https://doi.org/10.2352/issn.2169-2629.2019.27.26

Line Spread Function of Specular Reflection and Gloss Unevenness Analysis

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Abstract

In this paper, we examined the physical meaning of the widely used gloss evaluation. Gloss is one of the important qualities for materials. A visual test of the sharpness of a specular reflection image, i.e. gloss, on the surface of materials is often performed to estimate the gloss of materials. If the specular reflection image is sharp, we estimate that it has high gloss. This means that gloss can be estimated by measuring the sharpness of the specular reflection image. In this case, a line light source such as a fluorescent lamp is often used. Here we call it the line light source observation method. We developed a measurement apparatus based on the line light source observation method. As a result of experimental verification, it is confirmed that the Line Spread Function of Specular Reflection (SR-LSF) can be derived from the line light source observation images. However, the reflected image of line light source observation method is considered to be strictly different from SR-LSF. On the other hand, it is clarified that the line source observation method is an approximate SR-LSF measurement method. We also introduce the reconstruct method of gloss unevenness image by following visual observation conditions and image processing in human brain.

1. Introduction

Gloss is one of the important qualities for materials. When a printed image is observed under a light source, gloss on the surface is observed in addition to the printed image. In the 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. The physical nature of gloss and gloss unevenness are specular reflection phenomena.

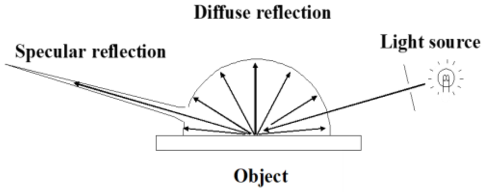


Figure 1. Schematic diagram of a dichromatic reflection model.

As shown in Fig. 2, a visual test of the sharpness of a specular reflection image on the surface of materials is often performed to estimate the gloss of materials. If the specular reflection image is sharp, we estimate that it has high gloss. Pellacini et.al. analyzed more detail by a psychophysically-based light reflection model [1]. This means that gloss can be estimated by measuring the sharpness of the specular reflection image. In this case, a line light source such as a fluorescent lamp is often used. Here we call it line light source observation method.

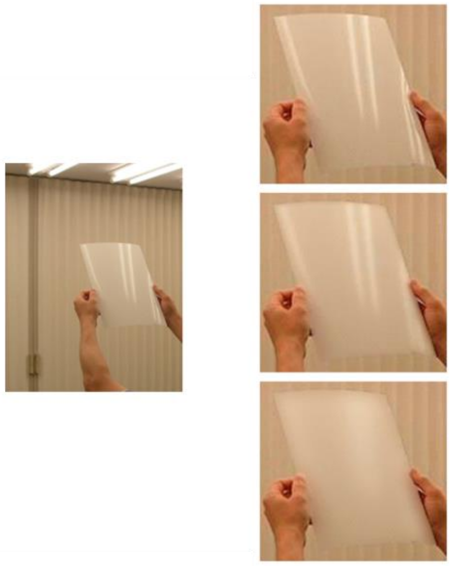


Figure 2. Photographs showing the visual inspection of paper gloss. The upper right is high gloss paper, the middle one is glossy, and the bottom one is matt paper.

It is considered that the line spread function (LSF) theory, which estimates the sharpness of an image, could be applied to analyze gloss [2]. We will discuss line spread function of specular reflection (SR-LSF). However, the line light source observation method is considered to be strictly different from the SR-LSF measurement method.

In this paper, we discuss the relationship between the line light source observation method and the SR-LSF. We develop a measurement apparatus based on the line light source observation method. It is confirmed that the SR-LSF can be derived from the line light source observation images. The measured images include gloss unevenness. It is known that it is easier to perceive gloss unevenness on slightly difference angle than just center of mirror reflection angle. The measured image includes areas of any different angles from the mirror reflection angle, and they are lined up in a straight line because of the light source is line. We propose a technique to make gloss unevenness image by using the measured images. It is considered that the technique is equal to the image processing in human brain.

2. Theory

2.1 Line Spread Function of Specular Reflection (SR-LSF)

The Line Spread Function (LSF) is of importance in many measurements used to determine image quality [2]. The advantages of the LSF are that it is a one-dimensional function and that it is easy to use and to measure in Fig.3. The spread of the measured line image of specular reflection is defined as the SR-LSF. The SR-LSF is a one-dimensional integral of the SR-PSF. Authors have introduced the SR-PSF that is a gonio-reflectance distribution [3]. The universal method to describe the physical reflectance properties is through the bidirectional reflectance distribution function (BRDF). It means the SR-PSF is a BRDF also. Based on these knowledges, the SR-LSF is the gonio-reflectance distribution of reflected line light source image.

