# Efficient Gonio-spectral Imaging for Diffuse Objects Based on Optical Reflectance Properties

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## Abstract

Precise color and texture reproduction based on gonio-spectral reflectance properties of object is required in many fields such as E-commerce, digital archives, criminal investigation and so on. However, spectral imaging at all geometries requires much measurement tasks and huge data storage. In this paper, efficient gonio-spectral imaging was performed for diffuse objects of Lambertian-like reflection by taking account of its optical reflectance properties. The proposed method assumes relative spectral distribution of reflected light could be regarded being constant, and only the power changes. This is preserved for wide range of geometries, except for neighbor of specular direction. Therefore, gonio-spectral images were created from only one basic spectral image at certain geometry. It was achieved by modulating power of the basic spectral image at each pixel with relative power change between illumination geometries. The relative power change was calculated from grayscale data of image reproduction geometry and that of basic spectral imaging. And also, spatial resolution was enhanced by recording grayscale images at higher resolution than basic spectral image. Experiments were performed to Japanese washi paper and cloth. Basic spectral data was obtained at geometry 45/0, and grayscale images were taken at geometry 81/0 and 87/0. From created spectral images, color images were reproduced under illuminant A and D65. Light-and-shade induced by surface textures were precisely represented together with color information based on spectral data. Good correspondence between appearance of real sample and reproduced images was achieved with smaller number of sampling points and less data amount than the previous method.

## Introduction

Diffuse objects such as papers or cloths are very common materials, and they have deep relation to our daily life. In the fields such as E-commerce and digital archives of electronic museums, it is very important to record the color and material feelings of diffuse objects precisely with digital data, and display them faithfully on the monitor. For the matter of color, a number of studies have been performed extensively, and precise color reproduction have achieved by recording spectral reflectance properties, which is color information peculiar to objects.[1-9] Additionally, gonio-spectral reflection properties, which are spectral reflection properties concerning illumination and observation geometries, were recorded for faithful reproduction of material feelings of objects together with precise color information.[10-13] These techniques are expected to be one of the new phases in imaging science of next generation.

Generally, enormous memory capacity and high computational costs are required for recording and processing spectral images because of the large data amounts. Problems on explosion of data amount will be critical in case recording gonio reflectance properties also. Therefore efficient methods for gonio-spectral imaging are indispensably required. A lot of studies have been performed on the encoding of the spectral information, most of them based on the expansion of spectral function into a system of orthogonal basis functions that are estimated from a set of typical color spectra by using such as principal component analysis.[14-18] However concerning the spectral reflectance including gonio reflection properties, few methods were reported yet.

In this paper, we propose an efficient method for recording and reproducing gonio-spectral images of diffuse objects. The proposed method is based on optical reflectance properties of diffuse objects and visual properties of human eyes. In the following chapter, reflection properties of paper, which is a representative example of diffuse surfaces, was investigated. At first, it was performed at spatially coarse scale, and global gonio-spectral reflection properties were examined. Then spectral reflectance properties of texture, which consists of light-and-shade induced by surface roughness, were examined at spatially fine scale. From these preliminary experiments, we modeled the gonio-spectral reflectance properties. Based on this model, proposed method was developed. Gonio-spectral images were created from spectral image at one geometry and gonio grayscale images. In this process, image fusion proposed by Imai et al.,[4] which combines low-resolution spectral image with high-resolution grayscale image, was applied. It was also applied to gonio direction, and further promotion of efficiency was aimed. Experiments were performed to Japanese washi paper and cloth. Gonio-spectral images were created by the proposed method. Color images based on created spectral data were reproduced under different illuminant and different geometries. This paper is concluded with discussions on effectiveness of the proposed method by examining image reproduction results.

## Gonio Reflection Properties of Diffuse Surfaces

In this chapter, reflection properties of a paper, which is a representative example of diffuse surfaces, was investigated. The measurement results were used for development of the proposed method. At first, global property of gonio spectral reflectance was measured. The sample for analysis was Japanese washi paper (Okamura Takao Paper Mill, "Ranka"). Averaged gonio-spectral reflection property at area of 60 mm by 150 mm was obtained by gonio spectrophotometer (Murakami Color Research Laboratory, GCMS-4) at 10 nm wavelength intervals from 390nm to 730nm. The incident angle of illumination was set from 9 degree to 80 degree at 1 degree interval, and observation angle was fixed at 0 degree from surface normal. Finally, gonio-spectral reflectance properties were obtained from data of the seventy-two geometries.

