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Measurement of Gloss Unevenness with Different Reflection Angles

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Abstract

In this study, we introduced a measurement method for gloss unevenness as a function of reflectance angles. Gloss is one of the most important qualities of materials, and it is evaluated subjectively by the intensity of reflected light and gloss unevenness. People can estimate the texture of a material using gloss unevenness, which is found in the small peripheral part of the gloss area and can easily be recognized by observing the reflected light while moving the object or eyes. However, it is not easy to photograph and quantify gloss unevenness. One reason is the area where gloss unevenness is observed is a small area near specular reflection. Second, the appearance of gloss unevenness changes depending on the reflection angle. We developed a measurement apparatus to measure gonio-photometric gloss unevenness. We introduced two solutions: a wide-area gloss unevenness measurement technology using telecentric imaging and a rotating mirror optical system that defects reflected light at an angular resolution of 0.02°. We analyzed three materials—mirror, plastic, and paper—and proposed three indicators as a quantitative evaluation method for gloss: intensity of reflected light at the specular angle, full width at half maximum (FWHM) of Bidirectional Reflectance Distribution Function (BRDF), and gloss unevenness image at the FWHM.

1. Introduction

Gloss is one of the most important qualities of materials. When a printed image is observed under a light source, gloss on the surface is observed in addition to the printed image. With gloss, the reflected light intensity and gloss unevenness are important phenomena [1]. Gloss unevenness is caused by the non-uniformity of the surface of the material, and people can estimate the texture of a material by using this gloss unevenness. Gloss unevenness was observed in the small peripheral part of the glossy area. People can easily recognize the entire image of gloss unevenness by observing the reflected light while moving the object or eyes. However, it is not easy to photograph and quantify gloss unevenness. One reason is that the area where gloss unevenness is observed is a small area near specular reflection. Second, the appearance of a gloss unevenness changes depending on the reflection angle and distance [2]. A schematic diagram of the visual inspection of gloss unevenness is shown in Figure 1.

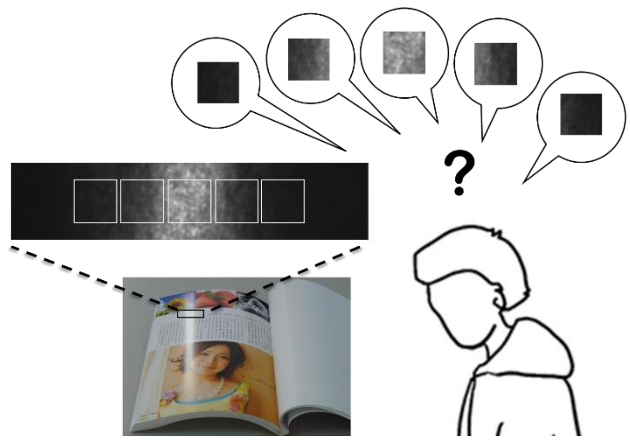


Figure 1. *Schematic diagram of a visual inspection of gloss unevenness. In general, gloss unevenness is distributed near specular reflection. Which part are you looking at as gloss unevenness? How should it be quantified?*

In a dichromatic reflection model, the intensity of the reflected light is the sum of diffuse reflection and specular reflection. As shown in Figure 2, a part of the incident light is absorbed, scattered, and widely reflected in all directions; this phenomenon is known as diffuse reflection. The printed image exhibited a diffuse reflection phenomenon. Specular reflection is a mirror-like reflection of the light source from the surface and is much more directional. Gloss is a specular reflection phenomenon. Gloss is a reflection angle distribution of the incident light, which is related to BRDF. Research on BRDF measurements can thus be applied to the measurement of gloss and gloss unevenness.

The reflectance at the deviation angle, called the gonio-reflectance, can be measured using a goniophotometer [3]. As shown in Figure 2, a goniophotometer has a movable detector for measuring reflectance at various angles for a given angle of incident light. The gloss area, BRDF, is the gonio-reflectance distribution when the incident light is at a certain angle.

