Estimation of Surface Topography using Collimator and Telecentric Optical Systems

Masanori Maki[1], Shinichi Inoue[2] and Norimichi Tsumura[1]; [1]Graduate School of Advanced Integration Science, Chiba University, CHIBA, JAPAN; [2]Mitsubishi Paper Mills Limited, TOKYO, JAPAN

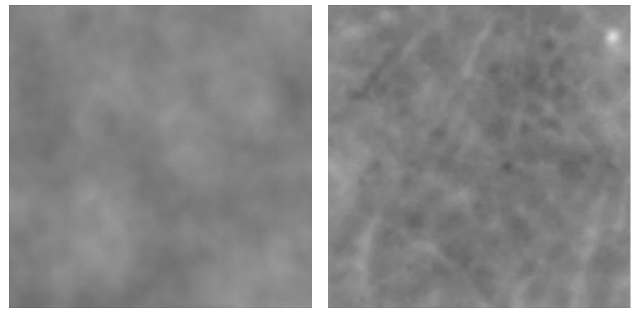
Abstract

Both of gloss and gloss unevenness are important quality for printing paper. It is difficult to measure gloss unevenness of printing paper with gloss meter. It is assumed that gloss unevenness is caused by surface topography. Thus, measuring surface topography is useful in evaluating gloss unevenness. In this paper, we propose a new method that is composed of a collimator optical system and a telecentric optical system for the low price and quick evaluation. The statistical properties of the surface normal distribution are acquired by the collimator optical system. The spatial frequency property of the unevenness is acquired by the telecentric optical system. To estimate surface topography, we assume that surface topography is expressed as the Perlin noise. The method is proposed to derive the parameters which decide about the Perlin noise model from the measured statistical properties. We estimate the surface topography with this method and verify the validity of the proposed model.

1. Introduction

Printing papers are widely used in mass production. The printing processes should be controlled appropriately to maintain the quality of the papers as well, such as equable color and gloss. In the practical situation, however, we can observe the difference for gloss unevenness in the printing papers. This is because that gloss unevenness cannot be measured by a gloss meter which is conventional used in the printing industry. It is assumed that gloss unevenness is caused by surface topography of printing paper. It is expected to be useful to measure the surface topography in evaluating gloss unevenness. Surface topography can be measured with a profilometer. Profilometers have two kinds of methods. One is a contact method, and the other is a non-contact method. For example, stylus profilometers are a contact method. These can measure surface topography accurately, though these scratch a measured surface. Confocal microscopies are a non-contact method. These can measure surface topography without scratching. However, most of the profilometers are expensive and need a long time to measure the surface topography.

In this paper, therefore, we propose a new method that uses collimator optical system and a telecentric optical system for the low price and quick evaluation of gloss unevenness. To acquire surface topography, we use the statistical properties of the surface normal distribution and the spatial frequency property of the unevenness. The statistical properties are acquired with the collimator optical system and the spatial frequency property of the unevenness is acquired with the telecentric optical system. We consider the method that estimates surface topography from the statistical properties of the surface normal distribution and the spatial frequency property of the unevenness. In this paper, we



(a) (b)

***Figure 1**. The two kinds of depth maps. (a) is the Perlin noise. (b) is measured surface topography.*

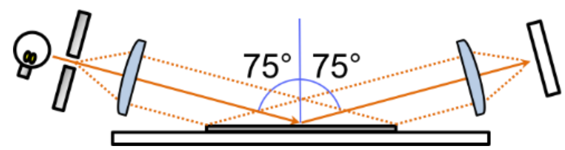


***Figure 2**. The apparatus diagram of the collimator optical system. The lighting and viewing angle are set to be 75 degree.*

assume that surface topography is expressed as the Perlin noise to consider the method that estimates surface topography.

