Goniospectral Imaging of 3D Objects

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Abstract

A multiband imaging system with multi-angle illumination and a processing algorithm for multiband images acquired by the system are presented for extracting goniospectral information of 3D objects. Based on a dichromatic reflection model, multiband images are separated into diffuse and specular components. Then, the model parameters are determined pixelwise and archived. Using these parameters, an image of the 3D object under an arbitrary spectral and spatial distribution of illuminant can be predicted and displayed. A fundamental experiment to confirm the principle of this method is presented.

Introduction

In the electronic museum or the internet shopping, reproducing the optical properties of 3D object such as color and glossiness with high fidelity is desired for observers or consumers to recognize more exactly how the object is. We have offered some efforts to improve the color reproduction of the object so far.[1] Our technique using a multiband camera can estimate the spectral information of the object and therefore allows the color reproduction of the object under an arbitrary light source. However, those obtained images do not include goniophotometric information necessary to reproduce the glossiness of the object. Exclusive gonio-spectrophotometer commercially available can measure only an average value in the aperture, therefore it is not suitable for the measurement of an object with two or three dimensional variation of goniospectral information.

In this paper, we propose a new method to obtain such information of the object as well as spectral information. For this purpose, light sources are located at several different positions and multiband images are taken under the illumination of each light source. The images are then analyzed and the parameters representing goniospectral characteristics of the object are extracted and archived. Once the spectral and spatial distribution of the light source is given, an image to be reproduced is calculated from these parameters and displayed on a CRT.

A technique similar to ours but using only three bands (RGB) has been proposed by Sato and Ikeuchi.[2] However, our technique has an advantage in a sense that recovering the spectral information allows to simulate the reproduction under an illuminant with an arbitrary spectral distribution.

Formulation

The imaging system is shown in Fig. 1. Light sources are placed at several different positions. One of light sources is turn on and illuminates a 3D object and its multiband images are captured by a CCD camera with color filters. In our experiment, five broad band color filters were used.

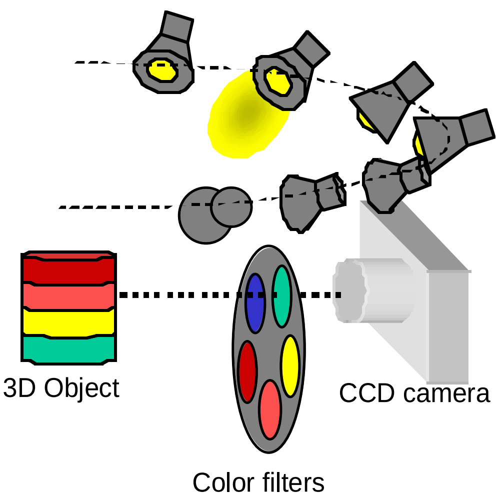

Figure 1. Multiband imaging system with multi-angle illumination.

Consider the behavior of pixel values at a fixed position in the multiband images obtained. Let us denote a position vector in an image by **r**, *i*-th illumination direction by $\mathbf{s}^{(i)}$ and the multiband image by a vector $\mathbf{g}(\mathbf{r}, \mathbf{s}^{(i)}) = [g_1(\mathbf{r}, \mathbf{s}^{(i)}), g_2(\mathbf{r}, \mathbf{s}^{(i)}), ..., g_M(\mathbf{r}, \mathbf{s}^{(i)})]^T$, $(i=1,...,N)$ where M represents the number of bands. According to the dichromatic reflection model[3], vectors at a fixed position, $\{\mathbf{g}(\mathbf{r}, \mathbf{s}^{(i)})\}_{(i=1,...,N)}$ approximately are aligned on a common plane spanned by a vector of diffuse component (body color) and a vector of specular component (illuminant color) since any vector is supposed to be a summation of those two components. Figure 2 schematically illustrates this property.

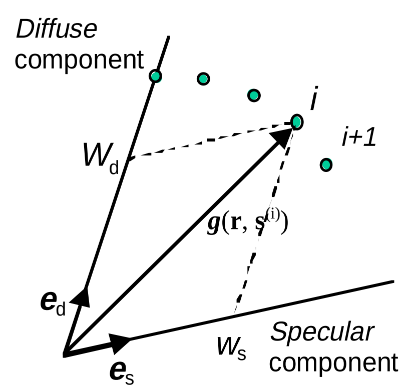

Figure 2. Multiband pixels subject to dichromatic reflection model.

