Accurate Measurement of Full Spectral Reflectance Texture by Removing Shadow and Illuminant Effects

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Abstract

We propose the full spectral reflectance texture acquisition method for accurate color rendering. Full spectral reflectance texture contains spectral reflectance at each texcel. This texture can be used for full spectral rendering which is able to deal with important color phenomena such as metamerism and fluorescence. We have developed multi-band 3D scanner with the cooperation with the MINOLTA. It can measure 3D shape and multi-band texture image at the same time. Texture image is always affected by illuminant, shade and shadows. Therefore, irradiance at each polygon is needed to avoid these effects. Polygon-wise irradiance was calculated by using omnidirectional light distribution that surrounds measured object and hidden polygon information which describes the region that a ray of light is occluded by other polygon. In the experiment, we measured the spectral reflectance texture of six colored box and skin of human male. The experiment showed that proposed method is effective for estimation of full spectral reflectance texture.

Introduction

Full spectral rendering method has capacity to produce more realistic image compared to the conventional rendering method. The main difference between these two rendering method is the number of parameters used to represent the color of the material and illuminant. In conventional rendering method, the color is represented by RGB triplets. In contrast, full spectral rendering method represents the color by arbitrarily spaced samples from spectral reflectance or spectral radiance data which is usually more than three. Physical interaction between illumination and material occur in wavelength domain. To simulate physical phenomenon and produce realistic image, we need to use enough number of samples to characterize the spectrum. In this sense, full spectral rendering method is advantageous.

Full spectral renderer was first developed by Hall and Greenberg.[1] Johnson and Fairchild carried out the simulation of two important color phenomena,[2] metamerism and fluorescence by full spectral rendering, which is impossible to simulate by conventional rendering method. Ward demonstrated that the physical accuracy of rendered color can be improved by considering spectrum.[3] Bergner et al. developed spectral volume rendering[4] which is extension of conventional full spectral rendering to the volume data. In full spectral rendering, a texture contains reflectance at each wavelength. Accurate measurement of spectral reflectance is important to produce realistic image.

The simplest way to measure point-wise full spectral reflectance is to measure the spectral radiance of the material, and to divide it by the spectral radiance of standard white plate under same illumination and geometry. This method is used to measure point-wise spectral reflectance. Standard white plate should be placed at measured point since the amount of irradiance changes depending on the geometry. Figure 1 shows the dependence of irradiance to the geometry. Figure 1 shows spectral radiance of box (Fig. 2) under fluorescent lamp measured by spectroradiometer. The box is made of drawing paper. Measured point is 2° field of left face, right face and top face. All peaks in Fig. 2 are the characteristics of the fluorescent lamp. From Fig. 2, we can observe the difference of radiance at three faces of the box. The difference is caused by difference of irradiance incident on each face since all three faces have the same reflectance. Therefore measurement of standard white plate is necessary to avoid the dependence to the geometry.

Multi-band camera is used in the acquisition of full spectral reflectance texture, Band output is transformed to spectral radiance. Spectral radiance of each texcel location can be calculated by the transformation from band image. However, the number of texcels is so many that measurement of standard white plate at every texcels location is impossible.

In this paper, we propose a full spectral reflectance texture acquisition system which is applicable to the object in the natural scene in which object shape and illumination is not restricted. Irradiance correction is done by using 3D shape information of the object and light map of surrounding illuminants. The proposed method is applied to six boxes and human male in the experiment. The experiment showed that the proposed method is effective to record the full spectral reflectance texture accurately.

