Spectral Estimation of Fluorescent Objects Using Visible Lights and an Imaging Device

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Abstract

A method is proposed for estimating the spectral radiance factor of fluorescent objects by using visible lights and an imaging device. We use neither an ultraviolet light (black light) nor a monochromator, but use an easy imaging system consisting of a multi-band camera and two ordinary visible light sources. The imaging system can provide fluorescent characteristics at every pixel of an object surface. The camera outputs are modeled using the Donaldson matrix with the two factors of reflected radiance and luminescent radiance. An algorithm is then presented for estimating both radiance factors from two sets of spectral images of the camera outputs, captured under two light sources. This solution method is based on use of two sets of observations under the known illuminant spectra to obtain two unknown components. The feasibility of the proposed method is examined in experiments using fluorescent paints in detail. The light sources of an incandescent lamp and an artificial sun lamp are selected as a set of suitable light sources. The accuracy of the estimated radiance factors is confirmed.

Introduction

In these days fluorescent substance applies to many everyday materials, for instance paints, plastics, papers, cloths, or even human teeth. Fluorescence is a phenomenon where the material is excited by electromagnetic radiation in the specific wavelength region and the excited state relaxation emits electromagnetic radiation in another longer wavelength region. When the excitation wavelengths of the material are in ultraviolet region, the emission wavelengths are usually in visible region. Likewise, when the excitation wavelengths are in the visible range, the emission occurs in longer wavelengths. This shift of wavelength causes a compelling visual effect, when it occurs within the visible range or turns the ultraviolet radiation into visible light. This fluorescent effect often improves visual appearance of object surfaces. In particular, many fluorescent surfaces appear brighter and more vivid than the original color surfaces. For this reason, fluorescent materials are important and attractive as target objects of imaging science and technology.

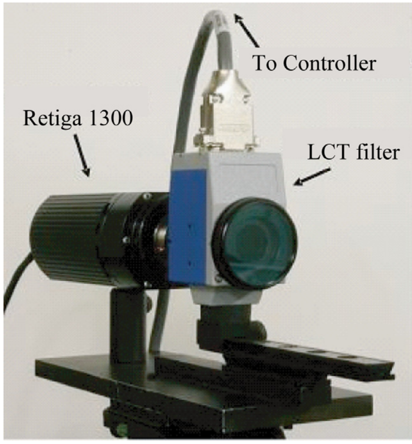
The spectral radiance factor of a fluorescent material consists of the sum of two components: a reflected radiance factor and a fluorescent (luminescent) radiance factor. Therefore the radiance factor is a function of two wavelength variables: the excitation wavelength of incident light and the emission/reflection wavelength. Such fluorescent characteristics can be measured by several methods [1-5]. The most accurate one is the two-monochromator method which was originally developed by Donaldson [1]. The results of fluorescent measurements are summarized as a Donaldon matrix, which is an illuminant independent matrix representation of the bispectral radiance factor of a target object in the used measurement geometry where the radiance factor is expressed at each excitation and emission wavelength. The reflectance information about the object is located in the diagonal elements of the Donaldson matrix. Practical implementation of the two-monochromator method was discussed in several papers (e.g., see [6]). The radiance factor measurement was applied to many practical problems such as transparent fluorescent inks [7], fluorescent halftoning [8], data encryption [9], color mixing [10], and rendering [11].

However the two-monochromator method is expensive, and only available in laboratory setup, but not in natural scene. Haneishi et al. [12] proposed an estimation method of the Donaldson radiance factor by using an ultraviolet light and a spectro-radiometer. Although the measuring system of this method is easier than the previous measurement method, there is a problem in estimation accuracy of reflectance radiance factor. Moreover, use of the ultraviolet light cannot be recommended from safety side.

