Modeling Gonio-spectral Reflection Properties of Paper Sheets for Efficient Gonio Imaging

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Abstract

In this paper, we proposed a gonio-spectral reflection model for paper sheets based on the dichromatic reflection model. The model was the linear combination of the surface and body reflection components. The surface reflection component was assumed as Torrance-Sparrow model, and the body reflection as Lambertian reflection. Several paper sheets in wide range of roughness were measured, and the results were compared with the model. The model showed good correspondence with the measurement results, and it was confirmed to be appropriate for paper sheets. Parameters of the model were properly estimated from 5 data points for papers without sharp peak reflection such as paper for plain copy, Japanese *washi* paper and matt-coated paper. The proposed model is effective for efficient gonio imaging, since the parameters are estimated from small number of data points.

Introduction

Gonio-spectral imaging method[1-4] obtains the material characteristics as well as the accurate color information based on spectral reflectance properties, and it is effective as the image acquisition method for the Internet museum (E-museum), the Internet shopping (E-commerce) on the World Wide Web and so on. For gonio-spectral imaging, paper sheets are one of the common subjects since they are widely used in our daily life, archives of documents, art paints and so on. For efficient gonio-spectral imaging, optical reflection model is indispensable since it reduces the numbers of measurement geometries and data amounts. However many reflection models have been developed mainly in the field of computer graphics, they were not always appropriate for paper sheets.

In this paper, we propose a gonio-spectral reflection model for paper sheets. This model is developed based on the dichromatic reflection model.[5] The model is compared with the measurement results of several paper sheets, and the appropriateness is discussed. The model parameters are estimated from the limited number of data points, and the prospect of the efficient gonio imaging is shown.

Gonio-Spectral Reflection Model for Papers

Gonio-spectral reflection properties of paper sheets are modeled based on dichromatic reflection model.[5] Dichromatic reflection model assumes reflected light from inhomogeneous dielectric materials as the linear combination of two components: surface reflection and body reflection. The surface reflection component was assumed as Torrance-Sparrow model,[6] and the body reflection as Lambertian reflection. Torrance-Sparrow model was applied since they are considering masking and shadowing effects that are significant to rough paper surfaces.

The model specifies that a surface point will reflect light from the direction $\boldsymbol{i} = (\theta_i, \phi_i)$ to the direction $\boldsymbol{r} = (\theta_r, \phi_r)$, where θ and ϕ denote polar and azimuth angle respectively as shown in fig. 1, with the following spectral radiance factor normalized by reference Lambertian plane $\boldsymbol{f_r}$:

$$f_r(\theta_i, \phi_i; \theta_r, \phi_r) = \frac{\rho_d}{\cos\theta_i} \boldsymbol{e_d} + \frac{\rho_s \cdot GAF}{\cos\theta_i \cos\theta_r \cos\theta_a} \exp\left[-\frac{\theta_a}{2\sigma^2} \right] \boldsymbol{e_s} \quad (1)$$

where the reflectance parameters of the surface are ρ_d, the diffuse component, and ρ_s, the specular component. The unit vectors showing spectral distribution are $\boldsymbol{e_d}$, the diffuse component, and $\boldsymbol{e_s}$, the specular component. The geometrical parameter θ_a is the angle between the surface normal and the half vector between the incident and reflected directions. The parameter σ is the distribution of the facet angle of the V-cavities in the Torrance-Sparrow model concerning with the surface roughness, and *GAF* is the geometrical attenuation factor showing shadowing and masking effects.[6]

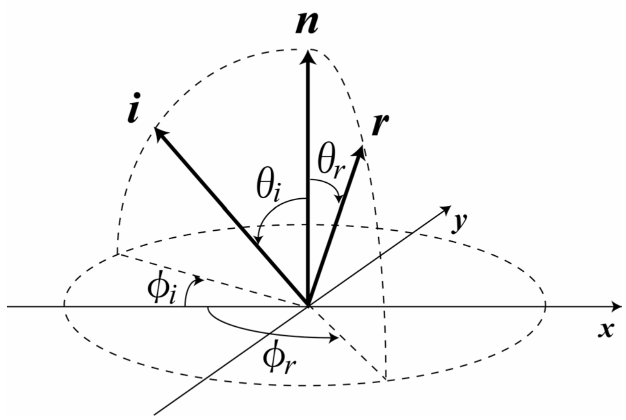


Figure 1. Schematic diagram of measurement geometries.