The above property is mathematically expressed as

$$\mathbf{g}(\mathbf{r}, \mathbf{s}^{(i)}) = \mathbf{g}_d(\mathbf{r}, \mathbf{s}^{(i)}) + \mathbf{g}_s(\mathbf{r}, \mathbf{s}^{(i)}) = w_d(\mathbf{r}, \mathbf{s}^{(i)})\, \mathbf{e}_d(\mathbf{r}) + w_s(\mathbf{r}, \mathbf{s}^{(i)})\, \mathbf{e}_s, \quad (1)$$

where $\mathbf{e}_d(\mathbf{r})$ and $\mathbf{e}_s$ denote unit vector of diffuse component and specular component, respectively. Scalar $w_d(\mathbf{r}, \mathbf{s}^{(i)})$, $w_s(\mathbf{r}, \mathbf{s}^{(i)})$ denotes the magnitude of each component.

The above equation does not represent the relationship between spectral information of the object and its multiband images. The following equation connects these two.

$$\mathbf{g}(\mathbf{r}, \mathbf{s}^{(i)}) = w_d(\mathbf{r}, \mathbf{s}^{(i)})\, \mathbf{e}_d(\mathbf{r}) + w_s(\mathbf{r}, \mathbf{s}^{(i)})\, \mathbf{e}_s = \mathbf{H}\{w_d(\mathbf{r}, \mathbf{s}^{(i)})\, \mathbf{L}\mathbf{f}(\mathbf{r}) + w_s(\mathbf{r}, \mathbf{s}^{(i)})\, \mathbf{L}\mathbf{f}_1\}. \quad (2)$$

Here $\mathbf{H}$ denotes a system matrix whose row represents overall spectral sensitivity of camera with filter. This matrix transforms spectral radiance of light to multiband pixel values. $\mathbf{L}$ denotes a diagonal matrix whose diagonal elements represent spectral radiance of illuminant. $\mathbf{f}$ denotes a vector proportional to the spectral reflectance of the object. On the other hand, $\mathbf{f}_1$ is a vector whose elements have a constant value, accordingly $\mathbf{L}\mathbf{f}_1$ represents spectral radiance proportional to illuminant.

What we want to know here are two scalar functions, $w_d(\mathbf{r}, \mathbf{s}^{(i)})$ and $w_s(\mathbf{r}, \mathbf{s}^{(i)})$ which represent goniophotometric characteristics of the object and a vector $\mathbf{f}(\mathbf{r})$ which represents illuminant-independent spectral information of the object. Obtaining these values, we can simulate to change the spectral radiance characteristics of illuminant by replacing the matrix $\mathbf{L}$ by a different one. Moreover, we can simulate to change the placement of illuminant by changing the position vector $\mathbf{s}$ of the scalar functions, $w_d(\mathbf{r}, \mathbf{s})$ and $w_s(\mathbf{r}, \mathbf{s})$. In the next two sections, we show how to know these parameters.

Spectral Radiance Estimation from Multiband Images

In order to estimate spectral radiance from multiband images with lower dimension, pseudo inversion of the matrix $\mathbf{H}$ is needed. However, the direct measurement of $\mathbf{H}$ is not easy. In this study, we determine the inverse matrix by using a set of color patches as follows. For each color patch, the spectral radiance under an illuminant is measured by a spectrophotometer, while the corresponding pixel data are captured by the multiband camera. For example, for *k*-th patch, denoting the spectral radiance by $\mathbf{v}_k$, multiband pixel data by $\mathbf{g}_k$, the relationship between them can be expressed as,

$$\mathbf{g}_k = \mathbf{H}\mathbf{v}_k. \quad (3)$$

Estimation $\mathbf{v}'_k$ is then given by

$$\mathbf{v}'_k = \mathbf{H}^{-}\mathbf{g}_k. \quad (4)$$

The inverse matrix $\mathbf{H}^{-}$ is determined so that estimation error averaged over all patches, $<|\mathbf{v}'_k - \mathbf{v}_k|^2>$ is minimized. Such estimation is called Wiener estimation and the pseudo inversion is given by the following equation:

$$\boldsymbol{H}^{-} = \boldsymbol{V}\boldsymbol{G}^T(\boldsymbol{G}^T\boldsymbol{G})^{-1}, \quad (5)$$

where $\mathbf{V}$ is a matrix whose *k*-th column is spectral radiance of *k*-th color patch, $\mathbf{v}_k$ and $\mathbf{G}$ is a matrix whose *k*-th column is multiband pixel data of *k*-th color patch, $\mathbf{g}_k$.