Figure 1 shows depth maps by the Perlin noise and measured surface topography. In this research, we use a computer simulation for imaging by two optical systems, because it is expensive to make many different varieties of paper samples for the analyzing and modeling the property of the gloss unevenness. We use the Perlin noise in the computer simulation as surface topography and represent the collimator optical system and the telecentric optical system in the computer. To use this computer simulation, we acquire the statistical properties of the surface normal distribution and the spatial frequency property of the unevenness. We acquire feature values from the statistical properties and the spatial frequency property of the unevenness. After that, we analyze relationship between Perlin noise parameters that mean surface topography and calculated feature values by using the multiple regression analysis. This relationship represents the method that estimates surface topography from the surface normal distribution and the spatial frequency property of the unevenness. Finally, we verify the validity of this method that estimate surface topography.

2. Acquiring the statistical properties of the surface normal distribution

We used the collimator optical system to acquire the statistical properties of the surface normal distribution. Figure 2 shows the apparatus diagram of the collimator optical system. This optical system that is used to measure the point spread function of specular reflection was proposed by Inoue et al. [1]. This optical system has the collimator optical system, light source and CCD camera. A pinhole pattern is projected to the paper sample with collimator lens, and the reflection light intensity distribution is measured by the two-dimensional CCD camera with the collimator optical system. The lighting and viewing angles are set to be 75 degree.

Figure 3 shows the collimator optical system in received side. The collimator optical system has a focus in one side of a lens, and another side is an optical system used as parallel light. In the collimator optical system, focal position is determined by the angle of parallel light. The pixel of the CCD camera is position in this apparatus. The angle corresponding to the position for every pixel can be calculated. The reflection angle and normal vector on the paper sample can be calculated from the angle of parallel light. Figure 4 shows the ray trajectory in the collimator optical system. The reflection light intensity of each pixel is determined by normal vector of micro surface. For this reason, we acquired normal distribution of paper samples. In this optical system, the LED lamp is used as the light source. The CCD camera has 512x512 pixels, and has 16 bits gray levels. The paper sample is set on the central sample bed. This system is used in the darkroom under total darkness conditions . We prepared the black glass (refractive index 1.567) as a standard and the measure data is calibrated by this standard at each time.

Figure 5 shows the measurement results at the center area of measured images. We acquired distribution function of normal vectors, then the gaussian distribution is fit on to the distribution functions. From the resultant gaussian distribution, center column of the measured results as,

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp(-\frac{(x-\mu)^2}{2\sigma^2}) \quad (1)$$

where μ is mean and σ^2 is variance. Figure 6 shows the fitted normal distribution function and column normal distribution. In this paper, the variance of fitted normal distribution function is feature value to represent surface topography.

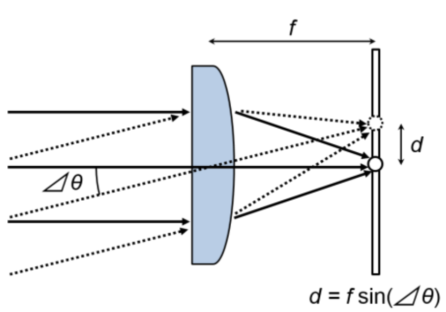


Figure 3. *Schematic diagram of a collimator lens system. The focal point distance (d) can be calculated from the focal length(f) and the difference of angle(Δθ)*