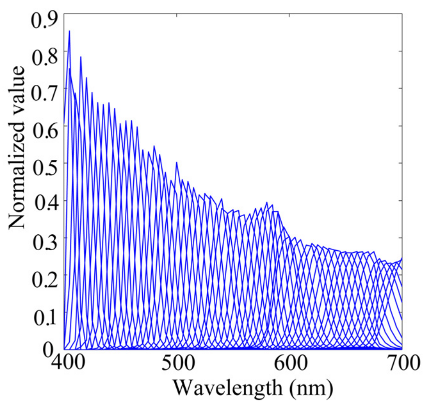
The present paper proposes a method for estimating the spectral radiance factor of fluorescent objects by using visible lights and an imaging device. We use neither an ultraviolet light (black light) nor a monochromator. Our imaging system consists of a multi-band camera system and two ordinary light sources, which is operated in only the visible wavelength range of [400, 700nm]. The camera outputs are modeled using the Donaldson matrix with the two factors of reflected radiance and luminescent radiance. Then we present an algorithm for estimating both radiance factors from the camera outputs, captured under two light sources. This solution method is based on use of two sets of observations under the known illuminant spectra to obtain two unknown components. The feasibility of the proposed method is examined in experiments in detail. The estimation accuracy is shown for various fluorescent paints.

Imaging system

Figure 1(a) shows our imaging system. The multi-band camera system consists of a monochromatic CCD camera (QImaging Retiga 1300) with 12-bit dynamic range and Peltier cooling, a VariSpec™ Liquid Crystal Tunable Filter (LCTF), and a personal computer. The spectral transmittance of the LCTF has bandwidth of about 10 nm in the visible range [400-700nm]. The spectral images are captured normally at wavelength points of equal intervals of 5 nm. The image resolution is 1280×1024 pixels. Figure 1(b) shows the total spectral sensitivity functions of the imaging system. We use two visible light sources emitting different continuous spectra for capturing images of fluorescent objects. In principle, fluorescent characteristics can be obtained independently at every pixel.



(a) System overview



(b) Total spectral-sensitivity functions.

Figure 1 Multi-band camera system.

Estimation of Luminescent and Reflected Radiance Factors

First we model the camera outputs with the Donaldson matrix including the two radiance factors. Then we present an algorithm for estimating both radiance factors from the camera outputs. When a fluorescent object is illuminated by two visible lights, the luminescent radiance factor is estimated using two sets of spectral sensor outputs. The reflected radiance factor is then estimated as a common bias term.

Imaging model

For a general object surface without fluorescence component, sensor outputs of the imaging system are described as a linear equation

$$\rho_i = \int_{400}^{700} E(\lambda)S(\lambda)R_i(\lambda)d\lambda\ , \qquad (1)$$

where $E(\lambda)$ is the illuminant spectrum, $S(\lambda)$ is the surface-spectral reflectance, and $R_i(\lambda)$ is the spectral sensitivity function of the i-th sensor. In contrast, a fluorescent object has a unique property to absorb radiation at shorter wavelength of illumination, and then to re-emit that energy at longer wavelength of visible light. Therefore, the sensor output can be defined as

$$\rho_i = \iint_{400}^{700} E(\lambda_{in})S(\lambda_{out},\lambda_{in})d\lambda_{in}R_i(\lambda_{out})d\lambda_{out}\ , \qquad (2)$$

where $S(\lambda_{out},\lambda_{in})$ is a bispectral radiance factor so-called the Donaldson radiance factor [1] which is a bispectral function to reflect the fluorescent property using an emission wavelength λ_{out} and an excitation wavelength λ_{in} .

Let **S** be a Donaldson matrix representing the tabular form of complete bispectral radiance factor $S(\lambda_{out},\lambda_{in})$. We assume that the excitation wavelengths λ_{in} are tabulated in the vertical direction, the emission wavelengths λ_{out} in the horizontal direction. Then, the reflected radiance factors appear on the diagonal where the excitation and emission wavelengths are equal, $\lambda_{out} = \lambda_{in}$, and the array of bispectral luminescent radiance factor data appear on the off-diagonal. Because of this two-dimensional property of a fluorescent object, a typical two-monochromator approach, which involves monochromatic irradiation and monochromatic measurement, may provide an accurate method for the determination of total spectral radiance factors of fluorescent objects. Figure 2 illustrates the bispectral radiance factor $S(\lambda_{out},\lambda_{in})$ of a red fluorescent paint, which was measured by using a monochromator, a spectroradiometer, and a standard white reference. However, the instrumentation is complex and the measurement procedures are lengthy.

