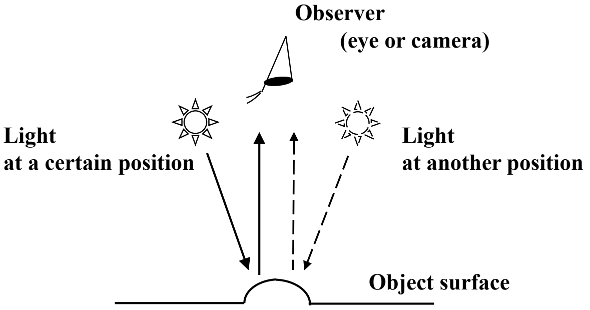


Figure 1. *Schematic diagram of the gloss phenomena. The observed gloss position changes as the direction of incident light changes. The main cause is the mesoscopic undulations of the object surface.*

The material, the texture, may be estimate from the gloss unevenness, as shown in Figure 2. We humans estimate the texture of an object by moving the object, the direction of incident light, and the viewing position.

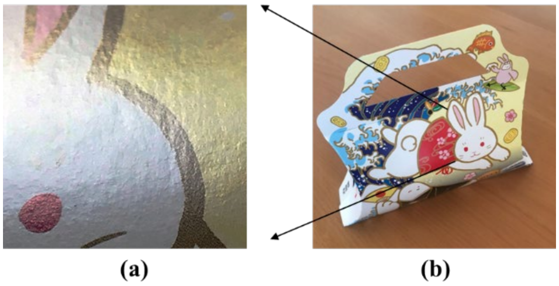


Figure 2. *An example photographs of gloss unevenness. (a) Enlarged photograph of an area where gloss unevenness is observed (30 x 30 mm). It can be seen that this material is cardboard. (b) An overall photograph of a certain candy package. Without the gloss unevenness, the texture cannot be recognized. The material appears to be plastic, cardboard, or metal can.*

The reflectance of an object surface at different angles can be measured. The reflectance at a declination angle is named gonio-reflectance and can be measured with a goniophotometer [1], as shown in Figure 3. The universal way to describe physical reflectance properties is via the bidirectional reflectance distribution function (BRDF) [2,3,4]. However, its measurement area range is too large, e.g., 5.0 mm. Gloss unevenness is a phenomenon in much smaller areas.

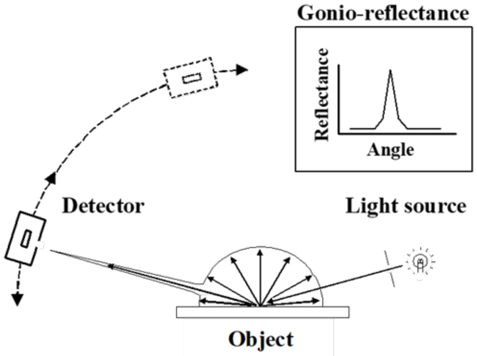


Figure 3. *Schematic diagram of goniophotometer and a part of BRDF.*

Gloss unevenness can be captured with a camera. Measurement and analysis of gloss unevenness under certain conditions have been reported [5,6]. Methods for measuring gloss unevenness at different angles have been proposed [7]. However, the normal of an object surface is three-dimensional. Measurement under many conditions is required by those method. Furthermore, a way to integrate these gloss unevenness images is required.

In this paper, we introduce a measuring method for gloss unevenness with three directional lights. We developed multiple directional incident lights optics. The optical system simultaneously illuminates with light from three different directions, angles, and capture image of a multidimensional gloss unevenness in one shot. In experiments, we demonstrate that the proposed method can not only measure the gloss unevenness image, but also estimate the shape of the surface, the surface normal distribution. It expresses the surface geometry of the object. These pieces of information are needed by many reflection models in computer graphics (CG). In addition, we discuss the application of this gloss unevenness measurement technique to the detection of scratches and paint irregularities in industrial quality control.

2. Experiments and Results

We focused on two techniques to develop the measuring method for multidimensional gloss unevenness in one shot. One is the multiple directional lighting optics to illuminate the object from multi direction simultaneously. The other is the multispectral imaging method to measure multiple reflect light separately.