Figure 1 shows the result of gonio-spectral reflectance properties of the paper. The reflected light was almost diffused however it was not perfectly Lambertian. As the observation direction approached to specular direction, intensity of reflected light slightly went up. The correlation coefficient of spectral distribution between geometries was an average of 0.999. Consequently, relative spectral distribution hardly changed between measurement geometries, however only the power changed.

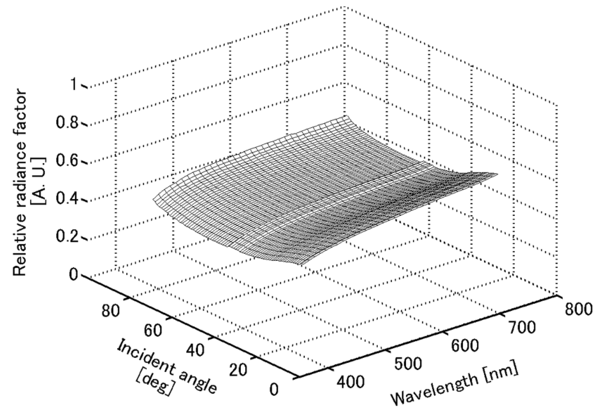



*Figure 1. Gonio-spectral reflection property of Japanese washi paper at coarse scale*

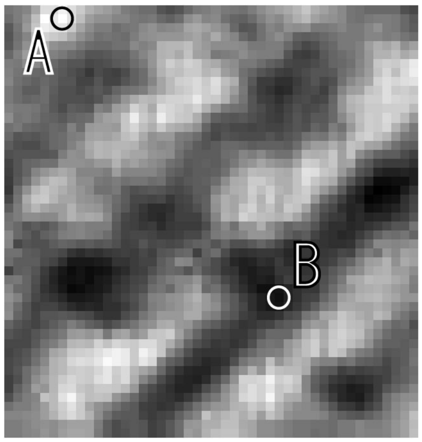
Secondly, spectral image of texture, which consists of light-and-shade induced by surface roughness, were measured. Spectral reflectance distribution at each point was analyzed. Sample for analysis was Japanese washi paper (Yamada Shokai, "Nunomeshi"). Patterns of bump and dents like ripple marks were formed on the surface, and it presented feel of materials like a hard cloth. Spectral distribution at each point of the texture was obtained by spectral imaging system (Applied Spectral Imaging, SD-200).[19] Geometry of measurement was 45/0, and wavelength range was from 390 nm to 730 nm. Spectral resolution was about 1 nm at 400 nm, and it was 4 nm at 700 nm. The region of interest was 7.4 mm by 7.1 mm, and number of pixels was 2208, which corresponded to sampling at 160 ppi.

Figure 2 (a) shows grayscale image of the sample. Texture of light-and-shade was observed in it, however each point of the sample consists of similar material. Such texture occurs because direction of local surface normal is not constant for local bump and dents. Figure 2 (b) shows spectral distribution of two points shown with A and B in figure 2 (a). The point A was the brightest part and the point B was the darkest part in the image. However intensity was greatly different between two points, relative spectral distribution was almost same. The similar tendency was recognized also in other parts. As a result, spectral distribution of each point within a texture could be regarded as being constant, and only the power changes.