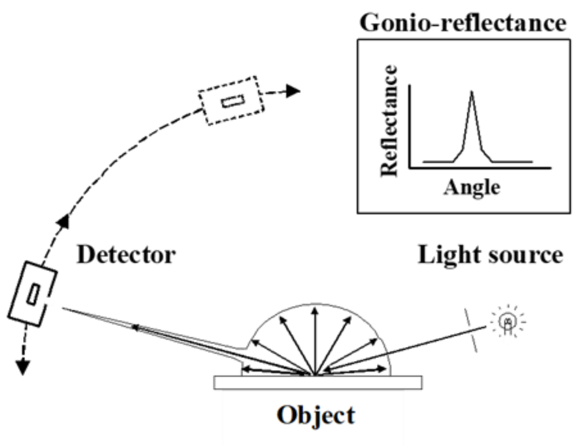


Figure 2. Schematic diagram of a goniophotometer and gonio-reflectance with a dichromatic reflection model.

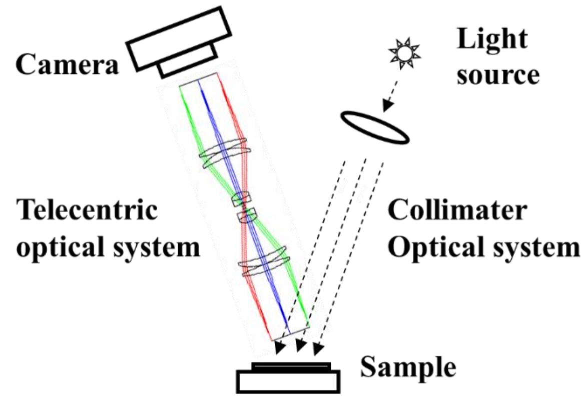


Figure 3. Schematic diagram of the developed measurement system with the telecentric optics system.

Measurement techniques for BRDFs, such as gloss, also called reflectometry, have been proposed for various lighting environments and observation conditions [4-11]. The BRDF was previously analyzed by the authors [8-11]. However, an important issue remains. The measured BRDF is the average intensity and not a gloss image. Therefore, gloss unevenness cannot be analyzed using these data.

Gloss unevenness can be measured by scanning the gloss intensity over a small area [12]. The authors measured the gloss unevenness image using a part of the line light reflection image [13], similar to scanning the image. However, these methods are difficult to perform and require a long processing time.

In this study, we proposed a method to obtain the gloss unevenness from the captured images and easily analyze the BRDF and roughness at each angle. We developed a measurement apparatus to measure gonio-photometric gloss unevenness. We analyzed three materials: black glass, plastic, gloss coated paper and inkjet paper. We presented the quantitative gloss evaluation method using three indicators: peak intensity at specular reflection, FWHM of BRDF, and gloss unevenness image at FWHM. These parameters could be measured using the developed apparatus.

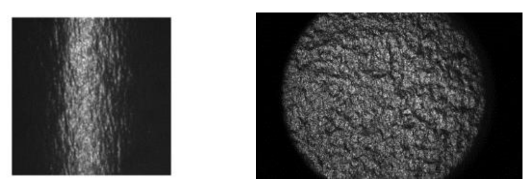
2. Theory

2.1 Telecentric optical system

We devised a measurement technique that equalizes the incident light angle and the measured light angle at all points on the sample surface. A parallel light source was applied to the incident light, and a telecentric optical system was applied to the measurement light, as shown in Figure 3. The parallel light source was realized using a collimator optical system.

A telecentric optical system is a system that allows only light parallel to the optical axis to pass through the system, as shown in Figure 3. The intensity of the specular reflection light was evaluated for each position because only light parallel to the optical axis was measured.

Figure 4a shows an image of a linear light source captured with a normal lens and camera, where it is seen that the gloss decreases, centering on specular reflection. Figure 4b shows an image of the proposed parallel light source captured with a telecentric optical system camera. As all reflection conditions are the same, gloss unevenness can be better observed. The average value of this surface is the intensity of reflected light at the specular angle, which is the BRDF value under these conditions.



(a) (b)

Figure. 4. Measured gloss unevenness images using (a) a usual lens system and (b) the Telecentric optical system apparatus. The sample is an Inkjet paper.

2.2 Definition of gloss unevenness

Gloss unevenness can be considered as a property equal to random noise. In imaging science, image noise is defined as the deviation from the mean of a surface. Root mean square (RMS) granularity is a typical evaluation method. This value is obtained by subtracting the average value from each value in the image as noise and taking the standard deviation.