Materials and Methods

Samples for analysis were eight kinds of white paper sheets in wide range of roughness as shown in Table 1. For each paper sheets, we prepared one raw white sample, and three colored samples of cyan, magenta, yellow printed by an inkjet printer (Seiko Epson, PM-800C) with color image data of 100% pixel values of each primaries.

Gonio-spectral reflection properties of each sample were measured by gonio spectrophotometer (Murakami Color Research Laboratory, GCMS-4) in the plane of incidence at 284 geometries shown in Table 2 from 390 nm to 730 nm wavelengths at 10 nm intervals. Spectral radiance factor normalized by the reference diffuse white plate in the gonio spectrophotometer was obtained.

Table 1. Samples for analysis

Sample	Specification
G	Glossy paper (Seiko Epson, PMA4SP1)
SG	Semi-glossy paper (Seiko Epson, KA420MSH)
PPC	Paper for plain copy (NBS Ricoh, 90-1312)
MC	Matte coated paper (Seiko Epson, MJA4SP1)
J1	Japanese *washi* paper (Inaba Washi, Jyun-ganpi Momoyama)
J2	Japanese *washi* paper (Dai-insyu Paper Mill, C2.65kg)
J3	Japanese *washi* paper (Okamura Takao Paper Mill, Ranka)
J4	Japanese *washi* paper (Inaba Washi, No. 388)

Table 2. Geometries for measurements

#	Illumination		Observation	
	θ_i [deg]	ϕ_i [deg]	θ_r [deg]	ϕ_r [deg]
1	20	0	From 0 to 70 (Δ 1)	180
2	30			
3	45			
4	60			

The appropriateness of the dichromatic model for the gonio-spectral reflection properties of paper sheets was examined qualitatively by the linearity of the data plots on the CIE1931 chromaticity diagram, and quantitatively by the RMSE of the spectral radiance factor between the measurements and the approximation by dichromatic reflection model. The spectral distribution of surface reflection component e_s was assumed to be equal to the illuminant, thereafter it was derived from the data of white glossy paper (G) at geometry 45/45 in which specular reflection components are considered to be dominant. And we derived the spectral distribution of body reflection components e_d from the data of the geometry 45/0, which is one of the typical geometry for the measurement of diffuse color.

Thereafter the appropriateness of gonio reflection model, which is the linear combination of the Torrance-Sparrow model and the Lambertian reflection, was confirmed by the RMSE of the Y value of the CIE1931XYZ 10 degree standard observer under illuminant D65 between the measurement and the model approximation. The model parameters, ρ_d , ρ_s and σ were estimated by non-linear optimization using the function "fminsearch" of the numerical calculation software (MathWorks, MATLAB 6.0).

The model parameters related to gonio properties, ρ_d , ρ_s and σ were also estimated from the small number of data points to show the availability of efficient gonio imaging. The number of data points were 284 points (all data points), 5 points: (θ_i, θ_r) = (45,0), (45,35), (45,45), (45,55), (45,70) and 3 points: (θ_i, θ_r) = (45,0), (45,45) (45,70). They all include specular reflection geometry. The deviation between the measurement and the model was evaluated by RMSE normalized by measured data.

Results and Discussions

Figure 2 shows two examples of gonio-spectral reflection properties of magenta paper sheets for the incident angle $\theta_i = 45$ degree. Glossy paper (G) and semi glossy paper (SG) showed strong mirror-like reflection at specular angle, and constant diffuse reflection at other geometries. The matt-coated paper (MC) showed Lambertian-like reflection due to coated substances, and there were no specular peaks. The paper for plain copy (PPC) and the Japanese washi papers (JP1-JP4) reflected more as the observation angle θ_r increased.