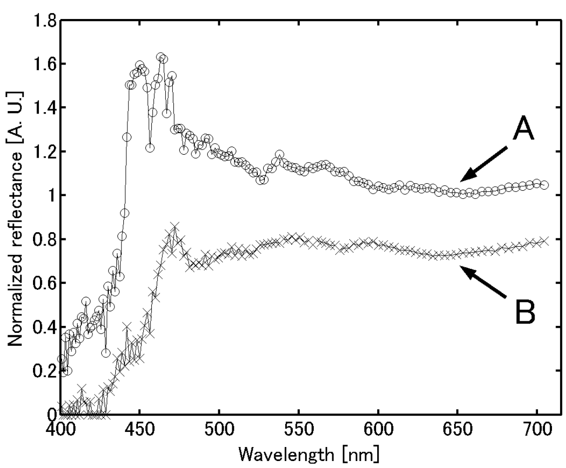
From these preliminary experiments, gonio-spectral reflectance properties and textures of diffuse objects were modeled. At coarse scale, relative spectral distribution was almost constant, and only the power changed. In this case gonio-spectral reflection property can be divided into spectral component and gonio component. Accordingly, spectral radiance at position $\mathbf{r}$ is represented as follows.

$$\mathbf{f}(\mathbf{r},\theta)=G(\mathbf{r},\theta)\mathbf{o}(\mathbf{r}) \qquad (1)$$

Parameter $\theta$ is a geometric parameter to describe incident and reflection directions. $G(\mathbf{r},\theta)$ is a parameter that represents gonio reflection property. And $\mathbf{o}(\mathbf{r})$ represents normalized spectral distribution independent of measurement geometry.




*(a) Grayscale image of the texture*




*(b) Spectral distribution at point A and B*

*Figure 2. Spectral distribution property of light-and-shade of texture, (a) grayscale image of the texture, and (b) spectral distribution at point A and B*

Then at the fine scale, relative spectral distribution at positions within small distance $\Delta\mathbf{r}$ around the position $\mathbf{r}$ is almost same. Accordingly spectral radiance at position $\mathbf{r}+\Delta\mathbf{r}$ is represented as follows,

$$\begin{aligned}\mathbf{f}(\mathbf{r}+\Delta\mathbf{r},\theta) &= T(\mathbf{r}+\Delta\mathbf{r},\theta)\,\mathbf{f}(\mathbf{r}) \\ &= T(\mathbf{r}+\Delta\mathbf{r},\theta)\,G(\mathbf{r},\theta)\,\mathbf{o}(\mathbf{r})\end{aligned} \tag{2}$$

where $T(\mathbf{r},\theta)$ is intensity at position $\mathbf{r}$ in a texture. Both $T(\mathbf{r},\theta)$ and $G(\mathbf{r},\theta)$ are independent of wavelength, and only represent fluctuation of intensity. Therefore those two variables were summarized into one variable $k(\mathbf{r},\theta)$ named gonio-texture coefficient. Consequently, gonio spectral radiance of reflected light from diffuse objects is represented as follows.

$$\mathbf{f}(\mathbf{r},\theta) = k(\mathbf{r},\theta)\,\mathbf{o}(\mathbf{r}) \tag{3}$$

According to this model, gonio-spectral reflection property of diffuse objects is represented by product of relative spectral distribution and intensity of texture.

## Efficient Gonio-spectral Imaging for Diffuse Objects

Based on the reflection model shown in the previous chapter, an efficient gonio-spectral imaging was proposed. According to the model shown in equation 3, relative spectral distribution $\mathbf{o}(\mathbf{r})$ is constant among measurement geometries, however the intensity fluctuates by gonio-texture coefficient $k(\mathbf{r},\theta)$. Therefore gonio-spectral images were created by modulating power of a spectral image at one geometry with gonio-grayscale image.

