Reproducing Gloss Unevenness on Printed Paper Based on the Measurement and Analysis of Mesoscopic Facets¹

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Abstract. In this article, the authors reproduce gloss unevenness on a paper surface by expanding the Torrance–Sparrow model, which is based on the measurement and analysis of mesoscopic facets on paper. As the conventional Torrance–Sparrow model only considers macroscopic and microscopic facets, the authors expand the model to be able to consider mesoscopic facets. The normal vectors of mesoscopic facets on a paper surface were measured by using a collimator lens system with a small pinhole aperture, and the authors obtained the normal vector map by moving the stage for the paper. Gloss unevenness was reproduced by generating the same probability distribution as the measured distribution of the normal vectors. As a result, the authors succeeded in reproducing gloss unevenness using an expanded Torrance–Sparrow model. © 2014 Society for Imaging Science and Technology. [DOI: 10.2352/J.ImagingSci.Technol.2014.58.3.030501]

INTRODUCTION

Gloss is an important quality of printing paper. Gloss is a specular reflection phenomenon, i.e., an optical phenomenon. Many reflection models have been proposed, and practical applications are used in computer graphics.^{1–5} In conventional simple reflection models, it is assumed that all microscopic facets have the same statistical properties; therefore, these models render a homogeneous gloss reproduction. However, the gloss that appears on paper is not homogeneous in real life. A number of measurement technologies have been developed and reported to evaluate the gloss.⁶⁻¹³ Some of them, in particular, have reported measurement technologies and evaluation methods with respect to gloss on paper.¹⁴⁻¹⁷ Conventionally, gloss is evaluated as averaged behavior on the surface of paper. A typical evaluation method is standardized for use with gloss in the Japanese Industrial Standards (JIS).

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Macroscopic facet > Mesoscopic facet > Microscopic facet

Figure 1. Classifying a paper surface into three types of facet.

Inoue et al. measured the point spread function (PSF) for specular reflection, and showed that the PSF is helpful in evaluating gloss on printed paper.¹⁴ In practice, the gloss on a paper surface is not even. Fujiwara et al. reported on the measurement and analysis of gloss.¹⁵ Inoue et al. constructed a simple experimental setup to measure the intensity distribution of reflected light on a paper surface, and analyzed gloss unevenness on printed paper with various gloss levels.^{14,16,17}

A reflective paper surface can be classified into three types of facet, as shown in Figure 1: (1) a macroscopic facet which represents the shape of the paper surface; (2) a microscopic facet which represents the roughness of the paper surface that the human visual system cannot perceive; and (3) a mesoscopic facet which is an intermediary between a macroscopic facet and a microscopic facet. As shown in Figure 2, gloss unevenness caused by mesoscopic facets is observed when evaluating paper quality in practical situations. In this article, we define gloss unevenness as "the spatial change of specular reflectance," and we define surface color texture as "the spatial distribution of diffuse reflectance color."

In this article, therefore, we consider that gloss unevenness is caused by the mesoscopic facets that the conventional Torrance–Sparrow model⁵ does not consider. Mesoscopic facets on printed paper are introduced as an expansion of the Torrance–Sparrow model to reproduce gloss unevenness. In this article, it is demonstrated, based on actual measurements, that gloss unevenness can be expressed by fluctuations in the normal vectors allowing mesoscopic facets to generate random numbers. Measurements are

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Figure 2. Evaluating paper gloss (right). Enlarged image of gloss area (left). There is gloss unevenness on printing paper in general.

performed using a collimator lens system with a small pinhole aperture and we obtain a normal vector map by moving the stage for the paper.