Parameter Estimation using Phong Model

Separation of Two Components from Multiband Images

First of all, specular component $\mathbf{e}_s$ can be determined from pixels on a reference white object ($BaSO_4$ plate in this experiment) imaged together with the target object. On the other hand, the diffuse component is determined as follows. If illumination angle is varied widely enough, it is supposed that there exist illumination angles at which the light from the object does not include specular component. In the multiband vector space (see Fig. 2), such vector makes its angle from the specular component maximum. Thus, if one finds such a vector and normalize it, it would basically be a unit vector of diffuse component. Practically, however, the vector array has variation from the plane more or less due to noise, system's instability, non-linearity, etc. Therefore we first determine the plane which best fits the vector array by the least square method, then project each vector onto the plane. After that, the vector whose angle from the specular component is maximum is found and $\mathbf{e}_d(\mathbf{r})$ is calculated.

Once unit vectors, $\mathbf{e}_d(\mathbf{r})$ and $\mathbf{e}_s$ become known, two scalars, $w_d(\mathbf{r}, \mathbf{s}^{(i)})$, $w_s(\mathbf{r}, \mathbf{s}^{(i)})$ can also be calculated from $\mathbf{g}(\mathbf{r}, \mathbf{s}^{(i)})$ using Eq. (1).

Model Parameter Estimation

It is convenient if $w_d(\mathbf{r}, \mathbf{s}^{(i)})$, $w_s(\mathbf{r}, \mathbf{s}^{(i)})$ are approximated by any simple analytical functions of illumination direction $\mathbf{s}$ instead of recording all the estimated values of $w_d(\mathbf{r}, \mathbf{s}^{(i)})$, $w_s(\mathbf{r}, \mathbf{s}^{(i)})$ (i=1,..., N). We modeled these components on the basis of Phong model[4] as

$$w'_d(\mathbf{r}, \theta) = A_d(\mathbf{r}) \cos(\theta - \phi_d(\mathbf{r})) \quad (6)$$

$$w'_s(\mathbf{r}, \theta) = A_s(\mathbf{r}) \cos^{n(\mathbf{r})}(\theta - \phi_s(\mathbf{r})), \quad (7)$$

where illumination direction s is replaced by angle θ for notational convenience. $A_d(\mathbf{r})$, $\phi_d(\mathbf{r})$, $A_s(\mathbf{r})$, $\phi_s(\mathbf{r})$, and $n(\mathbf{r})$ are the model parameters and determined so that values w'_d and w'_s approximated by this model best fit to the values wd and w_s determined in the separation step. MATLAB optimization tool box was used for this fitting.

Image Reproduction Under Different Illuminant

For this purpose, first we must estimate the spectral information $\mathbf{f}$ of the object. The estimate $\mathbf{f}'$ can be obtained by the Wiener estimation of spectral radiance and the division operation by the matrix $\mathbf{L}$.

$$\mathbf{f}'(\mathbf{r}) = \mathbf{L}^{-1}\mathbf{H}^{-}\,\mathbf{e}_d(\mathbf{r}) \quad (8)$$

Under an illuminant with spectral radiance $\mathbf{L}^{(disp)}$ and illumination direction $\mathbf{s}^{(disp)}$, the estimated distribution of the spectral radiance from the object is expressed as

$$w'_d(\mathbf{r}, \mathbf{s}^{(disp)})\mathbf{L}^{(disp)}\mathbf{f}'(\mathbf{r}) + w'_s(\mathbf{r}, \mathbf{s}^{(disp)})\, \mathbf{L}^{(disp)}\, \mathbf{f}_1$$

If there are more than one point light sources or a spatially broad light source such as fluorescent lamp, the above expression is modified as

$$\Sigma_{disp}\{w'_d\,(\mathbf{r}, \mathbf{s}^{(disp)})\mathbf{L}^{(disp)}\mathbf{f}(\mathbf{r}) + w'_s\,(\mathbf{r}, \mathbf{s}^{(disp)})\,\mathbf{L}^{(disp)}\,\mathbf{f}_l\},$$

where the summation is performed over every illumination direction.

Finally, to generate the signal to be sent to a CRT, color matching function of the CRT is multiplied to the above spectrum as,

$$\mathbf{T}\Sigma_{disp}\{w'_d\,(\mathbf{r}, \mathbf{s}^{(disp)})\mathbf{L}^{(disp)}\mathbf{f}(\mathbf{r}) + w'_s\,(\mathbf{r}, \mathbf{s}^{(disp)})\,\mathbf{L}^{(disp)}\,\mathbf{f}_l\},$$

where **T** is a matrix whose rows are the color matching functions. Receiving this RGB signal, a well-calibrated CRT may reproduce tristimulus values same as the color of the object under the virtual illuminant.