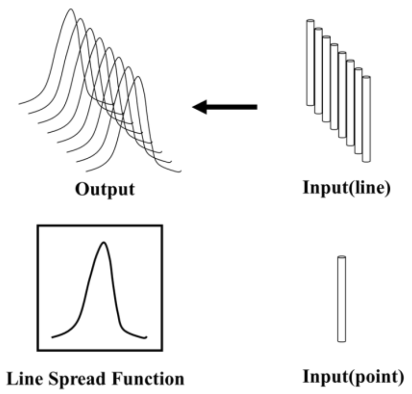


Figure 3. Schematic diagram of Line Spread Function.

The reflectance at the deviation angle from the specular reflection angle is named gonio-reflectance, which can be measured by a goniophotometer [4]. As shown in Fig.4, the goniophotometer has a movable detector to measure the reflectance at different angles at a certain angle of incident light. Therefor the SR-LSF is, specifically, the gonio-reflectance distribution when the incident light is a fixed angle. However, the gonio-reflectance measurement by a goniophotometer is not easy to perform. Measuring technique of gonio-reflectance is developing, for example, Arney et.al. introduced a micro-goniophotometer [5].

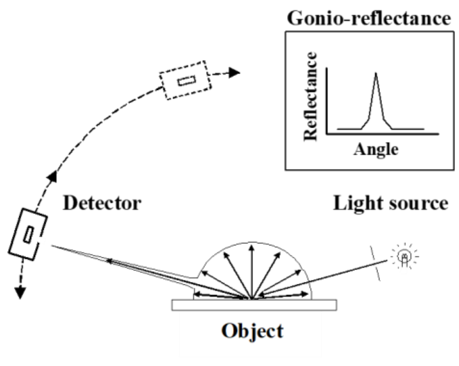


Figure 4. Schematic diagram of goniophotometer and gonio-reflectance.

2.2 Line light source observation method

Observers generally evaluate for gloss by reflecting a line light source onto the object surface. This visual observation condition is looks like the measurement technique of SR-LSF. The observer pays attention to the intensity of mirror reflection of the line light source, the spread of the line light source image, and the gloss unevenness around the line light source image.

The line light source is, for example, a fluorescent light. In most cases, the light source is considered as a collection of point light sources, and the light spreads over a wide angle. The angle of incident light is different on each position on the surface of the observation object. Human's eyes have a viewing angle also. Therefore, in this method, the incident angle and the observation angle at each position on the object surface become a combination. As mentioned above, The SR-LSF is the gonio-reflectance distribution when the incident light is a fixed angle. It does not meet this condition.

The focus position is also an important issue. There are differences between whether the observer focuses on the object surface or focuses on the light source. The observer focuses on the object surface at least when observing gloss unevenness. The focus position is assumed that on the object surface in this paper.

3. Experiments to confirm the relation between the line light source observation method and SR-LSF

3.1 Developed apparatus based on the line light source observation method

We developed a measurement apparatus based on the line light source observation method. Figures 5 and 6 show the apparatus in this paper. The length is 250 mm from the light source to the center of sample bed. The length is 250 mm from the camera to the center of sample bed also. The light source and the camera angles are set to 45 degree. The line light source aperture is 0.5 mm. The line light source is on a slid stage which move from minus 20mm to plus 20 mm and set to 45 degree in the center of it. This mechanism can be used for changing the angle of line light source. The image resolution of the CCD camera is 1920×1080 pixels, and it has 8-bit output level per pixel. The pitch of one pixel corresponds to 0.037 mm on the object plane. 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 material is set on the sample bed, and the image is measured in a darkroom. We prepared and measured a black glass whose refractive index is 1.567 to perform the calibration process for the measured values.

The developed apparatus is similar to gonio photometer. There are two important difference. Considering the light source in one dimension, this light source is a point light source. Point light sources emit light in all directions from a specified point. This makes the light source angle different depending on the position on the sample bed. The incident light is a parallel light which emit same angle in gonio photometer. The optical system of camera is a normal lens system. It has angle of view also. This makes the measured angle different depending on the position on the sample bed. In this way, different combinations of illumination and measurement angles occur depending on the position on the sample bed. In this apparatus, the light source angle can be changed. The position of the camera is fixed so that each image position is the same. They make easy to combinate the images measured.