One more factor must be considered when analyzing gloss unevenness. In terms of the amount of light, high-gloss surfaces, such as plastic, have a large amount of reflected light, whereas the amount of glossy light on printing paper is much smaller. These differences in the amount of light could be 100 or 1000 times. Meanwhile, people adjust their sensitivity to the illumination level such that the amount of light is within the observable range. If gloss unevenness is defined by the absolute value of the amount of light, the magnitude of the reflected light strongly affects the magnitude of the gloss unevenness, making it impossible to compare the gloss unevenness between materials. Therefore, we define the gloss unevenness as the variation in the ratio of the amount of light in Eq. 1.

$$GlossUnevenness(x, y) = \frac{Gloss(x,y) - Mean.Gloss(x,y)}{Mean.Gloss(x,y)} \quad (1)$$

where Mean.Gloss(x, y) is the moving average of gloss(x, y) and x and y are the positions. The standard deviation of GlossUnevenness(x, y) is the RMS granularity of gloss unevenness.

3. Experiments

3.1 Developed apparatus

We developed a measurement apparatus that can mechanically control the incident light. The light source (SPL-100A, Chuo Precision Industrial Co., Ltd.) was a white LED. The collimated light emitted from the collimator lens is reflected by a mirror before entering the sample bed. The angle of the mirror can be changed by 0.01° using the machine; thus, the incident light can be changed by 0.02°. The angle of the CCD camera (DMK 33UX174, Imaging Source) was fixed at 20° to the sample surface. This geometry allows the camera to measure the reflected light at a fixed angle when the incident light changes; in other words, the device can measure the BRDF. The distance from the light source to the center of the mirror was 200 mm, the distance from the center of the mirror to the center of the sample stand was 40 mm, and the distance from the camera to the center of the sample bed was 190 mm. The diameter of the light source was 52 mm. The light reflected by the mirror enters the sample table at 20° to ensure that the camera can capture a specular reflection image (Figure 5). Figure 6 shows the photograph of the apparatus.

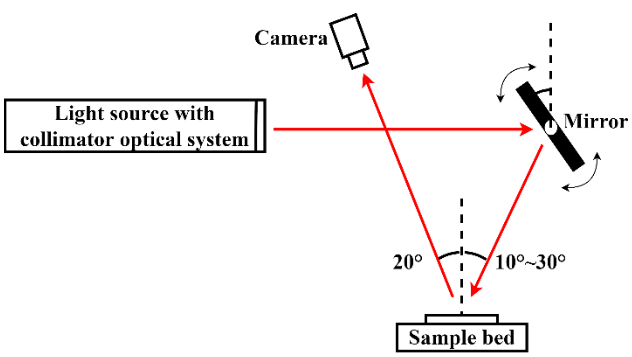


Figure 5. Schematic of the geometry. The arrows represent light reaching the camera. The angle of the mirror is variable, which also changes the angle of incidence.

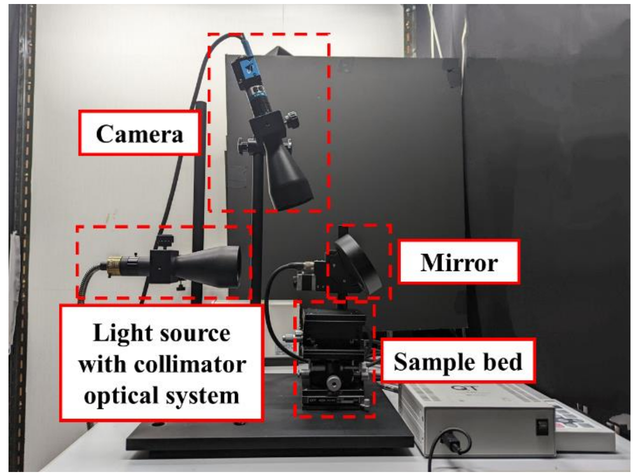
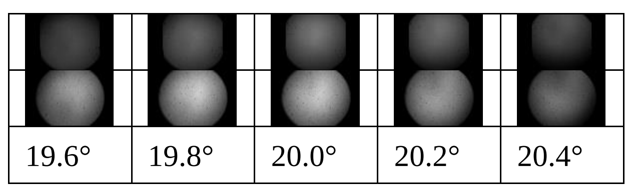


Figure 6. Photograph of the measurement apparatus.