2.1 Multiple directional lighting optics

A collimator optics system was used for the multi-directional illumination optics. A schematic diagram of the collimator optics system is shown in Figure 4. In collimator optics, there is a focal point on one side of the lens and parallel light on the other side. Parallel light can be emitted by the illumination system if the light source is set at the focal point. The distance from the center, d, is calculated from the light angle, Δθ, and the focal length, f, as follows:

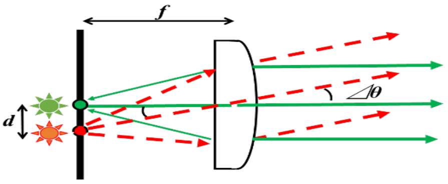


__Figure 4.__ Schematic diagram of collimator optical system. Focal point distance, d, can be calculated from focal length, f, and light angle, Δθ.

$$d = f \cdot \tan(\Delta\theta) \tag{1}$$

A collimator is a collimated light projection system. Usually, there is one light source and its position is at the focal point and in the center. In the newly developed device, as shown in Figure 4, multiple light sources are positioned to simultaneously project collimated light at the desired angle.

2.2 Multispectral imaging method

The specular reflection light is visible to the human eyes, in the visible spectrum. Specular reflection is an even reflection of light in visible spectrum, just as a mirror accurately reflects the original image. Therefore, it can be separated by color filters. Our idea is that if we colorize the incident light with a color filter, we can detect the specular reflection light with the same color filter and identify each reflection light by color, even if the incident light which is from different directions at the same time.

2.3 Telecentric optics system

We devised a measurement technique in which the incident light angle and the measurement light angle are in a constant relationship at all points on the sample surface. Because collimator optics are used, the angle of incident light is the same everywhere. To make the measurement angle also the same everywhere, telecentric optics are applied. Telecentric optics system is an optical system that allows only light parallel to the optical axis to pass through. Therefor the measurement light angle is in a constant at all points on the sample surface. A schematic diagram of the telecentric optics system is shown in Figure 5.

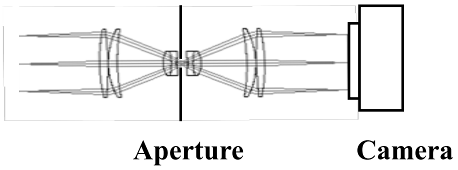
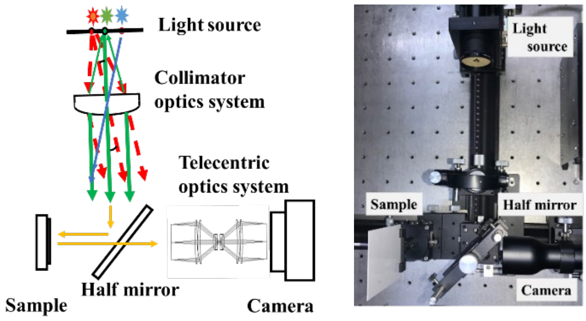


__Figure 5.__ Schematic diagram of the telecentric optics system.

2.4 Developed apparatus

We developed a measurement apparatus consisting of the simultaneous multiple directional incident lights system in Figure 6. The collimated light emitted from the collimator lens is reflected by a half mirror before entering the sample. The angle of the CMOS color camera (DFK 33UX249, Imaging Source) was fixed at 0° to the sample surface. This geometry allows the camera to measure the reflected light at a fixed angle when the incident light changes. The distance from the light source to the center of the sample was 139 mm, the distance from the camera to the center of the sample bed was 146 mm. The diameter of the light source was 50 mm.

The image resolution of the camera was 1920×1200 pixels, and it had a 12-bit output level per pixel. The pitch of one pixel corresponds to 0.02 mm on the object plane along the y axis. The output values can be used as the light intensity because the linearity between the output values and light intensity was confirmed in advance. The sample material was set on the sample bed, and the images were acquired in a darkroom. For calibration of the measured values, a mirror was prepared and measured. The reflected light intensity of the mirror was set to 1000, and the reflected light intensity of the sample was expressed as a relative value. The apparatus is developed by Chuo Precision Industrial Co., Ltd..

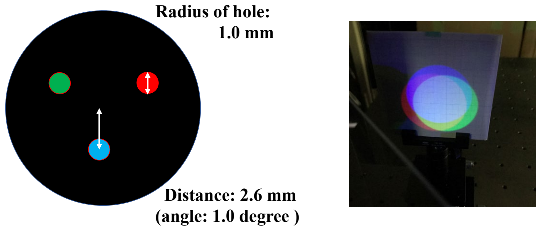


(a) (b)

__Figure 6.__ (a)Schematic diagram of the developed measurement system with the multiple directional lighting system. (b) Photograph of the developed measurement apparatus.