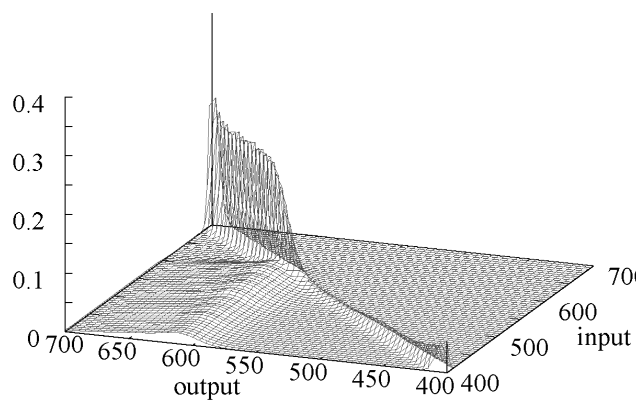


Figure 2 Bispectral radiance factor measured from red fluorescent paint.

We derive a new approach to obtain fluorescent spectral radiance factors from the sensor outputs of the multi-band camera system under two illuminations. Note in Fig. 2 that the input and output axes represent excitation and emission wavelengths, respectively. The z-axis means the radiance factor. If an object is non-fluorescent, the radiance factor appears at only diagonal position as the surface-reflectance component by $S(\lambda_{out},\lambda_{in}) = 0$, $(\lambda_{out} \neq \lambda_{in})$. However, in the case of a fluorescent object, as shown in Fig.2, luminescent energy is emitted at longer wavelength than each excitation wavelength. This property of $S(\lambda_{out},\lambda_{in})$ can be represented in a matrix form. The imaging equation in (2) is then modeled as a matrix equation

$$\boldsymbol{\rho}^{M\times 1} = \mathbf{R}^{M\times N}\mathbf{S}^{N\times N}\mathbf{e}^{N\times 1}\ , \qquad (3)$$

where M and N indicate, respectively, the number of image sensors and the number of sampled points of spectral functions in the visible wavelength scale [400,700nm]. Obviously, the Donaldson matrix for a non-fluorescent object becomes diagonal as

$$\mathbf{S}_R = \begin{bmatrix} s_{11} & & & 0 \\ & s_{22} & & \\ & & \ddots & \\ 0 & & & s_{NN} \end{bmatrix}. \quad (4)$$

Note that a diagonal matrix $\mathbf{S}_R = diag\left(s_{11}, s_{22}, \cdots, s_{NN}\right)$ corresponds to the reflected radiance factor. The Donaldson matrix for a fluorescent object is represented in the form

$$\mathbf{S} = \mathbf{S_R} + \mathbf{S}_L = \begin{bmatrix} s_{11} & & & 0 \\ s_{21} & s_{22} & & \\ \vdots & \vdots & \ddots & \\ s_{N1} & s_{N2} & \cdots & s_{NN} \end{bmatrix}, \quad (5)$$

by summing the diagonal reflected radiance factor $\mathbf{S}_R$ and the off-diagonal luminescent radiance factor $\mathbf{S}_L$. In Fig. 2 a fluorescent peak located around 620 nm. We note that the peak height is almost independent on illumination wavelength. It is suggested that the luminescent radiance factors of most fluorescent objects are almost constant along excitation wavelength. Therefore the Donaldson matrix is rewritten as

$$\mathbf{S} = \begin{bmatrix} s_{11} & & & & \\ s_2 & s_{22} & & 0 & \\ s_3 & s_3 & s_{33} & & \\ \vdots & & \ddots & \ddots & \\ s_N & s_N & \cdots & s_N & s_{NN} \end{bmatrix}, \quad (6)$$

where the luminescent radiance factor for each emission wavelength is approximated with constant $s_k \; (k = 2,3,\cdots,N)$. The spectral imaging system is narrow-band characteristic. Therefore, we assume that M=N and the matrix $\mathbf{R}$ is defined as

$$\mathbf{R} = \begin{bmatrix} r_1 & 0 & \cdots & 0 \\ 0 & r_2 & & 0 \\ \vdots & & \ddots & \vdots \\ 0 & 0 & \cdots & r_N \end{bmatrix}. \quad (7)$$

Estimation of luminescent radiance factor

The estimation problem of the radiance factors comes down to estimation of the luminescent radiance factor $s_k \; (k = 2, 3, \cdots, N)$ from two sensor outputs $\boldsymbol{\rho}_1$ and $\boldsymbol{\rho}_2$ under illuminant spectral power distributions $\mathbf{e}_1$ and $\mathbf{e}_2$.