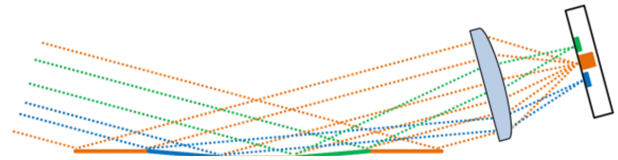


Figure 4. *The ray trajectory on the collimator optical system.*

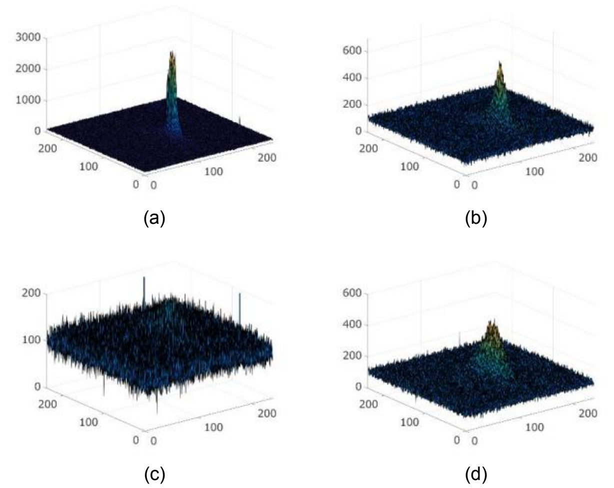


Figure 5. *The example of measurement results at the center 256x256 pixels of measured images. (a) is the coated paper 1(Glossiness 94.2). (b) is the coated paper 2(Glossiness 73.9). (c) is the coated paper 3(Glossiness 54.7) (d) is the inkjet paper(Glossiness 73.1).*

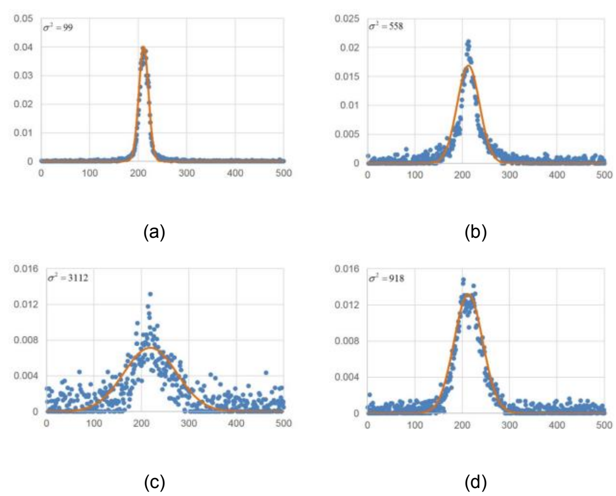


Figure 6. *The fitted normal distribution function and the column normal distribution. (a) is the coated paper 1(Glossiness 94.2). (b) is the coated paper 2(Glossiness 73.9). (c) is the coated paper 3(Glossiness 54.7) (d) is the inkjet paper(Glossiness 73.1).*

3. Acquiring the spatial frequency property of unevenness

We used the telecentric optical system to acquire the spatial frequency property of the unevenness. Figure 7 shows the apparatus diagram of the telecentric optical system. This optical system has telecentric lens, light source and CMOS camera. Parallel light is illuminated to the paper sample, and the reflection light intensity distribution is measured by the two-dimensional CMOS camera with telecentric lens. The lighting and viewing angles are set to be 75 degree.

Figure 8 shows the ray trajectory on the telecentric optical system. The simplest telecentric optical system in received side has the aperture between two lenses on the focal point of two lenses. The light that enters the objective lens to the direction of optical axis can reach the sensor in this optical system. The reflection light that can reach the sensor is determined by specular reflection on micro surface. For this reason, we acquired the spatial frequency property of the unevenness of paper samples. In this optical system, the LED lamp is used as the light source. The CMOS camera has 1280x960 pixels, and has 12 bits gray levels. This pixel size is 3.75um. The paper sample is set on the central sample bed. This system is used in the darkroom under total darkness conditions. We pre-measure the highest gloss paper sample not to be overexposed as standard and calibrated exposure by the pre-measured exposure at each time.

Figure 9 shows the example of measurement results. We calculated the wiener spectrum for each column in measured result to acquire features of the spatial frequency property of unevenness. We calculated it using with following equation,

$$F(u) = \frac{1}{M}\sum_{x=1}^{M} f(x)\exp(-2\pi j(ux)) \qquad (3)$$

$$P(u) = |F(u)|^2 \qquad (4)$$

where x is density of each column, u is frequency in discrete frequency domain, $F(u)$ is Fourier transform of a density fluctuation that is obtained from measured image for each column and $P(u)$ is wiener spectrum of each column. To obtain the wiener spectrum of measured image, we calculated average of each column wiener spectrum.