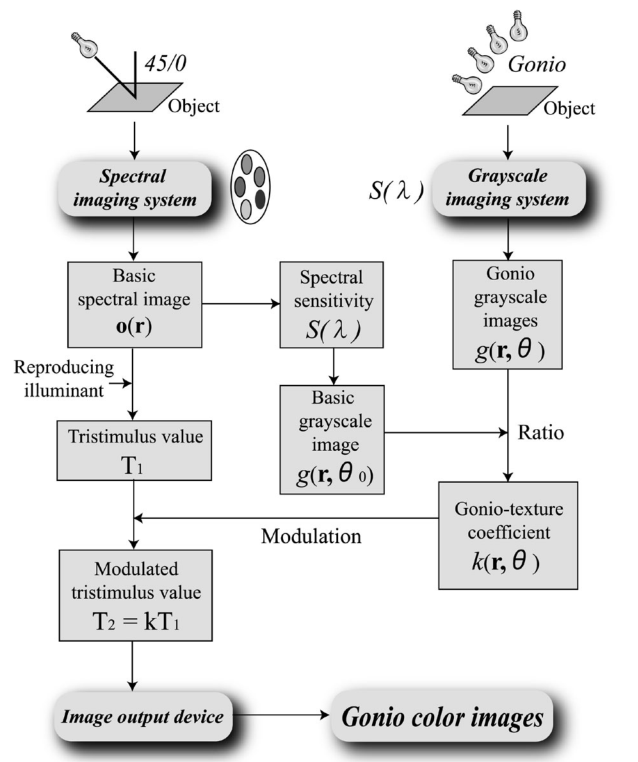



*Figure 3. Flowchart of the proposed method*

Figure 3 shows flowchart of the proposed method. At first, basic spectral image $\mathbf{o}(\mathbf{r})$ was obtained at geometry 45/0, and gonio-grayscale images $\mathbf{g}(\mathbf{r},\theta)$ were taken. Then gonio-texture coefficient was calculated from gonio-grayscale images. In case that $\mathbf{g}(\mathbf{r},\theta)$ is calibrated in proportion to intensity, gonio-texture coefficient $k(\mathbf{r},\theta)$ is represented as follows,

$$k(\mathbf{r},\boldsymbol{\theta}) = \frac{g(\mathbf{r},\boldsymbol{\theta})}{g(\mathbf{r},\boldsymbol{\theta}_0)} \tag{4}$$

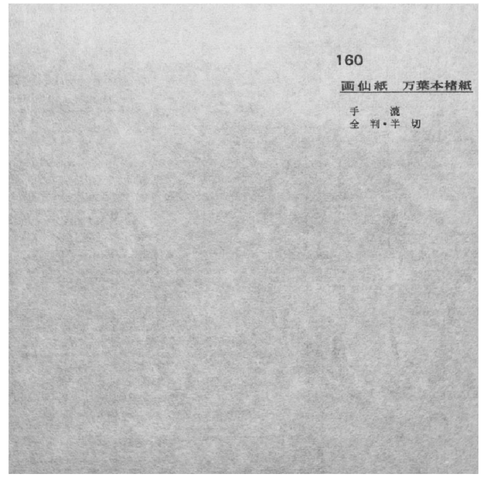
where $\mathbf{g}(\mathbf{r},\theta_0)$ is basic grayscale image at geometry 45/0. By substituting equation 4 for equation 3, gonio-spectral images were created from a spectral image at one geometry and gonio-grayscale images. Color images were represented based on the created gonio-spectral images. Spectral tristimulus value of basic spectral image was calculated beforehand in order to reduce computational complexity. Then it was modulated with gonio-texture coefficient.

In this process, image fusion proposed by Imai et al.[4] was also applied. Low-resolution spectral image was combined with high-resolution grayscale image. This method is suited for nature of reflected light in texture of rough surface. And also it makes opening area of each pixel in spectral imaging enlarge. By setting binning of CCD, amount of light per pixel is increased, and spectral measurements were achieved with high SN ratio. In case of grayscale imaging, binning of the CCD camera was not provided and spatial distribution of lightness in images was sampled at higher resolution. Furthermore this method is reasonable for human visual properties. The chromatic channels have much lower spatial resolution than the luminance channel in human eyes. This visual feature of the human eye was applied.

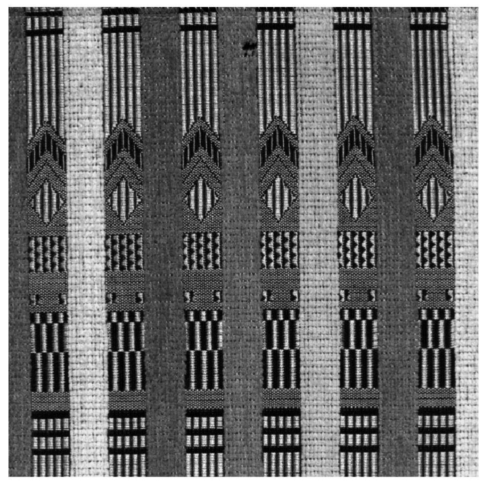
The proposed method is based on the optical reflectance properties of diffuse objects and visual properties of observers. Therefore reduction of data was performed reasonably without affecting to quality of reproduced images.