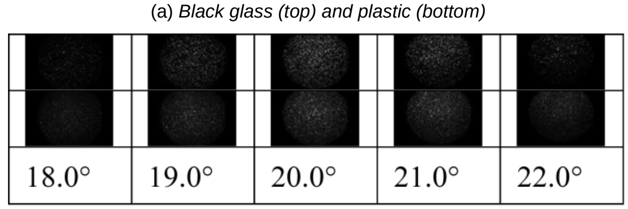
The image resolution of the CCD camera was 1920×1200 pixels, and it had a 12-bit output level per pixel. The pitch of one pixel corresponds to 0.039 mm on the object plane along the y axis. The output values can be used as the light intensity because the linearity between the output values and light intensity was confirmed in advance. The sample material was set on the sample bed, and the images were acquired in a darkroom. Black glass was prepared and measured to calibrate the measured values.

3.2 Measured gloss unevenness images

Reflected light source images were measured. There were three materials and one black glass. Since it is difficult to measure a sample with a curved surface due to the large difference in luminance, a flat sample was used in this study. The samples used were plastic, inkjet paper, and glossy-coated paper. Figure 7a shows images of black glass and plastic taken at different angles, and Figure 7b shows images of inkjet paper and glossy paper taken at different angles.



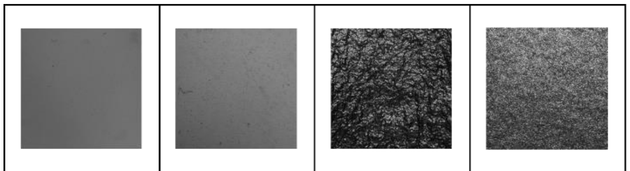
(a) *Black glass (top) and plastic (bottom)*



(b) *Inkjet paper (top) and glossy coated paper (bottom)*

Figure 7. Images taken at different incident angles.

Note that the shutter speed was changed to avoid saturation when each sample was taken; therefore, the brightness of the image did not represent the amount of light. A cropped image when the gloss was near FWHM is shown in Figure 8.



Black glass	Plastic	Inkjet paper	Glossy coated paper

Figure 8. *Images of sample at near FWHM*

These images show the texture of the sample surface. The overall shading was removed from these images, and the resulting noisy image was divided by the average according to Eq. 1, shown in color scale in Figure 9.

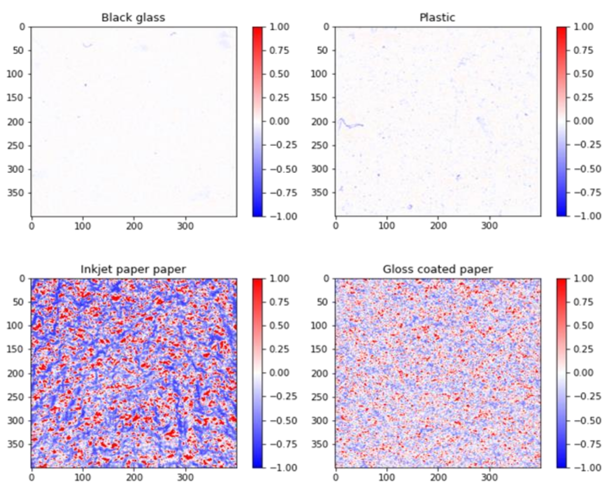


Figure 9. *Color scale of gloss unevenness. The numerical value of the color bar is GlossUnevenness(x, y) obtained by Eq. 1.*

The standard deviations (RMS granularity) of these surfaces were as follows: black glass 0.031, plastic 0.042, inkjet paper 0.963, and glossy coated paper 0.500. Black glass and plastic with high reflective strength have small deviations, whereas inkjet paper with uneven gloss and glossy paper have large deviations. This analysis facilitated a comparison of the surface roughness of the samples.

The center 400×400 pixels of the captured image were cropped, and the average pixel value for each square image was determined for each angle. The intensity is the average pixel value multiplied by the reciprocal of the shutter speed. This calculation allowed samples to be compared on the same scale. Figures10 and 11 show the BRDF of each material represented by the intensity The shape of the graph provides information about the gloss peak, gloss spread, and FWHM of the sample.