Figure 10 shows the averaged wiener spectrum of the spatial frequency property of unevenness and the feature values. The parameter α is constant in the flat part of the low frequency. The parameter γ is slope in the slope part of the high frequency. The parameter β is coordinate that is intersection of the flat part with the slope part. In this paper, these three parameters are feature values to represent surface topography.

4. Methods

4.1 Simulation

We used the computer simulation because it was expensive to make paper samples. We analyzed the relationship between features of the statistical properties of the surface normal distribution and the spatial frequency property of the unevenness and surface topography on the computer simulation. To analyze this relationship, we assumed that surface topography was expressed as the Perlin noise [2][3]. In this paper, we used the Perlin noise algorithm that was open to the public by Adrian

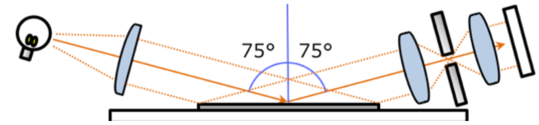


Figure 7. *The apparatus diagram of the telecentric optical system. The lighting and viewing angle are set to be 75 degree.*

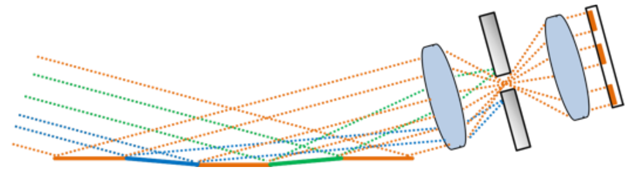


Figure 8. *The ray trajectory on the telecentric optical system.*

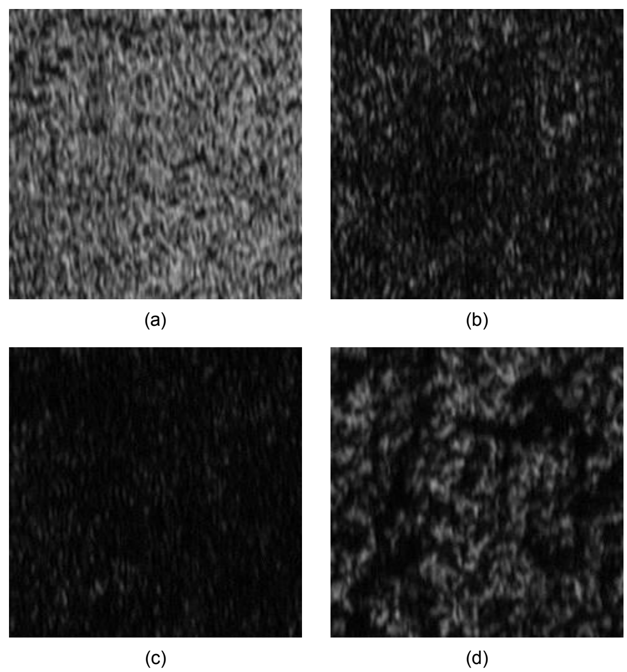


Figure 9. *The examples of measurement results. (a) is the coated paper 1(Glossiness 94.2). (b) is the coated paper 2(Glossiness 73.9). (c) is the coated paper 3(Glossiness 54.7) (d) is the inkjet paper(Glossiness 73.1).*

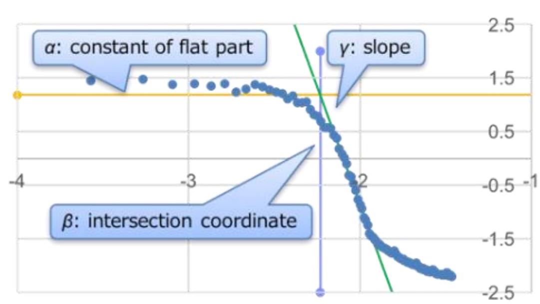


Figure 10. *The wiener spectrum of the spatial frequency property of the unevenness and calculated feature values from the wiener spectrum.*

Biagioli[4]. The Perlin noise is used to express natural appearing textures on computer generated surface in the computer graphics. In addition, this is used to create topographic data in computer games. Therefore, we thought that the Perlin noise can express surface topography.

