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Appearance Reconstruction of Mutual Illumination Effect between Plane and Curved Fluorescent Objects

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Abstract

This paper considers appearance reconstruction of 3D fluorescent objects with mutual illumination effect. We examined the mutual illumination between flat plane and curved objects, by placing a cylinder on a flat plane. First, the spectral images of the fluorescent objects with the mutual illumination effect are acquired under different illumination directions. The respective observed images are then decomposed into several components on the basis of spectral compositions and the spatial distributions of geometric factors. The surface normal vectors are estimated by utilizing the photometric stereo method. Second, the reference geometric factors are defined as geometric factors independent of illumination direction change. The reference geometric factors for mutual illumination on the plane are determined based on viewing from the normal direction of the cylinder. We reconstruct a new appearance of the two fluorescent objects under the fixed viewpoint but the different conditions of fluorescent material, illuminant spectrum, and illumination direction. We show that the total appearance of the reconstructed image predicts well the real scene.

Introduction

Appearance reconstruction of objects under different conditions is often necessary in daily life, which may be called appearance control or appearance editing [1]-[3]. We note that the appearance reconstruction strongly depends on the materials consisting the object surfaces. Most of the previous studies, however, are limited to non-fluorescent reflecting materials which have the reflection property of Lambertian or diffuse. In addition, mutual illumination between the object surfaces must be accounted into the appearance construction [4]-[5]. The analysis of fluorescent objects has been limited despite its growing importance as object materials in recent years [6].

In a previous study [7], we presented a method for appearance reconstruction of two fluorescent objects under different spectral characteristics of materials and illuminant. The scene appearance of two fluorescent objects was decomposed into several components each of which was described by the spectral functions and the geometric factors. We showed that the scene appearance of the target objects with different material characteristics under different illuminant could be reconstructed by replacing the terms of spectral functions with the target spectrum. We also presented a method to estimate the geometric factors of object surfaces for aiming at more general appearance reconstruction [8]. In previous studies, we assumed that fluorescent objects have plane surfaces. Object surfaces with mutual illuminations are not always flat plane, but sometimes may be curved.

In this paper, we consider the appearance reconstruction of fluorescent mutual illumination between a flat plane and a curved cylinder for aiming extension to more general object shapes. We suppose that a cylinder is placed on a flat plane as shown in Figure 1. First, the spectral images of fluorescent objects with the mutual illumination effect are acquired under different illumination directions. The respective observed images are then decomposed into several components on the basis of spectral compositions, where the spectral functions of each component are unchanged, and only the geometric factors are changed for different illumination directions.

The surface shape information is estimated by utilizing the photometric stereo method. Second, the reference geometric factors are defined as geometric factors independent of illumination direction change. The reference geometric factor for mutual illumination between a plane and a cylinder is then determined based on the observed geometric factors and the estimated surface normals. We reconstruct a new appearance of the two fluorescent objects under the fixed viewpoint but the different conditions of fluorescent material, illuminant spectrum, and illumination direction.

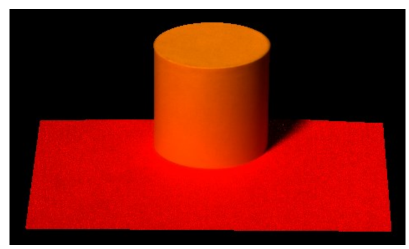

Figure 1 Sample of fluorescent objects with mutual illumination effect.