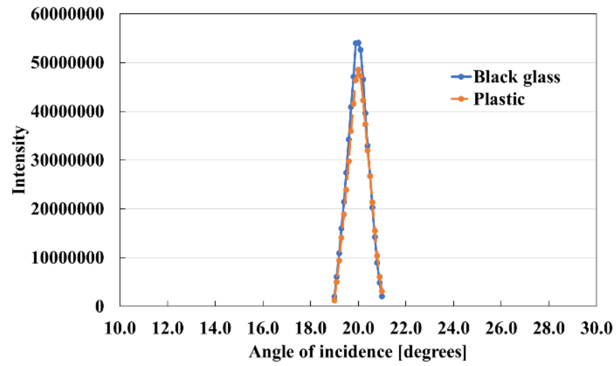


Figure 10. *BRDFs of black glass and plastic*

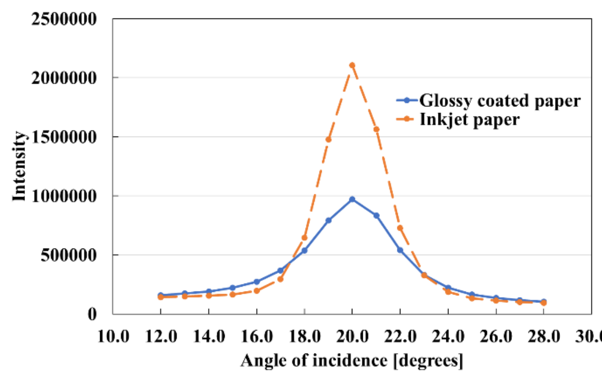


Figure 11. *BRDFs of glossy coated paper and inkjet paper*

At an angle of incidence of 20°, the intensity was the greatest because specular reflection was captured. As the angle of incidence increased from 20°, the intensity decreased because of diffuse reflection. These values depend on the sample, and the shape of the graph gives us the gloss peak, spread of the gloss, and FWHM of the sample.

The standard deviations of gloss unevenness for each angle are shown in Figures 12 and 13.

The standard deviations for black glass and plastic remain low, whereas glossy coated paper and inkjet paper show a bell shape. In particular, two peaks are seen for inkjet paper, and these peaks exist near the FWHM of intensity.

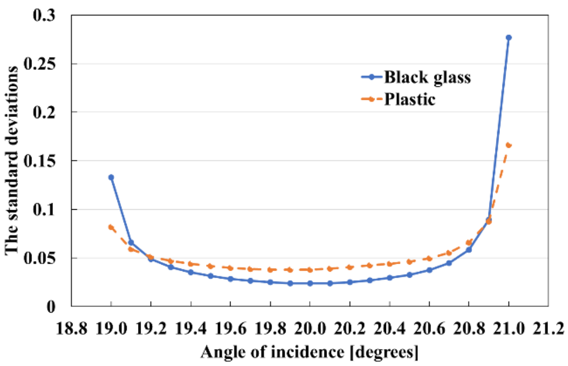


Figure 12. *RMS granularity of gloss unevenness for each angle for glossy coated paper and inkjet paper*

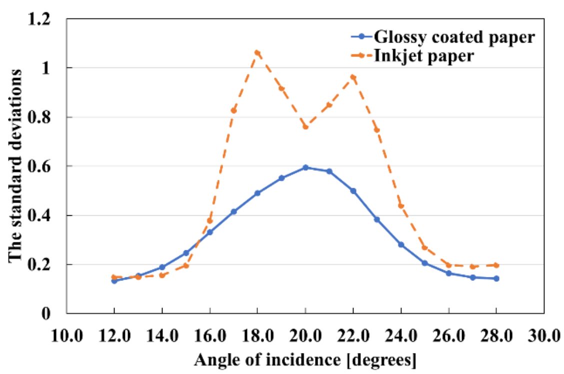


Figure 13. *RMS granularity of gloss unevenness for each angle for glossy coated paper and inkjet paper*

4. Discussion

4.1 RMS granularity at different incident light angles

Figures 12 and 13 show the RMS granularity at different incident light angles. In Figure 13, two peaks are seen at near the FWHM of the intensity on the inkjet paper. In the sample with such a rough surface, the standard deviation is larger around the slope of BRDF than at the angle of incidence where it peaks. This is also mentioned in 4.2. It may be related to where the roughness is best observed when people observe gloss unevenness. No such tendency is observed with paper in this experiment. In Figure 12, the black glass and the plastic show flat. The edges values are rapidly increasing. This is thought to be due to the large change in light intensity for these samples, which exceeded the measurement range as the angle of incidence increased and the reflected light approached zero. Since these surfaces are smooth, the standard deviation does not change significantly when the angle is changed.

4.2 Gloss Unevenness Image selection

With the proposed measurement method, it is possible to take the gloss unevenness image at incident light angle every 0.02°. However, we would like to discuss the representative values to be recorded. If gloss unevenness is a variation of the light intensity, it is desirable to have a wide range of light intensities. As the maximum range occurs on the slope of BRDF, the gloss unevenness image at FWHM of BRDF is recommended. From experience, gloss unevenness is represented better at a slightly different angle than at the peak of specular reflection. We need future research to consider this aspect.