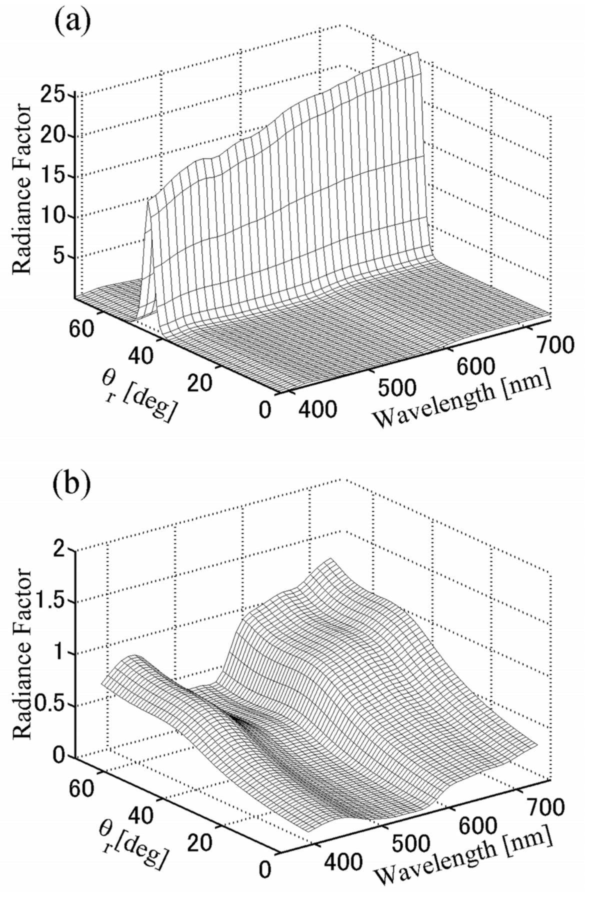


Figure 2. Gonio-spectral reflection properties of magenta paper sheets for the incident angle θ_i = 45 degree: (a) glossy paper (G), (b) Japanese washi paper 1 (J1).

Figure 3 shows the estimated spectral distribution of surface reflection components and body reflection components for the sample #G. These primaries were plotted on the CIE1931 chromaticity diagram together with the data at all geometries as shown in fig. 4. The plots were almost on the lines connected between the locus of illuminant "S" and the primaries "C", "M" and "Y". It showed the colors were almost represented by the additive mixture of two colors, the illuminant and one of the primaries. Therefore the appropriateness of dichromatic reflection model for paper sheets was proved qualitatively.

Figure 5 shows the RMSE of radiance factor between the measurements and the approximation by dichromatic reflection model. The deviation was the small value of less than 7% in spectral radiance. The appropriateness of dichromatic reflection model was also proved quantitatively.

Figure 6 shows gonio reflection measurement and reflection model plots for white samples. There were some deviations especially at specular region of glossy paper. However the model could show these profiles of papers with wide range of roughness. The RMSE of the fitting was about 8% of the measured values.

Figure 7 shows relationship of the fitting error and the number of data points for parameter estimation. Generally, the error was reduced as the number of data points increase; however it was not simply proportional relationship. The relationship was dependent on the type of the sample. The error was especially large for glossy paper since the spatially high frequency components were contained in the specular reflection component. For glossy papers, the parameter estimation should be performed with precise data sampling at specular reflection geometries. Except for the glossy paper, the average of the error was 5.0% for the case of 284 data points. It was about the same error lever for 5 data points (6.0%), and it was 12.9% even in the case of 3 data points.