2.5 Multiple directional lighting system

The simultaneous multiple directional lighting system has multiple light sources, each of which has a filter. In the experiment, a slit with a hole was placed at the focal point of the collimator, shown in Figure 7. The three holes were placed 120 degrees each. Each was positioned from the center of the slit so that it was incident with a declination of 1 degree with respect to the sample plane. The distace is 2.6 mm. The diameter of the holes as the light source was 1 mm. The LED light source was placed behind the holes to illuminate the light source uniformly. Red, green, and blue color-resolved filters were used as filters so that the three lights could be measured independently by the color camera on the measurement side. These are red: No.29, green: No.47, blue: No.61 (WRATTEN filters, Eastman Kodak Company).



(a) (b)

Figure 7. *(a) Schematic diagram of the aperture used as a light source. (b) Photograph of the sample table with light incident on it; the area where the Red, Green, and Blue lights overlap is the measurement area.*

The introduced measurement system basically measures the specular reflection of each incident light at each position. For example, if the sample is a mirror, incident light at an angle of 1 degree will only have a value at the 0.5degree normal facet position. Light that is resolved into Red, Green, and Blue will each have a value only at the corresponding facet. The gloss unevenness image which depends on surface undulation may be measured.

2.6 RGB intensity corresponding to surface normal angle

The introduced measurement system basically measures the specular reflection of each incident light at each position. For example, if the sample is a mirror, incident light at an angle of 1 degree will only have a value at the 0.5degree normal facet position. Light that is resolved into Red, Green, and Blue will each have a value only at the corresponding facet. The gloss unevenness image depend on surface undulation may be measured.

However, the real apparatus has a wider range of reflection angles to be measured. The aperture of the telecentric optics shown in Figure 5 and the aperture of the light source shown in Figure 7 are adjustable factors. When the range of angles of the surfaces from which light reflects from the three directions is extended and overlaps, the normal of facet can be estimated from the color component of the reflected light at that position. We examined the RGB intensity corresponding to the surface normal angle. A mirror with a known radius of curvature, R = 450 mm, was set as a sample in Figure 8.

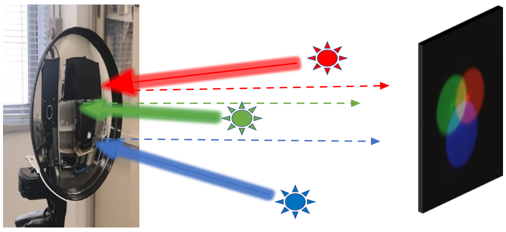


Figure 8. *Schematic diagram of the RGB intensity experiment corresponding to the surface normal angle. The curved mirror is used for the sample surface.*

As shown in Figure 9, the normal angle at each position of the curved mirror was obtained by calculation, as follows:

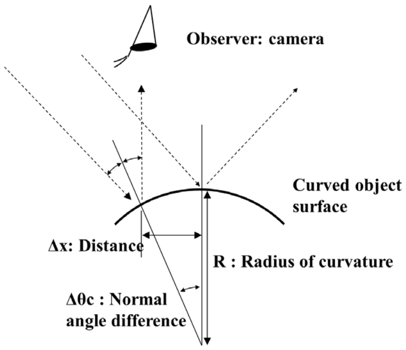
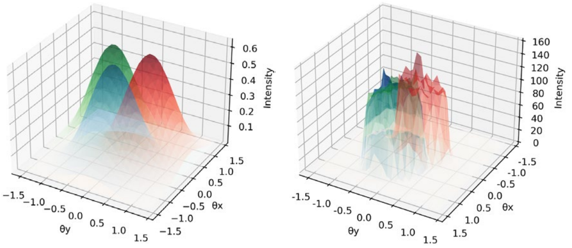


Figure 9. *Schematic diagram of directional illumination method on a curved surface. the normal angle difference, Δθc can be calculated from position distance, Δx, and the radius of curvature, R.*

$$\Delta\theta c = arcsin(\Delta x/R) \tag{2}$$

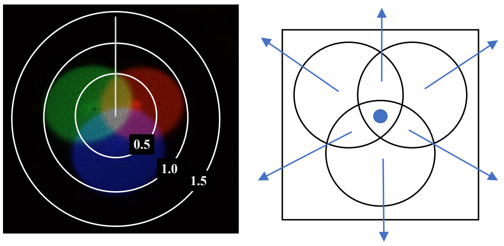
The predictions of the theoretical models are shown in Figure 10(a), and the measurement results are shown in Figure 10(b). Theoretically, the normal direction, angle, can be estimated by the ratio of R, G, and B components. The measurement results also showed that the normal direction and angle range could be measured. However, the measurement results were noisy and could not estimate the normal with high accuracy.