MEASUREMENT OF NORMAL VECTOR MAP *Basis Confirmation by Changing the Size of the Pinhole in the Collimator Lens System*

First, the apparatus that is used for measuring the reflection light angle distribution is introduced. Second, the reflection angle distribution of mesoscopic facets and macroscopic facets is measured experimentally using the apparatus. The measurement method is shown in Figure 3. Parallel light is projected onto the sample paper, and the intensity distribution of the reflected light is measured by a twodimensional CCD camera. The reflected light is inversely collimated as an image. The lighting and viewing angles are set to 75° in the experiments. The reflection angle is changed by the facet angle (i.e., facet normal). The observed position corresponding to the facet deviation angle is measured in the experiment. In this apparatus, an LED lamp is used as the light source. The focal length of the collimator lens is 50.1 mm. The CCD camera has a resolution of 512×512 pixels, and a 16-bit grayscale. We checked the linearity of the camera output (0-65,535) against the KODAK Gray Scale. We projected parallel light onto the KODAK Gray Scale and checked the output value at each density. The output values showed linear changes, and the output values were used as the light flux in this study. A paper sample was mounted on the central sample bed, and measured in a dark room. We used black glass with a refractive index of 1.567 as a standard, and the measurement parameter was set by this standard.

The angle distribution of reflection light corresponding to the facet deviation angle was measured in the experiment. In the apparatus, the measured area is decided according to the size of the light flux. The experiments were carried out for a basic analysis under the following two conditions.

 Macroscopic facet: using a light flux size of Ø5.0 mm, we measured the reflection light angle distribution of a macroscopic facet.



Figure 3. The method used in this study for measuring the specular reflection angle.

(2) Mesoscopic facet: using a light flux size of Ø0.2 mm, we measured the reflection light angle distribution of a mesoscopic facet.

We chose \emptyset 5.0 mm for the macroscopic facet because we used this size in our previous work for measuring the macroscopic behavior of specular reflection on a paper surface.¹⁴ We chose $\emptyset 0.2$ mm for the mesoscopic facet because this was the limit to which we could stably measure the output value. A pinhole whose size is $\emptyset 0.1$ mm is set up at the focal position of the collimator lens, so the size of the light flux is $\emptyset 0.1$ mm. The light flux sizes of $\emptyset 5.0$ mm and \emptyset 0.2 mm are made by setting up pinholes whose sizes are \emptyset 5.0 mm and \emptyset 0.2 mm, respectively, after the light flux has been collimated. During the course of measurement, the size of the pinhole was changed. The pinhole was not elliptical but circular. Because of the geometry of the measurement (i.e., the lighting and viewing angles were set to be 75°), the distribution of the measured area became elliptical. Art paper for printing was used in this measurement. The measured result of the reflection light angle distribution is shown in Figure 4. It is clear that the distribution of a mesoscopic facet is narrower than that of a macroscopic facet. When it was \emptyset 5.0 mm (macroscopic), we found that the result barely changed. With Ø0.2 mm (mesoscopic), each result changed to a different place on the same paper sample as above.



Figure 4. Measured results of reflection light: (a) the macroscopic area (Ø5.0 mm); (b) the mesoscopic area (Ø0.2 mm).



Figure 5. The calculated normal of each mesoscopic (\emptyset 0.2 mm) facet. Position (ψ , θ) shows the deviation angle of the normal.

The incident light angle is constant, so the surface normal of the facet can be estimated by calculation. Figure 5 shows the normals of the mesoscopic facets which are calculated from the measured results.

Measuring the Normal Vector Map of Mesoscopic Facets

Figure 6 shows a photograph of the device. The surface of the paper sample was measured continuously by moving the sample bed in 0.2 mm increments in the x and y directions, as shown in Figure 7. We moved it with the same step along the x and y directions in order to apply the measured data to computer graphics. There were 25 points in the x direction on each of the 25 lines in the y direction. The total number of data points was $625 (25 \times 25)$. The area was 5.0 mm \times 5.0 mm, almost the same as the measurements for a macroscopic facet. Each datum has an image of specular reflection distribution, and the normal vector is calculated from the position of the peak for this specular reflection distribution. We use the position of the maximum as the position of the peak for specular reflection distribution. In this article, we define a set of 25×25 facets as "measured-size facets." Figure 8 shows the distribution of the normal vectors for the measured-size mesoscopic facets, which is converted from xyz coordinates into RGB color values. The blue areas in the figure indicate that the direction of the normal vector is (x, y, z) = (0, 0, 1). In Fig. 8, the R and G values are multiplied by 100 to improve the visualization of the unevenness of the normal vectors. We can see that the distribution of the normal vectors is not



Figure 6. Photograph showing the measurement system for the normal vector of a mesoscopic facet.