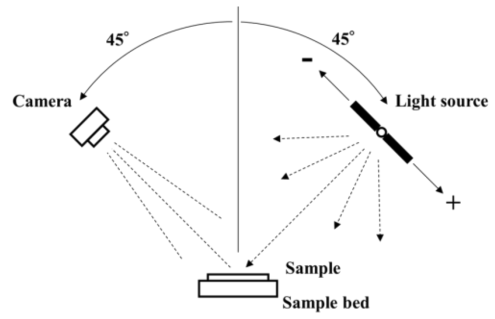


Figure 5. *Diagram of apparatus based on the line light source observation method.*

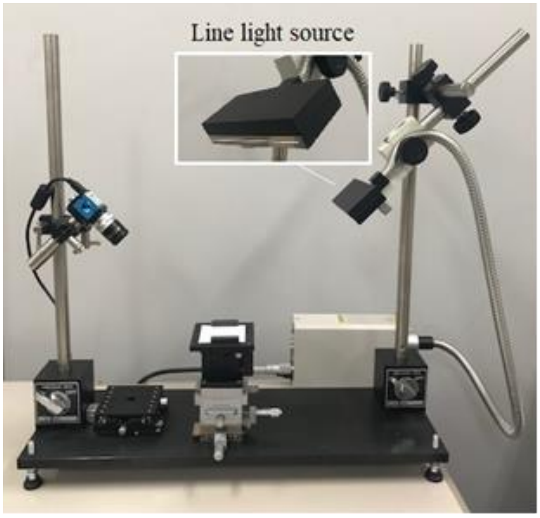
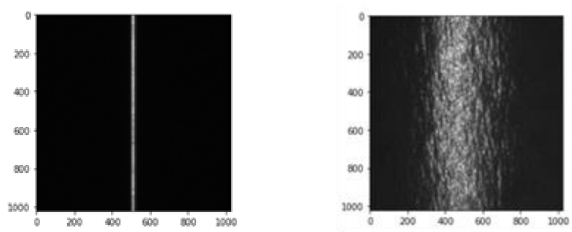


Figure 6. *Photograph of the measurement apparatus.*

3.2 Measured reflected line light source images

The reflected line light source images were measured. They were two materials and black glass. The samples are glossy coated paper and Inkjet paper. The Inkjet paper is photo-grade, resin-coated.



(a) (b)

Figure 7. *The measured reflection line images by using the apparatus. (a) is black glass and (b) is the Inkjet paper.*

Figure 7 shows the measured reflected line light source images by using the apparatus. The x and y axes describe the pixel position on the CCD camera. The intensity describes the output value of the CCD camera. The shape of the reflected line source light distribution of black glass is almost the same size as the original aperture of light source. In contrast, the reflection line light source distribution ofInkjet paper is broad.

3. 3 Relation between the light source angle and camera angle in position on the sample bed

It is necessary to confirm the physical meaning of the measured image. The line light source is on a slid stage. This mechanism can be used for changing the angle of line light source. We investigated experimentally the relation between the light source angle and camera angle in position on the sample bed in this apparatus. Figures 8 shows the schematic diagram of the light source and the camera angle in each position.

Table 1 shows results by mathematical calculation. Figure 9 shows the experimental measured light source images of black glass of changing the light source angles. The measured results agree well with the calculated results in Table 1. It is clear that the observed position in this apparatus shows the angle of light source and the angle of camera. From these results, we found that this apparatus functions as a goniophotometer within a narrow solid angle.

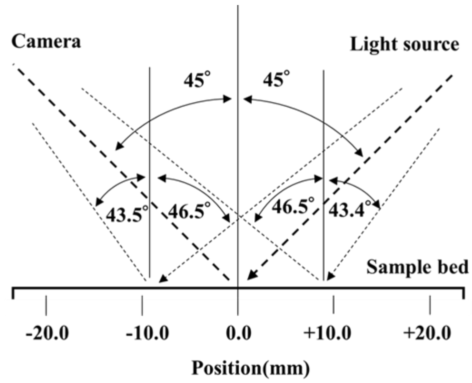


Figure 8. *Schematic diagram of the light source and the camera angle in each position*

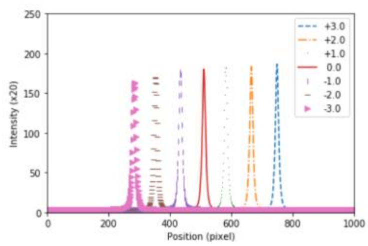


Figure 9. *The mirror reflection position in the light source angle.*

Table 1. The light source and the camera angle in each position.