(a) (b)

Figure 10. *(a) The predictions of the theoretical models. Intensity is relative. (b) The measurement results. where θx is the angle of rotation of the surface in the x-axis and θy is the angle of rotation in the y-axis.*

The measurement results are shown in Figure 11(a). The Red, Green, Blue reflection lights ditribute acording to the normal angle of surface. As shown in Figure 11(b), angular information of at least eight facets can be obtained in terms of color components. Measurements with overlapping RGB components in the center represent flats. Six normal directions can be estimated from each color component. Regions with no reflected light and no RGB components are flats with normals greater than about 1.0 degree.



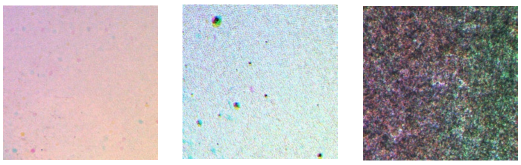
(a) (b)

***Figure 11.** (a) The measurement results of curved mirror. (b) Schematic diagram of the eight normal directions can be estimated from each color component.*

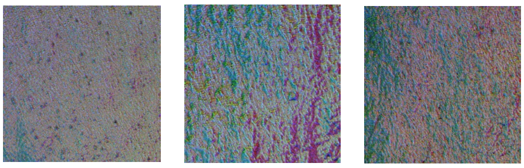
The developed measurement system with multiple directional lights optics is capable of measuring gloss unevenness. It can also measure three illumination conditions simultaneously. Furthermore, the normal angle of each faset can be estimated.

2.7 Measurement results of samples

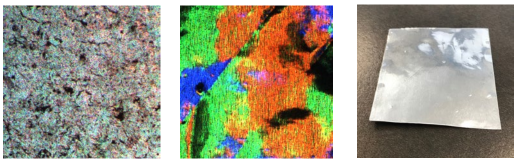
The gloss unevenness images were measured in Figure 12. There were six materials. These samples were flat shape. The samples used were plastic, pottery tile, glossy-coated paper, inkjet paper, gold leaf and aluminum sheet.



(a) Plastic **(b) Pottery tile** **(c) Paper (glossy)**



(d) Inkjet paper 1 **(e) Inkjet paper 2** **(f) Inkjet paper 3**



(g) Gold **(h) Alminium** **(i) Photo of (h)**

***Figure 12.** The measured gloss unevenness images. The size is 10 x10 mm on sample from (a) to (h). (i) Photograph of the sample (h).*

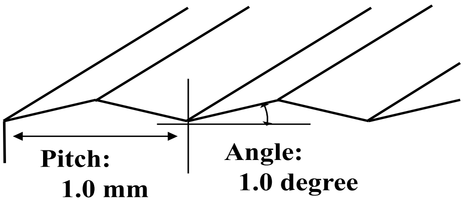
Gloss unevenness varied from material to material. Plastic had a uniform surface and little gloss unevenness (Fig. 12(a)). Plastic, pottery tile, paper (printing paper, high glossy, A1 grade), and inkjet papers all had white high gloss, but differences in gloss unevenness could be measured. Three types of inkjet paper were measured ((Fig.12(d,e,f)). Differences in gloss unevenness could be measured for the same material. This can be used for production control.

Figure 12(h) shows the measurement result of the aluminum plate surface. The characteristic undulations can be read. All samples were flat, except for the aluminum plate in (h). This is an example of a sample with large macroscopic undulations.

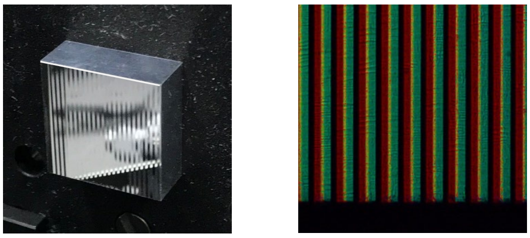
3. Discussions

3.1 Verification of measurement principle

To verify the measurement principle, a material with a known surface profile was measured. A calibration sample cut from aluminum (Figure 13), manufactured by Toray Precision Inc. It has a double-striped surface with a pitch of 1.0 mm (width of 0.5 mm) and angles of 1.0° and -1.0°. The surface is mirror-like. The photograph in Figure 13(a) shows that the sample surface has two separate reflections. The sample size is 25 x 25 mm.