Observation Model of a Fluorescent Object

Bispectral function

The bispectral radiance factor (Donaldson matrix [9]) $D(\lambda_{em}, \lambda_{ex})$ of a fluorescent object is a function of the excitation wavelength λ_{em} and the emission/reflection wavelength λ_{ex}. In this study the excitation range is set to $350 \le \lambda_{ex} \le 700$ (nm), and since our spectral imaging system operates in visible range, the emission/reflection range is set $400 \le \lambda_{em} \le 700$ (nm). The Donaldson matrix is decomposed into the reflected radiance factor $D_R(\lambda_{em}, \lambda_{ex})$ and the luminescent radiance factor $D_L(\lambda_{em}, \lambda_{ex})$, where $D_R(\lambda_{em}, \lambda_{ex})$ has surface-spectral reflect $S(\lambda)$ at $\lambda_{em} = \lambda_{ex}$. $D_L(\lambda_{em}, \lambda_{ex})$ has values only in the off-diagonal of $\lambda_{em} > \lambda_{ex}$, and it is further separated into $D_L(\lambda_{em}, \lambda_{ex}) = \alpha(\lambda_{em})\beta(\lambda_{ex})$, where $\alpha(\lambda_{em})$ and $\beta(\lambda_{ex})$ are called the emission spectrum and the excitation spectrum, respectively. We assume $\int_{350}^{700} \beta(\lambda_{ex}) d\lambda_{ex} = 1$ (see [10]).

Observation

The observation of an object surface at location $\mathbf{x} = (x, y)$ can be described as a continuous function of wavelength

$$\begin{aligned} y(\mathbf{x},\lambda_{em}) &= f_{\mathrm{ref}}(\mathbf{x})S(\lambda_{em})E(\lambda_{em}) \\ &+ f_{\mathrm{lum}}(\mathbf{x})\alpha(\lambda_{em})\int_{350}^{\lambda_{em}} \beta(\lambda_{ex})E(\lambda_{ex})d\lambda_{ex} \end{aligned} \tag{1}$$

Suppose that two surfaces are matte and illuminated uniformly by a single illuminant $E(\lambda)$ (see [11]). When we assume that the mutual illumination is based on only one reflection/emission between the two surfaces, the observations from surface i are represented as

$$\begin{aligned} y_i(\mathbf{x},\lambda_{em}) &= f_{i1}(\mathbf{x})S_i(\lambda_{em})E(\lambda_{em}) \\ &+ f_{i2}(\mathbf{x})S_i(\lambda_{em})S_j(\lambda_{em})E(\lambda_{em}) \\ &+ f_{i3}(\mathbf{x})(c_{i1}(\lambda_{em})+c_{i2}(\lambda_{em})+c_{i3}(\lambda_{em}))\alpha_i(\lambda_{em}) \\ &+ f_{i4}(\mathbf{x})c_{i4}(\lambda_{em})S_i(\lambda_{em})\alpha_j(\lambda_{em}) \end{aligned} \tag{2}$$

where ($i = 1, j = 2$) and ($i = 2, j = 1$),

$$\begin{aligned} c_{i1}(\lambda_{em}) &= \int_{350}^{\lambda_{em}} \beta_i(\lambda_{ex})E(\lambda_{ex})d\lambda_{ex}, \\ c_{i2}(\lambda_{em}) &= \int_{350}^{\lambda_{em}} \beta_i(\lambda_{ex})S_j(\lambda_{ex})E(\lambda_{ex})d\lambda_{x}, \\ c_{i3}(\lambda_{em}) &= \int_{350}^{\lambda_{em}} \beta_i(\lambda_{ex})\alpha_j(\lambda_{ex})\left(\int_{350}^{\lambda_{ex}} \beta_j(\lambda'_{ex})E(\lambda'_{ex})d\lambda'_{ex}\right)d\lambda_{ex} \\ c_{i4}(\lambda_{em}) &= \int_{350}^{\lambda_{em}} \beta_j(\lambda_{ex})E(\lambda_{ex})d\lambda_{ex}. \end{aligned} \tag{3}$$

Note that $f_{ij}(\mathbf{x})$ are variable of location $\mathbf{x}$ and independent of wavelength λ, which are called the geometric factors. Note also that the normalized spectra of $c_{i1}(\lambda))\alpha_i(\lambda)$, $c_{i2}(\lambda)\alpha_i(\lambda)$ and $c_{i3}(\lambda)\alpha_i(\lambda)$ are almost coincident with $\alpha_i(\lambda)$. We cannot distinguish these mutual components spectrally.