## Experiments

Gonio spectral images were obtained with the proposed method. Spectral images were taken by multispectral camera (RWTH-Aachen, ITE).[9] This device acquires multi band images by irradiating lights of limited wavelength range to samples. It is classified into active type system. In front of a light source, sixteen kinds of bandpass interference filters were installed. The central wavelengths were from 400 nm to 700 nm at 20 nm intervals, and the FWHM was 20 nm. Reflected light from the sample was imaged by 12 bit monochrome chilled CCD camera (Photometrics, CH250H). Binning of the CCD was set to three by three pixels, and the number of pixels was 677 by 677. The sixteen multispectral values were converted into sixty-one spectral data of 5 nm intervals from 400 nm to 700 nm by transformation matrix. Gonio grayscale images were also taken by CCD camera of the multispectral camera. In this case, binning of the CCD camera was not set, and the number of pixels was 2031 by 2031. The light source for grayscale imaging was a halogen lamp (Phillips, 12 V, 50 W). A short pass filter with sharp cut-off properties was installed. The cut-off wavelength was 630nm, and the light of wavelength longer than upper limit wavelength of multispectral camera was almost eliminated.




*(a) Japanese washi paper*

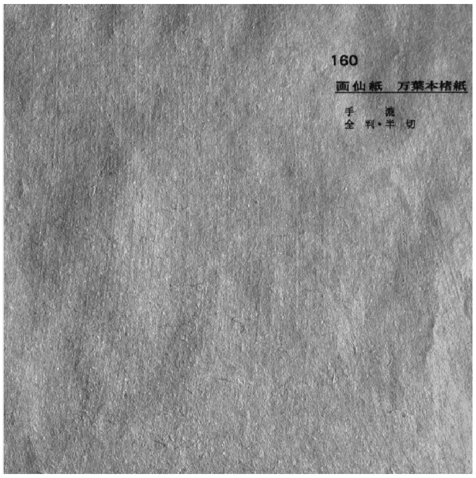


*(b) Cloth*

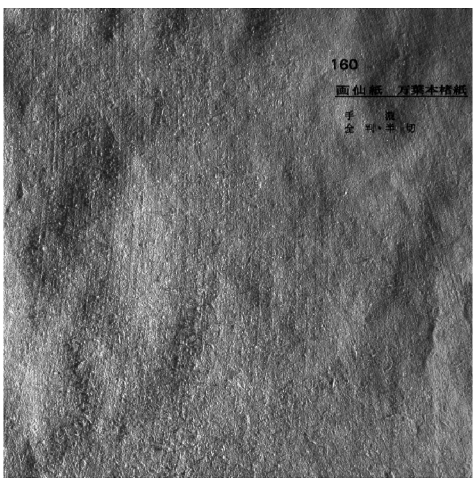
*Figure 4. Color images reproduced from the basic spectral data under illuminant D65, (a) Japanese washi paper, and (b) cloth*

With this system, gonio spectral images of Japanese washi paper (Okamura Takao Paper Mill, "Ranka") and a piece of cloth were taken. Basic spectral image was obtained at geometry 45/0, and gonio grayscale images were taken at geometry 81/0 and 87/0. Extreme oblique lighting was used for visualizing roughness, texture and bump and dents of samples surface. From the basic spectral image and grayscale images at geometry 81/0 and 87/0, spectral images were generated at geometry 81/0 and 87/0. And color images were reproduced under illuminant A and D65.

Figure 4 shows color images of samples reproduced from basic spectral images under illuminant D65. Color of samples was measured precisely with this system. The average color difference for 24 color patches (Macbeth Color Checker) was 1.2 in CIE $\Delta$ E94 unit.