(a)



(b) (c)

***Figure 13.** (a) Photograph of the calibration sample. (b) Schematic diagram of the calibration sample. (c) The measurement results of the calibration sample. In this result, Red and Green are measured regularly.*

The measurement results of this apparatus are shown in Figure 13(c). In this result, red and green are measured regularly, indicating that the normal direction can be measured.

3.2 Application: Scratch detector

The proposed system can be applied to a scratch detector. The system has high detection capability because it inspects three directions at the same time.

4. Conclusion

We have developed the optical system that simultaneously illuminates with light from three different directions, angles, and captures images of gloss unevenness in one shot. We proposed a method to not only measure the gloss unevenness image, but also to estimate the shape of the surface. Assuming the surface to be a collection of small facets, we proposed a mechanism that theoretically can estimate the normal of each facet. Although we were not able to estimate the precise normal with the actual device we developed, we confirmed that we could classify the normal of the facets as flat or inclined in six directions. Future work is to develop a technique to calculate normal vectors from the measurement results of this system and generate more realistic computer graphics.

Funding

This work was supported by JSPS KAKENHI Grant Number JP21K11954.

References

[1] F. B. Leloup, G. Obein, M. R. Pointer, and P. Hanselaer, “Toward the Soft Metrology of Surface Gloss: A Review,” Color research and Application 39(6), 559-570(2014).

[2] S. R. Marschner, S. H. Westin, E. P. F. Lafortune, and K. E. Torrance, “Image-based BRDF Measurement,” Applied Optics 39(16), (2000)

[3] A. Gardner, C. Tchou, T. Hawkins and P. Debevec, “Linear Light Source Reflectometry,” Proceeding SIGGRAPH '03 ACM SIGGRAPH 2003 Papers, 749-758(2003)

[4] S. Inoue and N. Tsumura, “Point Spread Function of Specular Reflection and Gonio-Reflectance Distribution,” J. Imaging Sci. Technol. 59 (1), 010501-1－010501-10 (2015).

[5] H. Fujiwara, C. Kaga, and I. Kano, “Measurement of Gloss Profile,” Japan Tappi J. 44 (10), 1092-1098 (1990).

[6] X. Zhu, S. Inoue, H. Sato, and Y. Mizokami, “Effect of light source distances and illuminances on the gloss perception of papers,” JOSA A, 39(6), B28-B38 (2022).

[7] S. Nakamura, S. Inoue, Y. Igarashi, T. Hoshi, H. Sato and Y. Mizokami, “Measurement of Gloss Unevenness with Different Reflection Angles,” Proc. 30th Color Imaging Conference, Scottsdale, (2022)

Author Biography

Shinichi Inoue received the B.E., M.E. and Ph.D. degrees in image science from Chiba University in 1983, 1985 and 1999, respectively. He worked for Mitsubishi Paper Mills, Ltd., from 1985 to 1999. He worked in Chiba University as a project associate professor before moving to Tokyo Polytechnic University. He is now a visiting researcher. His work has focused mainly on optical property measurements.

Yoshinori Igarashi graduated from the Department of Computer Science College of Engineering Nihon University in 1995. In 1995 Joined Chuo Precision Industrial Co., Ltd. and currently works in Engineering Department 2, Engineering Division. He is engaged in the design of mechanical stages and optical units. His work has focused on the measurement method of gloss and gloss unevenness.

Takeyuki Hoshi graduated from the Department of Mechanical Engineering, Nippon Institute of Technology in 1984. In 1984 Joined Chuo Precision Industrial Co., Ltd. He started his career in manufacturing at an optical equipment manufacturer, where he served as technical manager, and is currently deputy manager of the Ujiie Plant, Production Division.

Toshifumi Satoh received his PhD in mechanical engineering from the Meiji University, Japan (1995). He worked at Panasonic before moving to Tokyo Polytechnic University, where he engaged in research of thin films and flat panel displays. He is now a Professor of the Department of Engineering. His fields of interests are printable device and lighting system. Dr. Satoh is a president of the Imaging Society of Japan.