		Position(mm)												
		-18.6	-15.5	-12.4	-9.3	-6.2	-3.1	0.0	3.1	6.2	9.3	12.4	15.5	18.6
Light source angle (degree)	42.0	45.0	44.5	44.0	43.5	43.0	42.5	42.0	41.5	40.9	40.4	39.8	39.2	38.7
	43.0	46.0	45.5	45.0	44.5	44.0	43.5	43.0	42.5	41.9	41.4	40.8	40.3	39.7
	44.0	46.9	46.4	46.0	45.5	45.0	44.5	44.0	43.5	43.0	42.4	41.9	41.3	40.8
	45.0	47.9	47.4	46.9	46.5	46.0	45.5	45.0	44.5	44.0	43.4	42.9	42.4	41.8
	46.0	48.8	48.4	47.9	47.4	47.0	46.5	46.0	45.5	45.0	44.5	44.0	43.4	42.9
	47.0	49.8	49.3	48.9	48.4	47.9	47.5	47.0	46.5	46.0	45.5	45.0	44.5	43.9
	48.0	50.7	50.3	49.8	49.4	48.9	48.5	48.0	47.5	47.0	46.5	46.0	45.5	45.0
Camera angle (degree)	45.0	41.8	42.4	42.9	43.5	44.0	44.5	45.0	45.5	46.0	46.5	46.9	47.4	47.9

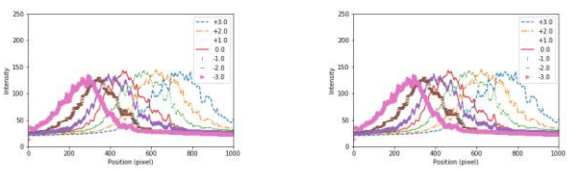
: Mirror reflection position

: Position which light source angle becoms 45 degree

3.4 Proposed conversion from line light source images into SR-LSF

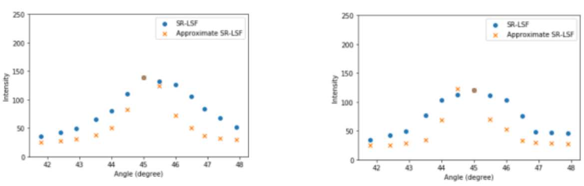
SR-LSF is determined by the intensity of the reflected light at each viewing angle relative to the incident light at the same angle. Looking at Table 1, there are several different reflection angle positions for the same angle of incident light angle. Figure 10 shows the line light source image average curves in each light source angle. Using these measured values, SR-LSF can be obtained.

For example, it is marked the position that incident light angle became 45 degree at Table 1. The camera angle, i.e. viewing angle, under that condition can be read from the table. Figure 11 shows the SR-LSFs in case of light source angle 45 degree. And the curves of the line light source image are plotted as the approximate LSF. It will discuss below.



(a) (b)

Figure 10. *The reflected line light source images in case of each light source angles. (a) is the glossy coated paper and (b) is the Inkjet paper.*



(a) (b)

Figure 11. *The SR-LSFs in case of light source angle 45 degree. (a) is the glossy coated paper and (b) is the Inkjet paper.*

4. Experiment to Image processing for gloss unevenness

Gloss unevenness is one of the important qualities in industry materials. This phenomenon is different depending on the view, so quantitative measurement is difficult. First, gloss unevenness appears only in a narrow area around the mirror reflection image. Second, its magnitude varies with the distance (angle) from the center of mirror reflection. The method of observing the reflected light source image is superior to the measurement which fixed the condition from the beginning, because human beings can arbitrarily select the area where the gloss unevenness can be observed well.

The observer changes the angle of the object and moves the light source image continuously on the object surface. By moving the light source image, the observer reconstructs the entire surface image of the gloss unevenness that appears only in a small area. It is considered to be processed in the human brain.

By following these visual observation conditions and image processing in the human brain, it is considered that an effective gloss evaluation system can be developed. On the other hand, it is necessary to confirm the physical meaning of these visual observation conditions and image processing.

The line source observation method has further important advantages. Application to measurement of gloss unevenness is possible. The focus is on the sample surface with this apparatus. Therefore, it is possible to take an image of gloss unevenness that appears near of mirror reflection. As mentioned above, the apparatus can be changing the angle of line light source. By moving the line light source image, it reconstructs the entire surface image of the gloss unevenness that appears only in a small area. It is considered to be processed in the human brain.