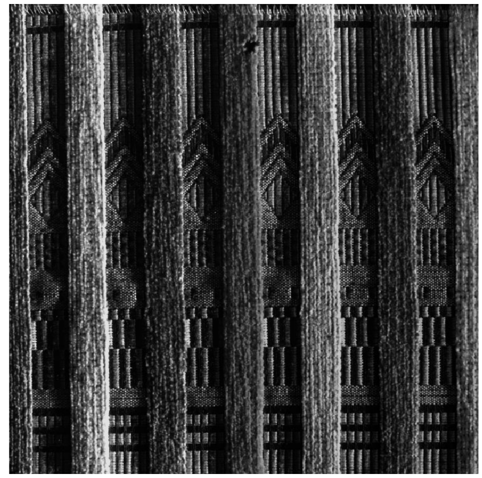

*(a) Geometry 81/0*



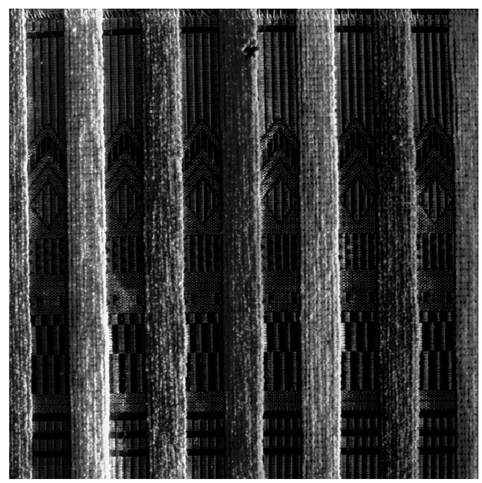

*(b) Geometry 87/0*

*Figure 5. Color images of Japanese washi paper reproduced from created spectral data under illuminant D65, (a) geometry 81/0, and (b) geometry 87/0*

Figure 5 is color images of a Japanese washi paper reproduced under illuminant D65. Figure 5 (a) is the image of geometry 81/0, and figure 5 (b) is that of geometry 87/0. Texture of light-and-shade induced by non-uniformity of fibers on the paper surface was represented sharply. And wiping marks formed in the process that the paper is rubbed on dryer were also represented. Such texture was not perceived at geometry 45/0. Appearance of the texture was differently reproduced at geometry 81/0 and 87/0.



*(a) Geometry 81/0 under illuminant A*



*(b) Geometry 87/0 under illuminant D65*

*Figure 6. Color images of cloth reproduced from created spectral data, (a) geometry 81/0 under illuminant A, and (b) geometry 87/0 under illuminant D65*

Figure 6 is the result for cloth. Figure 6 (a) is the image reproduced under the condition of geometry 81/0 and illuminant A, and figure 6 (b) is that of geometry 87/0 and illuminant D65. Surface roughness of the cloth was expressed well. And also, difference of materials, soft part and hard part, could be perceived from difference of gonio reflection properties. Surface texture induced by thread of the cloth was recorded precisely. Precise texture information was displayed together with accurate color information based on spectral data.

Consequently, gonio reflection properties including appearance of surface texture were precisely represented in the reproduced images. Materials feelings of the experimental samples were faithfully recorded and represented with smaller number of sampling points and less data amounts than the previous method.

## Conclusion

In this paper, an efficient method for gonio spectral imaging of diffuse objects was proposed. Gonio-spectral images were created from only one spectral image and gonio grayscale images. High-resolution imaging was also achieved by image fusion of low-resolution spectral image and high-resolution gonio grayscale images. It was achieved with smaller number of sampling points and less data amount than the previous method. The proposed method is based on optical reflectance properties of diffuse objects and visual properties of human eyes. Therefore reduction of data amount was performed reasonably without affecting quality of reproduced images. Experiments were performed to a Japanese washi paper and cloth. Good correspondence between appearance of real sample and reproduced images showed effectiveness of the proposed method. In order for spectral imaging to be used practically, it is important to increase efficiency of measurement and to reduce data amounts. The proposed method will be a technique contributing to solve this problem. In the future work, a new method applicable to various kinds of objects should be developed.