When a visible light with the spectrum $\mathbf{e}_j = \left[e_1^{(j)}, e_2^{(j)}, \cdots, e_N^{(j)}\right]^T$ is projected onto a fluorescent object, the sensor output $\boldsymbol{\rho}_j$ is calculated from Eqs.(3)-(7) as

$$\boldsymbol{\rho}_j = \begin{bmatrix} r_1 e_1^{(j)} s_{11} \\ r_2\left(e_1^{(j)} s_2 + e_2^{(j)} s_{22}\right) \\ r_3\left(\left(e_1^{(j)} + e_2^{(j)}\right) s_3 + e_3^{(j)} s_{33}\right) \\ \vdots \\ r_N\left(s_N \sum_{l=1}^{N-1} e_l^{(j)} + e_N^{(j)} s_{NN}\right) \end{bmatrix}, \; (j=1, 2). \quad (8)$$

When $\boldsymbol{\rho}_j$ is divided by the known camera sensitivity $\mathbf{R}$ and the illuminant spectrum $\mathbf{e}_j$, we have

$$\mathbf{s}^*{}_j = \mathbf{R}^{-1}\mathbf{E}_j{}^{-1}\boldsymbol{\rho}_j = \begin{bmatrix} s_{11} \\ \dfrac{e_1^{(j)} s_2}{e_2^{(j)}} + s_{22} \\ \dfrac{\left(e_1^{(j)} + e_2^{(j)}\right) s_3}{e_3^{(j)}} + s_{33} \\ \vdots \\ \dfrac{s_N \sum_{l=1}^{N-1} e_l^{(j)}}{e_N^{(j)}} + s_{NN} \end{bmatrix}, \quad (9)$$

where $\mathbf{E}_j$ is a diagonal matrix representing the spectral power distribution $\mathbf{e}_j$. Note that $\mathbf{s}_j^*$ is the projected component of a biased bispectral radiance factor $S(\lambda_{out}, \lambda_{in})$ to the emission wavelength axis λ_{out}.

The right-hand side of Eq.(9) is decomposed into two components:

(1) the modified luminescent radiance factor $\mathbf{s}_L^{(j)} = \left[0, \left(e_1^{(j)} s_2\right)/e_2^{(j)}, \cdots, s_N \sum e_l^{(j)}/e_N^{(j)}\right]^T$ under the light j and

(2) the reflected radiance factor $\mathbf{s}_R = \left[s_{11}, s_{22}, \cdots, s_{NN}\right]^T$.

Then we have a simplified expression

$$\mathbf{s}^*{}_j = \mathbf{s}_L^{(j)} + \mathbf{s}_R. \quad (10)$$

Equation (10) suggests that the reflected radiance factor $\mathbf{s}_R$ is independent of the light source. When making difference between the projected radiance factors for two lights as

$$\mathbf{s}_1^* - \mathbf{s}_2^* = \mathbf{s}_L^{(1)} - \mathbf{s}_L^{(2)} = \begin{bmatrix} 0 \\ \dfrac{e_1^{(1)} s_2}{e_2^{(1)}} - \dfrac{e_1^{(2)} s_2}{e_2^{(2)}} \\ \dfrac{\left(e_1^{(1)} + e_2^{(1)}\right) s_3}{e_3^{(1)}} - \dfrac{\left(e_1^{(2)} + e_2^{(2)}\right) s_3}{e_3^{(2)}} \\ \vdots \\ \dfrac{s_N \sum_{l=1}^{N-1} e_l^{(1)}}{e_N^{(1)}} - \dfrac{s_N \sum_{l=1}^{N-1} e_l^{(2)}}{e_N^{(2)}} \end{bmatrix}, \quad (11)$$

the reflected radiance factor $\mathbf{s}_R$ is canceled out, and only the luminescent radiance factor remains. That is, Eq.(11) can be rewritten simply as