To analyze the relationship between features of the statistical properties and the spatial frequency property of the unevenness and surface topography on the computer simulation, we programed the computer simulation. This simulator was composed of the surface creator using the Perlin noise algorithm, the collimator optical system simulator and the telecentric optical system simulator.

Surface topography in the computer simulation was expressed as mesh data had 4096x4096 vertexes, and the size of each mesh is assumed to be 1x1 um. The Perlin noise is expressed as the function had x, y and z coordinate as input. This function gives our fractional value between 0.0 and 1.0 as output. Figure 11 shows the example used the Perlin noise. We can acquire wave data using Equation 2.

$$d = 2A \cdot \mathrm{Noise}(x, y, 0) - A \qquad (2)$$

where d is depth in x and y that are coordinates in the Perlin noise. A is amplitude of wave data. Noise is the Perlin noise function. In this paper, we considered used range in the Perlin noise input value as adjustment of frequency and amplitude as adjustment of depth. We considered that used range and amplitude are parameters of surface topography. We let octave and persistence in the Perlin noise algorithm by Biagioli be 4 and 0.6 to simplify the analysis of relationship between features of the statistical properties and the spatial frequency property of the unevenness and surface topography.

To acquire the statistical properties and the spatial frequency property of the unevenness on the computer simulation, we programed measurement simulator of the collimator optical system and the telecentric optical system that represent the characteristic of each optical system simply. Figure 12 shows the example of simulation results measured Perlin noise surface topography using each optical system on the computer simulation.

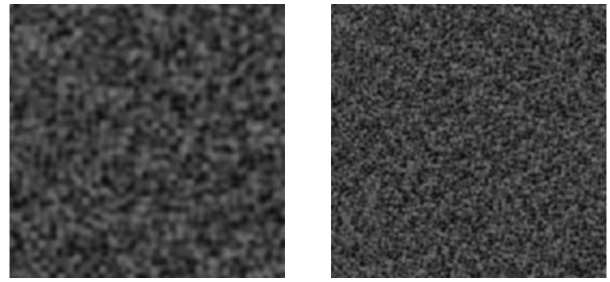
4.2 Analysis

We analyzed the relationship between features of the statistical properties and the spatial frequency property of the unevenness and surface topography on the computer simulation. We analyzed the relationship between two Perlin noise parameters and four feature values that are calculated from the statistical properties and the cycle of the unevenness using multiple regression analysis. As a result, we acquired Equation 3 and Equation4 that express relationship between surface topography and feature values.

$$A = 6.18 \times 10^{-4}\sigma^2 - 0.777\alpha - 552\beta - 8.97\gamma - 1244 \qquad (5)$$

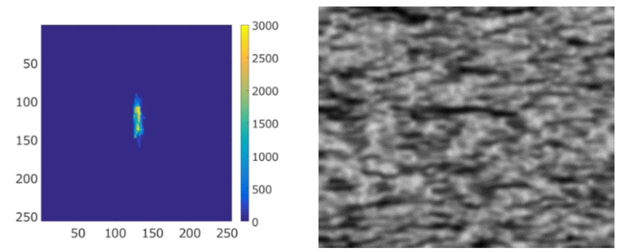
$$S = -8.31 \times 10^{-4}\sigma^2 - 8.59\alpha + 751\beta + 15.0\gamma + 1835 \qquad (6)$$

where A is amplitude as adjustment of depth. S is range in Perlin noise input value as adjustment of frequency. σ^2 is feature value of the statistical properties of the surface normal distribution. α, β and γ are feature values of the spatial frequency property of the unevenness.