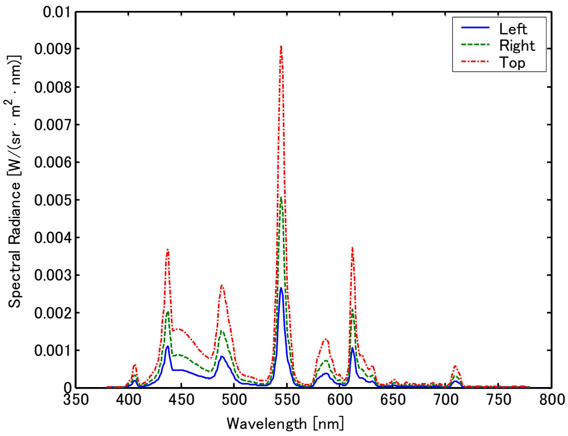


Figure 1. Difference of spectral radiance on three faces

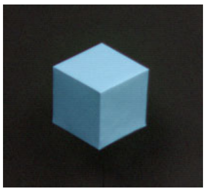


Figure 2. Measured box made of drawing paper.

Spectral Reflectance Texture Acquisition System

Spectral Radiance Texture Acquisition System

Figure 3 shows the 3D scanner VIVID 910 with multi-band filter unit which is developed in cooperation with the MINOLATA. Modified VIVID produces polygon mesh and texture image of the scanned object. The modified VIVID 910 differs from original VIVID 910 in representation of texture color. The texture color consists of five band camera outputs which have more spectral information than conventional three bands (RGB) camera. The color filters, SP-1, SP-7, SP-15, SC-60, SC-68(Fuji Photo Film) were used for the filter. The spectral transmittance of each filter is shown in Fig.4.

Recovering Spectral Radiance from Band Output Value by Wiener Estimation

The spectral radiance is digitized from 380 nm to 780 nm with 10 nm step. Let $\mathbf{e}$ as 31×1 vector of spectral radiance, $\mathbf{v}$ as 5×1 vector of band output. We assume that the relationship between the spectral radiance and band output value is represented as

$$\mathbf{e} = G\mathbf{v}, \tag{1}$$

where the size of matrix G is 31×5. The matrix G depends on the spectral sensitivity of the camera. Calibration is needed to estimate the matrix G. We measured spectral radiance of 24 colors from the Gretag Machbeth color checker by using a spectroradiometer. We also measured the same colors by the VIVID910 with multi-band filter unit. Wiener estimation method is used to these 24 known pairs to find the matrix G, it minimizes the error defined by

$$ERROR = \sum_{i=1}^{24} \left\| \mathbf{e}_i - G\mathbf{v}_i \right\|^2, \tag{2}$$

where i denotes the color in Gretag Machbeth color checker. This calibration is done only once. After the calibration, measured band output is converted to spectral radiance using the matrix G by Eq. (1). Table 1 shows the normalized error of wiener estimation. The normalized error defined by Eq. (3) is calculated for each 24 colors. Table 1 compares the quality difference by the number of color filter. We used color filters, SP-1, SP-15 and SC-68 for the estimation using only three filters. From Table 1, the accuracy will be improved by using more filters.

$$Normalized\ error_i = \frac{\left\| \mathbf{e}_i - G\mathbf{v}_i \right\|}{\left\| \mathbf{e}_i \right\|}, \tag{3}$$