Experiment

As a fundamental experiment, multiband images of a cylindrical object with four colored belts and a Macbeth checker were taken under tungsten lamp placed at seven angles. In this experiment, five broad band color filters (peak wavelengths(nm) are 420, 450, 500, 550, 600) were placed in front of a cooled monochromatic CCD camera. The CCD camera has 16bit quantization levels and 384×256 pixel resolution. Seven illumination angles were -45, -30, -15, 0, 15, 30 and 45 degrees where the condition that the camera and the illuminant have the same direction was defined as 0 degree.

We first determined a Wiener estimation matrix using 24 color patches of the Macbeth checker. Figure 3 shows a comparison between measured and estimated spectral reflectance of a color patch of the Macbeth checker as an example. The estimation error was evaluated by root mean square error (RMSE) for 24 color patches used to determine the estimation matrix. The mean RMSE was 0.0817. Though this number and comparison shown in Fig. 3 show that the estimation accuracy is relatively good, further improvement is desired by increasing the number of color samples. If the application is limited in a specific field, eg. oil painting or fabrication, the accuracy may be increased by using those corresponding samples.

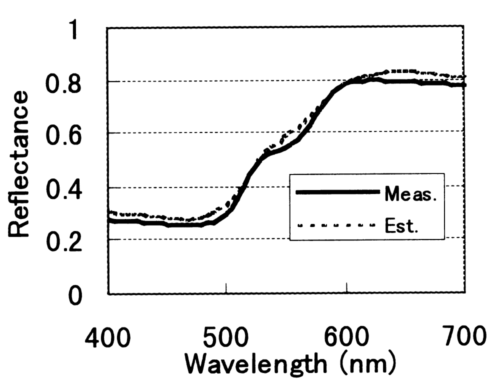

Figure 3. Comparison of measured and estimated spectral reflectance of a color patch of Macbeth checker.

From the multiband images obtained, the diffuse and specular components were separated and model parameters were calculated. Figures 4 (a) and (b) show the separated diffuse and specular component when illumination angle is –30 degree (right side of the object). We can make sure that the former does not have glossiness while the latter has only illuminant color and has high pixel values mainly in vertical area on the cylinder reflecting the light.

Figure 4(a). Diffuse component image.

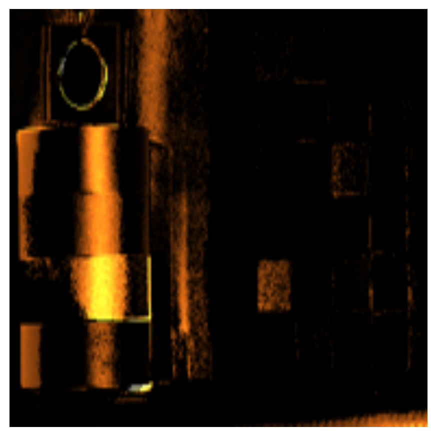

Figure 4(b). Specular component image.

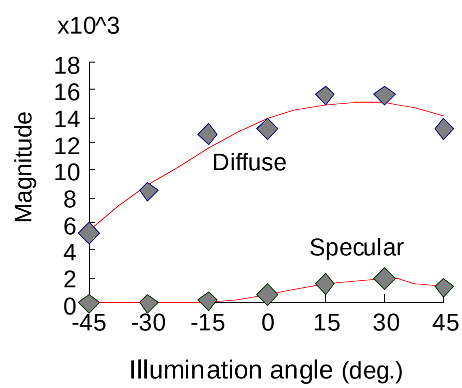

Figure 5. Magnitude of diffuse and specular components separated and its curve fitting.

Figure 5 shows weights w_d and w_s at a certain point on the cylinder. The plots represent the extracted component and solid lines represent the curve fitting to the points. This example shows that two components are successfully separated and expressed by the Phong model reasonably.

Figure 6. Reproduction simulation under spatially broad, daylight type illuminant.

Finally we show the reproduction simulation of the object under virtual illumination. Figure 6 shows the reproduced image of the object which is illuminated by spatially broad illuminant whose spectral radiance is a type of daylight. The object is more bluish than the original image under the tungsten lamp and the glossiness is not remarkable because of wide illumination.

We are planning to demonstrate this reproduction simulation on our web page:

http://www.icsd6.tj.chiba-u.ac.jp/~haneishi/

Conclusions

A method for extracting goniospectral information of 3D objects has been proposed. Through fundamental experiments using a simple 3D object, we confirmed that, from the set of multiband images the diffuse and specular components were successfully separated and its model parameters were determined, and consequently reproduction simulation under an arbitrary illuminant became possible. The present method may be applied to some fields such as electronic museum, internet shopping or cosmetic development and so on. Feasibility study using more complicated objects and application-oriented improvement of the system will be our future work.

Acknowledgement

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