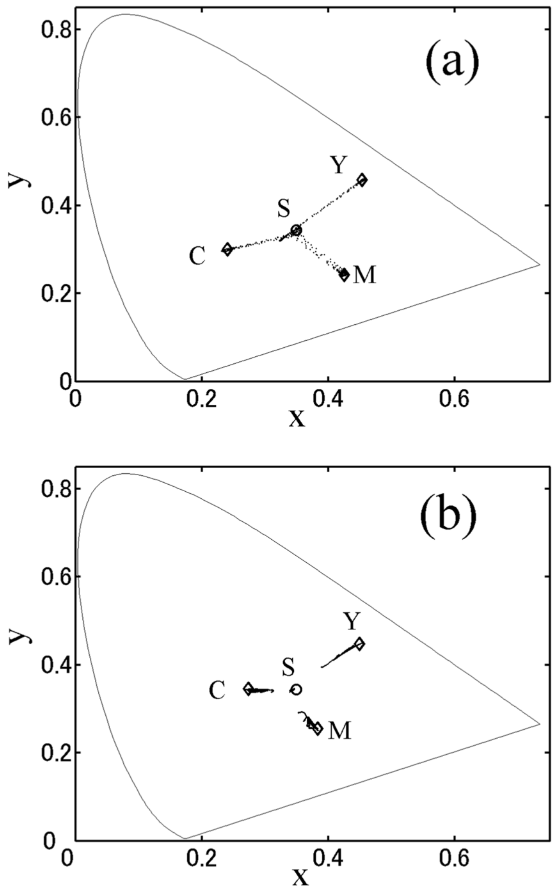


Figure 4. CIE1931 chromaticity diagram plotted with the gonio-spectral reflection properties of paper sheets: (a) glossy paper (G), (b) Japanese washi paper 1 (J1). The point "S" shows the xy locus of the illumination, and the "C", "M" and "Y" represent the loci of primaries; cyan, magenta and yellow respectively.

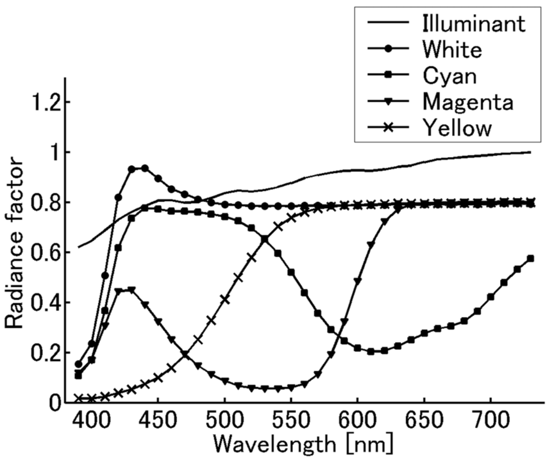


Figure 3. Estimated spectral distribution of surface reflection (Illuminant), and the body reflection (Cyan, Magenta, Yellow) of glossy paper (G).

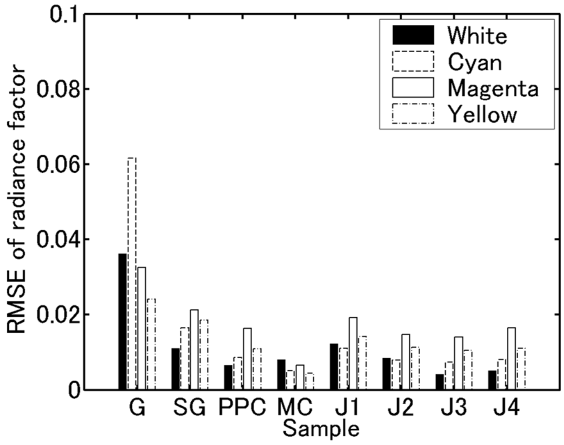
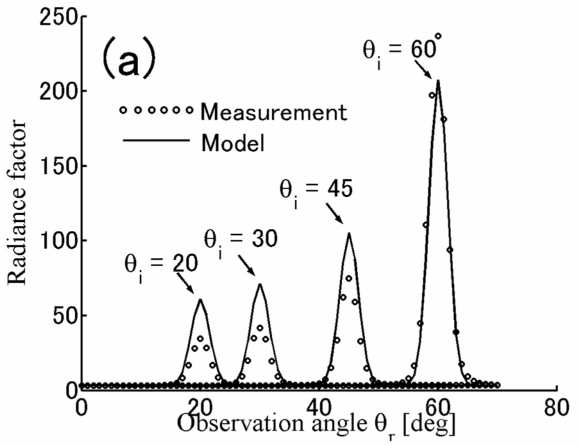