Table 1. Normalized error in wiener estimation

	5 filter	3 filter
Mean	0.15	0.19
Std	0.18	0.25
Max	0.87	1.23
Min	0.01	0.01

Figure 3. Modified VIVID 910 with multi-band filter unit

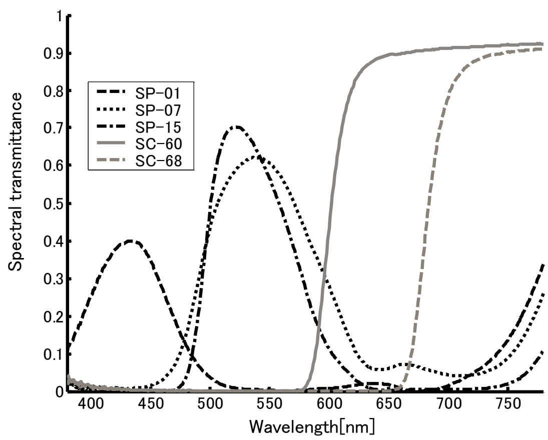


Figure 4. Spectral Transmittance of the filter

Figure 5. High dynamic range radiance image of mirrored ball

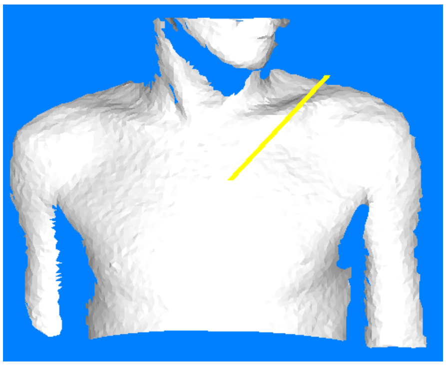


Figure 6. Visible surfaces from upper light source

Estimation of Light Distribution

Acquisition of omnidirectional light distribution is necessary to remove shadows, since the location which a ray of light is occluded by other object become shadow region. Therefore, shadows are created by the combination of object geometry and light distribution. We used mirrored ball method to measure omnidirectional light distribution $I(\lambda;\omega)$ which is spectral irradiance from solid angle ω.[5] A spectral radiance image $L(\lambda)$ of stainless steel mirrored ball is taken by the same method as described in previous section. The High dynamic range radiance (HDR) method is used to capture wide range of light distribution.[6] Figure 5 shows the HDR image of the mirrored ball in log scale.

Omnidirectional light distribution $I(\lambda;\omega)$ is calculated from spectral radiance image of mirrored ball using

$$L(\lambda) = \frac{F(\theta,n)}{\cos\theta} I(\lambda;\omega), \quad (4)$$

where index of refraction n of stainless steel is 1.7. The function F is fresnel coefficient. The angle θ is incident angle of the light from solid angle ω to the surface of mirrored ball.

Estimation of Shadow Region

For each polygon of the measured object, we calculated the direction which a ray of light is not occluded by the other polygon. First, hidden surface from the view point of incident angle ω is calculated by The Z-buffer method. Then, texcel i which corresponds to hidden polygon is calculated from VRML data. Figure 6 shows the visible polygon of human male from upper light source. Hidden surfaces are not shown. Straight line indicates the incident angle ω. Neck region is partially occluded by faces in Fig. 6. We defined the value of $\delta_i(\omega)$ for i -th polygon, solid angle ω to have one if a ray of light is reachable, zero in otherwise.

Removal of Shade and Shadow

Omnidirectional light distribution $I(\lambda;\omega)$ and hidden polygon indicator $\delta_i(\omega)$ are used to estimate the irradiance at each polygon. Shading effect is automatically removed by inclusion of cosine term in the calculation of irradiance. Spectral radiance image taken by proposed system is divided by polygon-wise irradiance to calculate spectral reflectance:

$$r_i(\lambda) = \frac{e_i(\lambda)}{\sum_{\omega} \delta_i(\omega) I(\lambda;\omega) \cos\theta_i(\omega) \Delta\omega}, \quad (5)$$

with the parameters:

$r_i(\lambda)$	Spectral reflectance at the texel location i
$e_i(\lambda)$	Spectral radiance which is calculated from multi-band image
$I(\lambda;\omega)$	Spectral irradiance from solid angle ω
$\theta_i(\omega)$	Angle between incident angle and normal of the corresponding polygon.
$\delta_i(\omega)$	1 if the ray of light incident on the texel location i from solid angle ω is not occluded by other polygons, 0 in otherwise.