$$\mathbf{s}_1^* - \mathbf{s}_2^* = \begin{bmatrix} 0 \\ \alpha_2 s_2 \\ \alpha_3 s_3 \\ \vdots \\ \alpha_N s_N \end{bmatrix}, \quad (12)$$

where the coefficient is given by

$$\alpha_i = \frac{e_i^{(2)} \sum_{l=1}^{N-1} e_l^{(1)} - e_i^{(1)} \sum_{l=1}^{N-1} e_l^{(2)}}{e_i^{(1)} e_i^{(2)}}, \; (i=, 2, 3, \ldots, N). \quad (13)$$

Each coefficient α_i is constant determined only by two illuminant spectra. The luminescent radiance factor $s_i (i = 2, 3, \cdots, N)$ is obtained as $(\mathbf{s}_1^* - \mathbf{s}_2^*)_i / \alpha_i$. The off-diagonal elements of the Donaldson matrix in Eq.(6) can be estimated in this way.

Estimation of reflected radiance factor

First, we calculate the modified radiance vector $\mathbf{s}_L^{(j)}$ from the estimated luminescent radiance factor s_k and the illuminant spectrum of *j*. Then, we can obtain an estimate of the reflected radiance factor $\mathbf{s}_R$ from Eq.(10) as

$$\mathbf{s}_R = \frac{1}{2}\sum_{j=1}^{2}\left(\mathbf{s}^*_j - \mathbf{s}_L^{(j)}\right). \tag{14}$$

Experiments

Experimental setup

The feasibility of the proposed method was examined in experiments in detail. Figure 3 shows a set of target objects used in our experiment for estimating the fluorescent radiance components. The samples are fluorescent paints *Tuerner Acryl Gouache* applied on a black Kent paper. In a preliminary experiment we investigated a pair of light sources suitable for the radiance factor estimation. Two visible lights of an incandescent lamp and an artificial sun lamp were selected as the best pair from various combinations of real light sources. Figure 4 shows the spectral power distributions of the two lights. Spectral images of the fluorescent objects were captured by the present spectral camera system under the two lights separately. Thus, we obtained two sets of spectral images which are 61-dimensional data sampled at 5 nm intervals in the region [400,700nm].

Estimation results

Figure 5 shows the estimation results of radiance factors for *Lumi red*, *Lumi green* and *Lumi yellow* shown in Fig. 3. The dashed curves represent the spectral radiance factors measured by using a monochromator and a spectrophotometer. The solid curves represent the spectral radiance factors estimated by the proposed method. The RMSE between the measurement and the estimate was calculated for representing the estimation accuracy. These values are 0.0013, 0.0036, and 0.0058 for Red, Green, and Yellow , respectively. Figure 6 shows the estimation results of the reflected radiance factor. In comparison with Fig. 5, the accuracy looks inferior to the luminescent radiance factor estimation. This is because reliability of the reflected radiance factor estimation depends on the estimation accuracy of the luminescent radiance factor.

The reliability of the proposed method was also confirmed in comparison with our previous method. Figure 7 shows the estimation results for the red fluorescent paint by the method in Ref.[13] using an ultraviolet light and a spectro-radiometer. Comparison between Fig. 7 and Figs. 5(a) and 6(a) suggests that the estimates of both radiance factors by the proposed method are more accurate than the previous one. We should note again that the method is based on a simple imaging system in the visible range, compared with use of an ultraviolet light and a spectro-radiometer. Moreover, the radiance factor estimation can be performed at every pixel on a fluorescent object surface.

Figure 3 Fluorescent objects used in an experiment.