Figure 5. RMSE of the spectral radiance factor between the measurements and the approximation by dichromatic reflection model. Each bar in the same sample shows the result of raw white sample, and three colored samples; cyan, magenta and yellow.



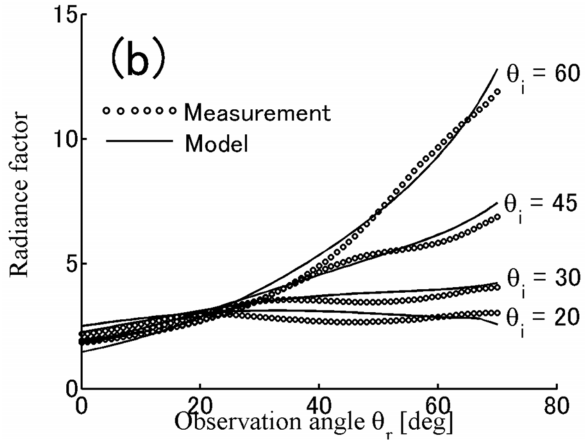


Figure 6. Gonio-spectral reflection measurement (dot) and reflection model (solid line) plots for samples: (a) glossy paper (G), and (b) Japanese washi 1 (J1). Radiance factor is plotted as a function of observation direction θ_r for different angle of incidence θ_i =20, 30, 45 and 60.

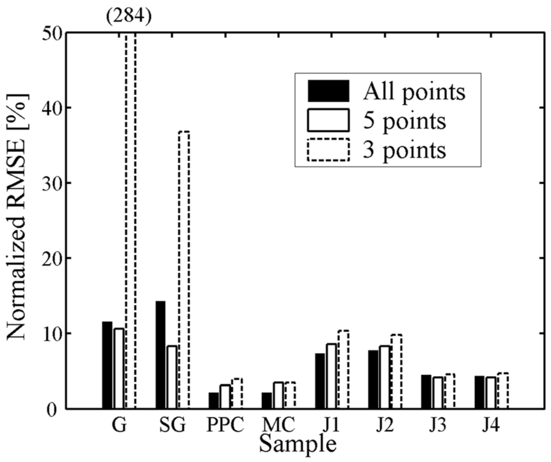


Figure 7. Relationship of RMSE of the fitting normalized by measured data and the number of data points for parameter estimation: the black bar is 284 points, the white bar with solid line is 5 points and the white bar with dashed line is 3 points.

Conclusion

Gonio-spectral reflection properties of paper sheets were modeled based on dichromatic reflection model. The surface reflection was the Torrance-Sparrow model, and the body reflection was the Lambertian reflection. This model showed good correspondence with the measured values of various papers in wide range of roughness. The model was proved to be appropriate for a gonio-spectral reflection model for paper sheets. Parameters of the model were properly estimated from 5 data points for papers without sharp peak reflection such as paper for plain copy, Japanese washi paper and matt-coated paper. For the rough approximation, it would be sufficient with 3 data points. The proposed model is effective for efficient gonio imaging, since the parameters are estimated from small number of data points.

References

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Biography

Yoshinori Akao received master's degrees in engineering from Kobe University, Japan in 1997. Currently, he is a researcher of National Research Institute of Police Science and also a doctorate course student of Chiba University. In 2002, he was a visiting researcher of Institute for Technical Electronics, Aachen University of Technology, Germany for three months. He is engaging in the R&D of forensic document examination, and his research interests include spectral imaging and optical instrumentation.