Figure 7. Measurement for mesoscopic facet per 200 μ m.



Figure 8. Visualized distribution of normal vectors in measured-size facets converted from xyz coordinates into RGB values.

homogeneous because Fig. 8 is not entirely blue. The white square in Fig. 8 is a signal caused by scarring on the surface of the paper sample.

RENDERING BY REFLECTION MODEL WITH CONSIDERATION OF MESOSCOPIC FACETS

Conventional Result by Original Torrance-Sparrow Model In this article, we discuss only specular reflection in the Torrance-Sparrow model, and we regard diffuse reflection as a Lambertian reflection. The Torrance-Sparrow model assumes that a rough surface is constructed from microscopic facets and that each facet reflects light as a mirror. The roughness of the surface is defined by the probability distribution of angles of the microscopic facets. The Torrance-Sparrow model can express a phenomenon where the peak of a surface reflection shifts from the mirror reflection. The



Figure 9. Lighting and viewing geometry in the Torrance–Sparrow model.

geometry of lighting and viewing in the Torrance–Sparrow model is shown in Figure 9. The angles θ_{in} , θ_{out} , and θ_h are the angles of incidence, reflection, and that between the half vector and the light-source direction, respectively. The angle θ_a is the angle between the half vector and the normal vector. The half vector **h** is a vector in the position that bisects the angle that is the vector **l** of the light-source direction and the vector **e** of the viewing direction, and it is defined as follows:

$$\mathbf{h} = \frac{\mathbf{l} + \mathbf{e}}{|\mathbf{l} + \mathbf{e}|}.\tag{1}$$

In the geometry shown in Fig. 9, the surface reflectance is denoted by the following equation:

$$R_{s,\lambda}(\theta_{\rm in}, \theta_{\rm out}, \theta_h, \theta_a) = r_{s,\lambda} \frac{G(\theta_{\rm in}, \theta_{\rm out}, \theta_h, \theta_a) F(n, \theta_h)}{\cos \theta_{\rm in} \cos \theta_{\rm out}} \times \exp\left(-\frac{\theta_a^2}{2\sigma}\right),$$
(2)

where $R_{s,\lambda}$ denotes the specular reflectance, $r_{s\lambda}$ is the scalar specular coefficient, σ is the roughness, *G* is the geometrical attenuation factor that defines interception of light by asperity on the surface, and *n* is the relative index of refraction. $G(\theta_{in}, \theta_{out}, \theta_h, \theta_a)$ is denoted by the following equation:

$$G(\theta_{\rm in}, \theta_{\rm out}, \theta_h, \theta_a) = \min\left(1, \min\left(\frac{2\cos\theta_a\cos\theta_{\rm out}}{\cos\theta_h}, \frac{2\cos\theta_a\cos\theta_{\rm in}}{\cos\theta_h}\right)\right).$$
(3)

The reflective coefficient of Fresnel, $F(n, \theta_h)$, is denoted by the following equation by using $c = \cos \theta_h$, $g = \sqrt{n^2 + c^2 - 1}$:

$$F(n,\theta_h) = \frac{1}{2} \frac{(g-c)^2}{(g+c)^2} \left(1 + \frac{(c(g+c)-1)^2}{(c(g-c)+1)^2} \right).$$
(4)

Figure 10 shows the result of the gloss reproduction used by the OpenGL Shading Language (GLSL) computer graphics system. GLSL has been designed to allow application programmers to express the processing that occurs at programmable points of an OpenGL pipeline. We reproduced the gloss according to the lighting angle where the Torrance–Sparrow model was introduced into the reflection model.^{5,18–21} Actually the color of the paper sample was white. We gave color to the paper sample in order to show the specular component effectively. In this work, the



Figure 10. Result of gloss reproduction used by GLSL with the conventional Torrance–Sparrow model.