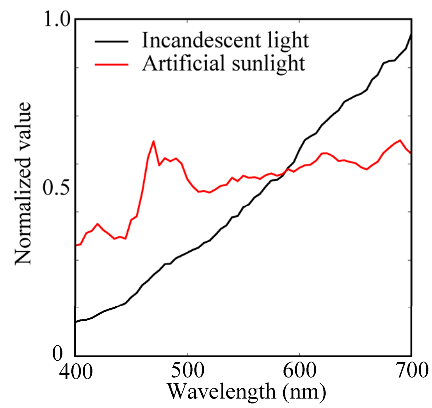
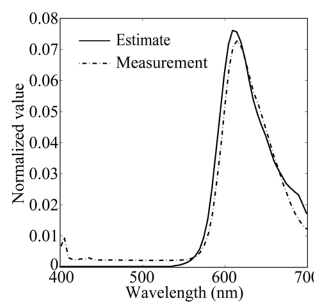
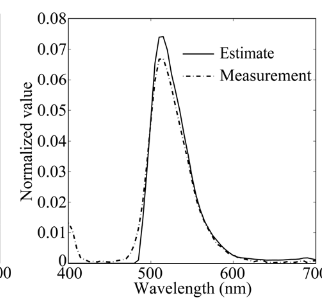


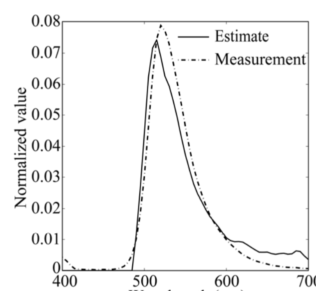
Figure 4 Spectral power distributions of two visible light sources used in the experiment.



(a) Red

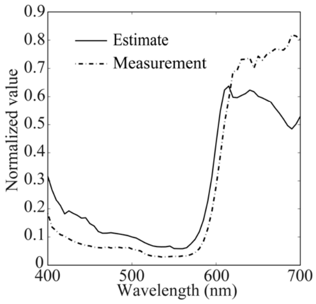


(b) Green

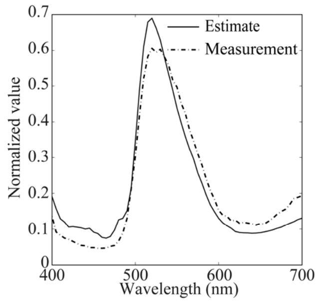


(c) Yellow

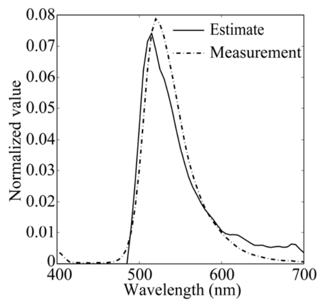
Figure 5 Estimation results of the luminescent radiance factor.



(a) Red

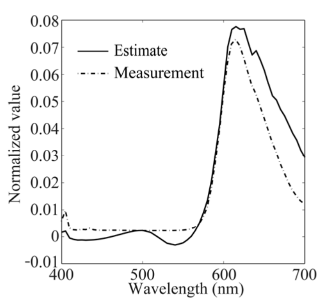


(b) Green

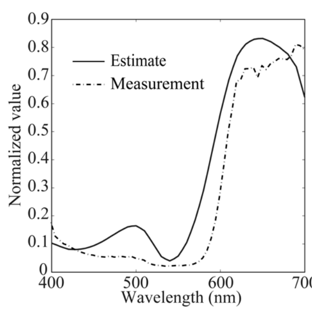


(c) Yellow

Fiigure 6 Estimation results of the reflected radiance factor.



(a) Luminescent radiance factor



(b) Reflected radiance factor

Figure 7 Estimation results for the red paint using the previous method [13].

Conclusion

We have proposed a method for estimating the spectral radiance factor of fluorescent objects by using visible lights and an imaging device. We used neither an ultraviolet light (black light) nor a monochromator, but used an easy imaging system consisting of a multi-band camera and two ordinary visible light sources. The imaging system can provide fluorescent characteristics at every pixel of an object surface. The camera outputs were modeled using the Donaldson matrix with the two factors of reflected radiance and luminescent radiance. An algorithm was then presented for estimating both radiance factors from two sets of spectral images of the camera outputs, captured under two light sources. This solution method was based on use of two sets of observations under the known illuminant spectra to obtain two unknown components. The feasibility of the proposed method was examined in experiments using fluorescent paints in detail. The light sources of an incandescent lamp and an artificial sun lamp were selected as a set of suitable light sources. The accuracy of the estimated radiance factors was confirmed in comparisons with the measurements and the previous method.

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Author Biography

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