4.3 Gloss quantification

The three important measurement data points for analyzing the gloss properties of a material are below and shown in Figure 14.
1) MAX.Gloss: reflection value at the specular reflection angle.
2) FWHM.Gloss: full-width half maximum of BRDF.
3) Image of gloss unevenness at FWHM.Gloss.

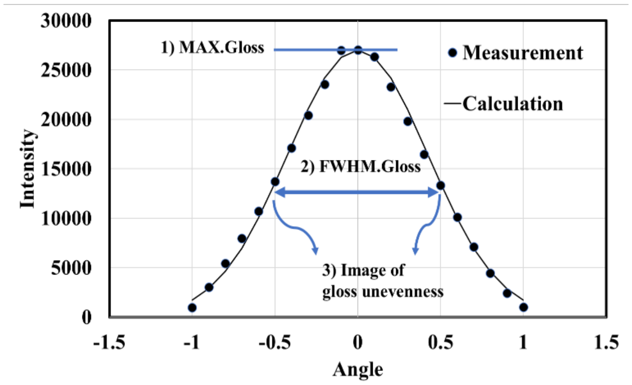


Figure 14. *Measured and calculated gloss data with, the three important indicators*

We propose the gloss curve, BRDF, is modeled with a normal distribution curve. The normal distribution curve is expressed using Eq. 2.

$$\boldsymbol{f(\theta)} = \frac{1}{\sqrt{2\pi\sigma^2}} \exp(-\frac{(\theta-\mu)^2}{2\sigma^2}) \qquad (2)$$

where μ is the peak angle of BRDF.
The following relationship between σ and FWHM is given in Eq. 3.

$$\boldsymbol{\sigma} \cong \frac{FWHM}{2.35} \qquad (3)$$

The maximum value of the curve occurs when μ and θ are 0.0. Therefore, the calculated curve, $\boldsymbol{f'(\theta)}$, can be approximated by Eq. 4.

$$\boldsymbol{f'(\theta)} = \text{MAX.Gloss}*\left(\frac{(\boldsymbol{\theta}-\boldsymbol{\mu})^2}{2(\frac{\boldsymbol{FWHM}}{\mathbf{2.35}})^2}\right) \quad (4)$$

The measured and calculated data are shown in Figure 14. The sample used for the measurement data was black glass. These results are in good agreement. Thus, the gloss curve can be modeled using MAX.Gloss and FWHM.Gloss. Furthermore, the gloss unevenness can be recorded as an image at the FWHM.

5. Conclusion

We captured images of the samples using a device that could mechanically control the angle of the incident light. As a result, we determined the intensity of the gloss peaks and the BRDF from the images taken at each angle. The FWHM of the gloss was obtained from BRDF. Gloss unevenness was also defined by the gloss and moving average of the gloss. These results relate to photography and human visual perception, thus providing a reference to elucidate how people define gloss unevenness.

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References

[1] 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).

[2] S. Inoue and N. Tsumura, "Effect of light source distance on apparent gloss unevenness," OSA Continuum 4(2), 720-731 (2021)

[3] 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).

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

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

[6] M. E. Becker, "High-Resolution Scatter Analysis of Anti-Glare Layer Reflection," SID 2016 DIGEST, 368-371 (2016).

[7] J. S. Arney, H. Heo, and P. G. Anderson, "A Micro-Goniophotometer and the Measurement of Print Gloss," J. Imaging Sci. Technol. 48 (5), 458-463 (2004).

[8] 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).

[9] S. Inoue, Y. Kotori, and M. Takishiro, "Paper Gloss Analysis by Specular Reflection Point Spread Function Part I," Japan Tappi J. 66 (8), 879 (2012).

[10] S. Inoue, Y. Kotori, and M. Takishiro, "Paper Gloss Analysis by Specular Reflection Point Spread Function Part II," Japan Tappi J. 66 (12), 1416 (2012).

[11] S. Inoue and N. Tsumura, "Measuring the BRDF and radius of curvature with patterned illumination," OSA Continuum 4(3), 1113-1124 (2021)

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

[13] S. Inoue and N. Tsumura, "Measuring Method for Line Spread Function of Specular Reflection," OSA Continuum 3(4), 864-877 (2020)