## References


1. P. D. Burns and R. S. Burns, “Analysis of multispectral image capture”, Proc. of 4th color Imaging Conference (Scottsdale, AZ), pp. 19-22 (1996).
2. D. Saunders and J. Cupitt, “Image processing at the national gallery: The VASARI project”, Natl. Gallery Tech. Bull., Vol.14, pp.72-85 (1993).
3. H. Maitre, F. Schmitt, J. Crettez, Y. Wu and Y. Hardberg, “Spectrophotometric image analysis of fine art paintings”, Proc. of 4th Color Imaging Conference, Scottsdale, AZ, pp. 50-53 (1996).
4. F. H. Imai and R. S. Berns, “High-Resolution Multi-Spectral Image Archives: A Hybrid Approach”, IS&T/SID's 6th Color Imaging Conference, Scottsdale, AZ, pp. 224-227 (1998).
5. M. Yamaguchi, T. Teraji, K. Ohsawa, T. Uchiyama, H. Motomura, Y. Murakami and N. Ohyama, “Image reproduction based on multispectral and multiprimary imaging: experimental evaluation”, Proc. of SPIE, Vol. 4663, pp.15-26 (2002).
6. M. Hauta-Kasari, K. Miyazawa, S. Toyooka and J. Parkkinen, “Spectral vision system for measuring color images”, J. Opt. Soc. Am. A, Vol.16, pp.2352-2362 (1999).
7. S. Tominaga, “Multichannel vision system for estimating surface and illumination functions”, J. Opt. Soc. Am. A, Vol. 13, pp.2163-2173 (1996).
8. H. Sugiura, T. Kuno, N. Watanabe, N. Matoba, J. Hayashi and Y Miyake, “Development of a multispectral camera system”, Proc. SPIE Vol. 3965, pp. 331-339 (2000).
9. B. Hill, F. W. Vorhagen, “Multispectral Image Pick-up System”, U.S.Pat. 5,319,472, German Patent P 41 19 489.6 (1991).
10. H. Haneishi, T. Iwanami, T. Honma, N. Tsumura and Y. Miyake, “Goniospectral imaging of three-dimensional objects”, J. Imag. Sci. Technol., Vol. 45, pp.451-483 (2001).
11. M. Tsuchida, Y. Murakami, T. Obi, M. Yamaguchi and N. Ohyama, “High fidelity image reproduction using angular distribution of reflected spectral intensity”, Opt. Rev., Vol.8 pp.444-450 (2001).
12. S. Tominaga, T. Matsumoto and N. Tanaka, “3D recording and rendering of art paintings”, IS&T/SID's 9th Color Imaging Conference, Scottsdale, AZ, pp. 337-341 (2001).
13. K. Tonsho, Y. Akao, N. Tsumura, Y. Miyake, “Development of goniophotometric imaging system for recording reflectance spectra of 3D objects”, Proc. SPIE Vol. 4663, pp. 370-378 (2002).
14. T. Jaaskelainen, J. Parkkinen and S. Toyooka, “Vector-subspace model for color representation”, J. Opt. Soc. Am. A, Vol.7, pp. 725-730 (1990).
15. D. H. Marimont, and B. A. Wandell, “Linear model of surface and illuminant spectra”, J. Opt. Soc. Am. A, Vol. 9, pp.1905-1913 (1990).
16. H. J. Trussell, “Applications of Set Theoretic Methods to Color Systems”, Color Res. Appl., Vol. 16, No.1, pp.31-41 (1991).
17. Th. Keusen, “Multispectral color system with an encoding format compatible with the conventional tristimulus model”, J. Imag. Sci. Technol., Vol. 40, No. 6, pp.510-515 (1996).
18. F. König and W. Praefcke, “Multispectral Image Encoding”, Proc. IEEE’s Intern. Conf. on Image Proc. ICIP, Vol. 3, pp. 123-126 (1999).
19. D. Cabib, R. A. Buckwald, Y. Garini and D. G. Soenksen, “Spatially resolved Fourier transform spectroscopy (spectral imaging): a powerful tool for quantitative analytical microscopy”, Proc. of SPIE, Vol. 2678, pp. 278-291 (1996).


## Biography

**Yoshinori Akao** received M.S. degree in Engineering from Kobe University in 1997. At present he is a researcher of National Research Institute of Police Science, Japan, and also Ph.D candidate of Chiba University. He has been engaged in R&D of document examination in criminal investigation. His works include spectral imaging, image processing and analysis of printed materials. In 2002, he was a visiting researcher of Technical Electronics Institute, Aachen University of Technology, Germany for three month.