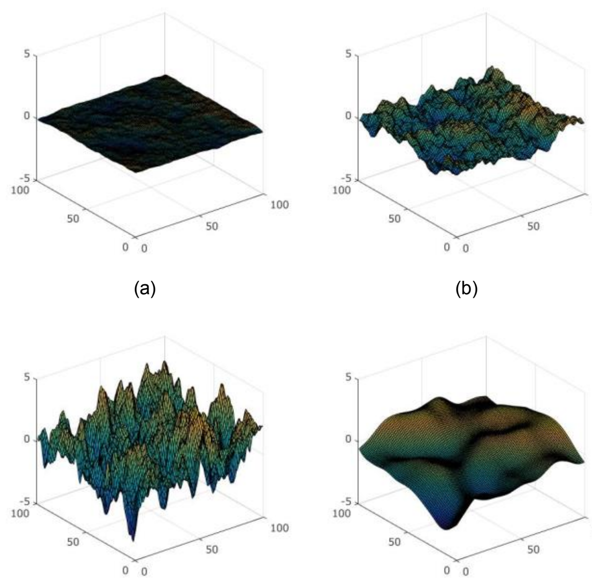
(a) (b)

Figure 11. *The example used the Perlin noise. (a) is smaller used range in the Perlin noise (means low frequency). (b) is larger used range in the Perlin noise (means high frequency).*



(a) (b)

Figure 12. *The example of simulation results measured Perlin noise surface topography on the computer simulation. (a) is measured with the collimator optical system. (b) is measured with the telecentric optical system.*



(a) (b) (c) (d)

Figure 13. *The example of estimated results of surface topography. (a) is the coated paper 1(Glossiness 94.2). (b) is the coated paper 2(Glossiness 73.9). (c) is the coated paper 3(Glossiness 54.7) (d) is the inkjet paper(Glossiness 73.1).*

4.3 Estimation

We estimated surface topography using Equation 3 that expresses relationship between surface topography and feature values of the statistical properties of the surface normal distribution and the spatial frequency property of the unevenness. We measured paper samples using the collimator optical system and the telecentric optical system. We calculated feature values from measured result using the method as discussed in the previous chapter. To acquire Perlin noise parameters that represent the surface topography, we applied these feature values to Equation 3. We acquired the surface topography using the Perlin noise.

5. Result and Discussion

Figure 13 shows the example of estimated results of surface topography as discussed in the previous section. To verify the validity of estimated results, we compared surface topography that is measured with the confocal microscopy and estimated surface topography. To compare these topography, we use the two-dimensional power spectral density that is used to characterize micro roughness parameters [5]. The computation of the power spectral density function adopted in this paper shows Equation 5.

$$S_2(f_x, f_y) = \frac{1}{L^2}\left[\sum_{m=1}^{N}\sum_{n=1}^{N} Z_{mn} \exp(-e\pi i \Delta L(f_x m + f_y n))(\Delta L)^2\right]^2 \qquad (7)$$

where S_2 denotes the two-dimensional power spectral density, L^2 is the scanned surface area, N is the number of data points per line and row, Z_{mn} is the profile height at position (m, n), f_x, f_y are the spatial frequency in the x-directions and y-directions and ΔL is the sampling distance. This computation is further followed by the transition to polar co-ordinates in frequency space and angular averaging (φ).

$$S_2(f) = \frac{1}{2\pi}\int_0^{2\pi} S_2(f, \varphi)\, d\varphi \qquad (8)$$

As the power spectral density function depends on only one parameter. In this paper, we compared measured and estimated surface topography using the power spectral density function depends on frequency parameter.

Figure 14 shows the example of measured results of surface topography with the confocal microscopy. Since the noise can be observed in the topography, it is not appropriate to use measured surface topography to compare measured and estimated surface topography directly.

In this paper, we use the tendency of the power spectral density represented measured and estimated surface topography. Figure 15 shows the power spectral density of measured surface topography. This shows that the glossiness of the paper sample increases as the power spectral density of the paper sample decreases overall. It is noted that we found the frequency characteristics overall is different between coated papers and a inkjet paper.