Experiment

Spectral reflectance texture of six colored box which is made of drawing paper and skin of human male is calculated for the evaluation of the proposed method. The colors of boxes are blue, orange, yellow, green, red and pink. Figure 7(a) shows the spectral radiance image of green box at 550nm. Figure 7(b) shows the spectral reflectance texture image of the green box at 550nm. In Fig. 7(b), differences of intensity between three faces are smaller than in Fig. 7(a). This implies the shadow and shade are removed correctly because the reflectance image should be uniform since the box is made of single material. Table 2 compares radiance image and reflectance image in the variance of the intensity between three faces. First, spectral radiance image and spectral reflectance image are transformed to one-dimensional intensity image by

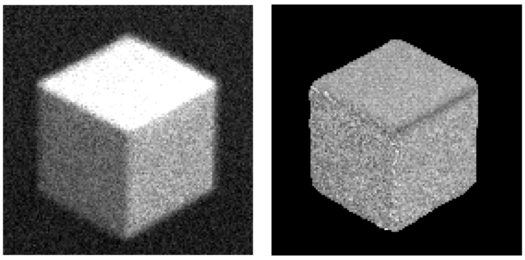
$$\begin{bmatrix} I_e \\ I_r \end{bmatrix} = \int \begin{bmatrix} e(\lambda) \\ r(\lambda) \end{bmatrix} V(\lambda) d\lambda. \quad (6)$$

Spectral luminous efficiency $V(\lambda)$ is multiplied to spectral radiance and spectral reflectance. Then, mean values of I_e and I_r from three faces are calculated from each intensity image. Then we calculated the coefficient of variation (CV) which is standard deviation divided by mean value. Table 2 lists the CV. Variation of intensity caused by shade and shadow is reduced in the reflectance image as shown in table 2. Estimated spectral reflectance of the green box is shown in Fig. 8. There is slight difference near 550 nm between three faces.

Figure 9 shows the radiance image and reflectance image of the skin of a human male. We converted spectral image to RGB image by using characteristic of CRT. Shade and shadow regions in Fig. 9(a) are removed in Fig. 9(b). The neck and arm region in Fig. 9(b) is much brighter than the other region. Inter-reflection of a ray of light is very strong at these regions. However, we did not consider the inter-reflection in Eq. (5). Therefore, estimated irradiance becomes smaller. The bright regions are produced by division by smaller irradiance.

Table 2. Coefficient of variance for reflectance and radiance image

	Radiance image	Reflectance image
Red	0.440	0.040
Green	0.525	0.046
Pink	0.573	0.025
Blue	0.537	0.066
Orange	0.464	0.025
Yellow	0.522	0.037



(a) (b)

Figure 7. Shadow removal of box (a) spectral radiance image (b) spectral reflectance image

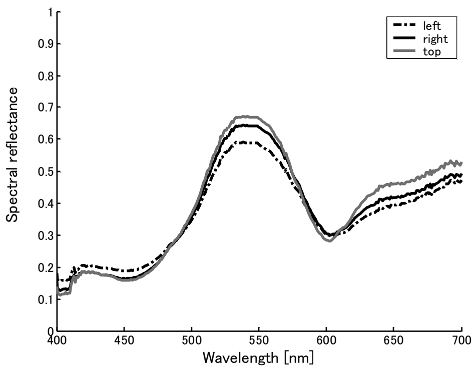


Figure 8. Spectral reflectance of three faces of the box

(a) (b)

Figure 9. Shadow removal of skin (a)spectral radiance image (b) spectral reflectance image

Discussion

We proposed a full spectral reflectance texture acquisition system which is applicable to the object in the natural scene in which object shape and illumination is not restricted. Texcel-wise irradiance is calculated from 3D shape of the object and omnidirectional light distribution. Experiment showed that proposed method is effective for the estimation of reflectance texture. Hidden surface removal processing is one of the reasons of the error in estimation of the reflectance. The direction of the polygon plane was not considered in hidden surface removal use in this research. Therefore, undesirable ray of light which is incident on back of the polygon is counted. Although measured objects are almost all convex, further improvements can be done for non-convex object. Optimization of the filter set used in the proposed system will improve the accuracy of the transformation from band-output value to spectral radiance. The reason for the error in Fig. 8 near 550 nm should be investigated in future research. We proposed the simple way to estimate the reflectance. However, the error caused by inter-reflection would be considerable for complex object. If the geometry of the entire scene and positions of all lights are known, more elaborate calculation such as inverse global illumination method[7] would be needed to improve the error.

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Biographies

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