It is known that the largest dispersion of gloss unevenness is in the middle of attenuation of the gloss curve (SR-LSF) .

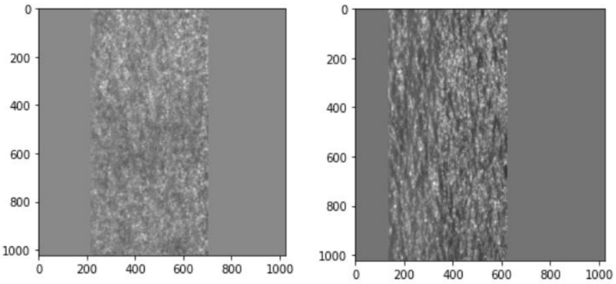
The gloss unevenness image was obtained by the following procedure.

Step 1: Determine the area of gloss unevenness from the approximate SR-LSF image.

Step 2: The angle of the light source image is changed and captured in the range where the gloss unevenness area continues.

Step 3: Obtain an approximate SR-LSF curve from each captured image.
Step 4: Subtract processing an approximate SR-LSF curve from each captured image.
Step 5: Synthesize the image in the gloss unevenness area to reconstruct the entire gloss unevenness image.

Figure 12 shows the reconstructed entire gloss unevenness image. The reconstructed entire gloss unevenness image can be seen that it represents the gloss unevenness well.



(a) (b)

Figure 12. *The reconstructed entire gloss unevenness images by using the apparatus. (a) is the glossy print paper and (b) is the Inkjet paper.*

5. Discussion

5.1 Confirmation that reflected line light source image is approximate SR-LSF

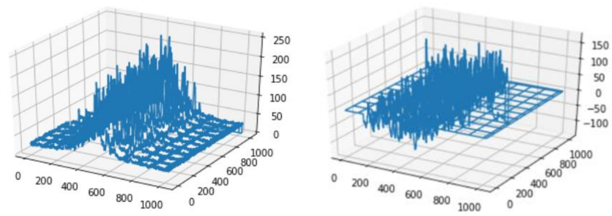
The measured line light source images are almost the same even if the light source angles are different, as shown in Fig. 10. According to this experimental results, one measured line source image can be used representatively. In this case, it should be noted that the measurement position when the light source angle is changed by 1/2 degree corresponds to a change of 1 degree in SR-LSF angle. The two carves are compared in Fig.11. As a conclusion, it is clarified that the line source observation method is an approximate SR-LSF measurement method.

5.2 Comparison with previous research about the gloss unevenness analysis

The gloss unevenness of materials has always been the object of quality evaluation in the industry. In most cases, this gloss unevenness is not strong, and even visually recognized by a skilled person, it is often difficult to distinguish. Research has been conducted to record an image of gloss unevenness.

As introduced in this paper, there is a method of capturing an image in which a light source image is reflected. In this case, gloss unevenness appears only in a small area, and its intensity is also not constant because it is attenuated. There is known a method of continuously measuring the intensity of light at a constant reflection angle by using a laser or parallel light as the incident light. In this case, it is necessary to know in advance the angle at which the gloss unevenness can be observed. Even with the same product, the angle at which gloss unevenness can be seen may differ slightly due to the cause.

The method of reconstructing gloss unevenness image proposed in this paper has many advantages. Gloss unevenness area can be observed easily in the approximate SR-LSF image. Gloss unevenness can be measured quantitatively as a difference by subtracting the approximate SR-LSF. By moving the line light source image, the system reconstructs the entire surface image of the gloss unevenness that appears only in a small area in Fig.13. These processes are considered to be equivalent to what is being processed in the human brain.



(a) (b)

Figure 13. *The measured reflection line images by using the apparatus. (a) is the row data of the Inkjet paper, (b) is the reconstructed entire gloss unevenness image.*

6. Conclusion

We proposed the line spread function of specular reflection (SR-LSF). We developed an apparatus based on the line light source observation method. As a result of computational simulation and experimental verification, it was clarified that the observation position in this apparatus shows the angle of light source and the angle of camera. From these results, it was found that this apparatus functions as a goniophotometer within a narrow solid angle. We introduced how to obtain SR-LSF using these measured values. And it is clarified that the line source observation method is an approximate SR-LSF measurement method. We also introduced a measurement method of gloss unevenness image by following visual observation conditions and image processing in human brain.

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