25 × 25 facets	100 × 100 facets
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Figure 11. The normal vector distribution consists of 4×4 measured-size normal vector distributions.



Figure 12. Result of the gloss reproduction used by GLSL for the measured normal vectors.

color of the diffuse component was set as purple, the value of the refractive index was set to 1.50, and the value of the roughness was set to 0.03 from the measurement. Fig. 10 shows that all of the normal vectors are even. Therefore gloss unevenness is not observed.

Distribution Model of Measured Normal Vectors

The left image in Figure 11 shows the same image as shown in Fig. 8: the distribution of normal vectors of measured-size mesoscopic facets at intervals of 200 μ m. This distribution has only 25 × 25 facets, which is not enough to render a larger print sample. Therefore, we combine 4 × 4 measured-size normal vector distributions to obtain an extended size for the normal vector distribution. The extended-size normal vector distribution consists of a right/left and top/bottom inversion of the measured-size normal vector distribution to avoid the edge effect of the measured-size distribution, as shown in the right image in Fig. 11. Figure 12 shows the rendering result for the extended-size normal vector distribution.



Figure 13. Probability histogram of the distribution of normal vectors: (a) x-components of the measurement value; (b) y-components of the generated value; (c) x-components of the generated value; (d) y-components of the generated value.

Distribution Model for Generated Normal Vectors

Each normal vector is resolved into its x-, y-, and z-components. We calculated probability histograms for the measured distribution of the normal vectors for each x- and y-component. Figures 13(a) and (b) show the measured histograms for each component. The globe-like shape of the distribution looks Gaussian because most normal vectors are vertical. The larger the gradient a normal vector has, the fewer numbers it has. In order to generate the distribution, each component is substituted by a random number according to the measured distributions of the normal vectors. The value x_n is calculated by the following equation:

$$x_n = \frac{r - g(i - 1)}{g(i) - g(i - 1)} \times x_0 + (i - 1) \times x_0, \tag{5}$$

where x_n denotes the random number according to the measured distribution, x_0 denotes x divided by i, i denotes the number of increments, r denotes the random number generated temporarily, and g(i) denotes the cumulative distribution function. Equation (5) is applied when g(i) is greater than r. The same calculation is applied to calculate y_n . Figs. 13(c) and (d) show the probability histogram of each x- and y-component generated by this algorithm.²² The levels of the frequencies are different from those of Figs. 13(a) and (b) because the probability histograms

are generated with the extended-size distribution of normal vectors.

In the next step, we consider the relationship among neighboring facets in the measured distribution of normal vectors. As the normal vectors for neighboring facets should change smoothly, we calculated the histograms of the variation of each x- and y-component of the measured normal vectors. This is shown in Figures 14(a) and (b), respectively. The generated normal vector of the mesoscopic facets is based on this variation.

Figure 15 shows the result of rendering by the generated distribution of normal vectors. As can be seen, we successfully reproduced the gloss unevenness by using the distribution model of the generated normal vectors. Compared with Fig. 10, in Fig. 15 there is unevenness in the gloss; thus, it is shown that gloss unevenness is caused by the mesoscopic facets.

CONCLUSION

In this article, we measured the distribution of normal vectors for mesoscopic facets. We calculated the probability histogram with consideration of the variations in the normal vectors. We reproduced gloss unevenness by using the Torrance–Sparrow model taking into consideration the mesoscopic facets, and found that gloss unevenness can be successfully reproduced by this expanded model. In future



Figure 14. Probability histogram of variation: (a) x-components and (b) y-components of normal vector.



Figure 15. Reproduction result of gloss unevenness by the generated normal vectors.

works, the accuracy of gloss unevenness reproduction is expected to be improved in generating normal vectors, and we will look to perform a subjective evaluation of the reproduced gloss unevenness.

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