Figure 16 shows the power spectral density of estimated surface topography using our method. This result shows the similar tendency that is found in the power spectral density of measured surface topography. For this reason, there is a possibility that the Perlin noise is used to represent surface topography and our method is used to estimate surface topography. It is again noted that he frequency characteristics is different between coated papers and the inkjet paper.

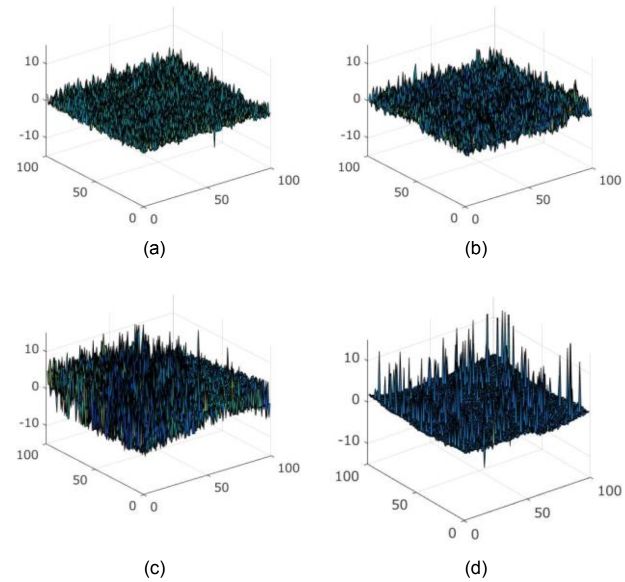


Figure 14. *The example of measured results of surface topography with the confocal microscopy. (a) is the coated paper 1(Glossiness 94.2). (b) is the coated paper 2(Glossiness 73.9). (c) is the coated paper 3(Glossiness 54.7) (d) is the inkjet paper(Glossiness 73.1).*

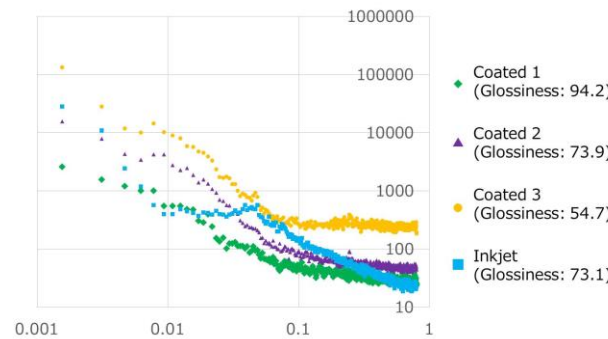


Figure 15. *The power spectral density of measured surface topography.*

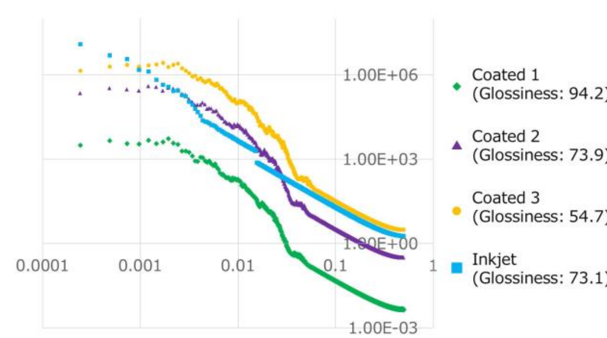


Figure 16. *The power spectral density of estimated surface topography.*

6. Conclusion

In this paper, we propose the new method to measure the surface of paper for lower price and quick evaluation. To estimate surface topography, we assume that surface topography is expressed as the Perlin noise. We estimated surface topography by our method and verified the validity of our method. There is the possibility that the Perlin noise is used to represent surface topography and our method is used to estimate surface topography. From the experiments we found that the proposed method can be used to observe the change of gloss unevenness, since characteristics of coated papers and the inkjet paper are well separately measured.

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