Therefore the first term in Eq. (2) represents the diffuse reflection by the direct illumination from the light source. The second term represents interreflection by the diffuse reflections between both surfaces. The third term represents self-luminescence by fluorescent emission. The fourth term represent interreflection caused by the fluorescent illumination emitted from the adjacent surface. Thus, the observed radiance factor consists of four spectral components of (1) diffuse reflection, (2) diffuse-diffuse interreflection, (3) self-luminescence, and (4) interreflection caused by fluorescent illumination.

Image Decomposition

The observation model in Eq. (2) is represented into a matrix form. Let $\mathbf{s}_1(\mathrm{or}\,\mathbf{s}_2)$ and $\boldsymbol{\alpha}_1(\boldsymbol{\alpha}_2)$ be 61-dimensional column vectors representing the reflectance and emission spectra. Also, let $\mathbf{c}_{ij}(i, j = 1{,}2)$ be 61-dimensional column vectors representing the spectral functions $[c_{i1}(\lambda), c_{i2}(\lambda), c_{i3}(\lambda)], [c_{i4}(\lambda)]$ (i,j=1,2). Using these, let $\mathbf{A}_1(\mathbf{A}_2)$ be 61 × 4 matrices representing the spectral component functions and $\mathbf{f}_1(\mathbf{x})\,(\mathbf{f}_2(\mathbf{x}))$ be 4-dimensional column vectors representing the geometric factors as follows:

$$\begin{aligned} \mathbf{A}_1 &= [\mathbf{s}_1.{*}\mathbf{e} \;\; \mathbf{s}_1.{*}\mathbf{s}_2.{*}\mathbf{e} \;\; \mathbf{c}_{11}.{*}\boldsymbol{\alpha}_1 \;\; \mathbf{c}_{12}.{*}\mathbf{s}_1.{*}\boldsymbol{\alpha}_2], \\ \mathbf{A}_2 &= [\mathbf{s}_2.{*}\mathbf{e} \;\; \mathbf{s}_1.{*}\mathbf{s}_2.{*}\mathbf{e} \;\; \mathbf{c}_{21}.{*}\boldsymbol{\alpha}_2 \;\; \mathbf{c}_{22}.{*}\mathbf{s}_2.{*}\boldsymbol{\alpha}_1] \\ \mathbf{f}_1(\mathbf{x}) &= [f_{11}(\mathbf{x}) \;\; f_{12}(\mathbf{x}) \;\; f_{13}(\mathbf{x}) \;\; f_{14}(\mathbf{x})]^t, \\ \mathbf{f}_2(\mathbf{x}) &= [f_{21}(\mathbf{x}) \;\; f_{22}(\mathbf{x}) \;\; f_{23}(\mathbf{x}) \;\; f_{24}(\mathbf{x})]^t \end{aligned} \tag{4}$$

where symbols $.*$ and t represent element-wise multiplication and matrix transposition, respectively. Then the observations with mutual illumination effects are modeled in a matrix equation as

$$\mathbf{y}_1(\mathbf{x}) = \mathbf{A}_1\mathbf{f}_1(\mathbf{x}), \quad \mathbf{y}_2(\mathbf{x}) = \mathbf{A}_2\mathbf{f}_2(\mathbf{x}) \tag{5}$$

The self-luminescent component is composed of two main fluorescent emission processes. One emission is excited by direct illumination from the light source, and another is excited by indirect illumination reflected from the other surface. These have the same spectral composition as $\alpha_i(\lambda)$ and so spectrally indistinguishable. However, these can be estimated separately based on the spatial distribution. Fluorescence emitted from any surface location on an object has non-directional characteristics, which is similar to the Lambert matte surface. Therefore, the two types of fluorescent emission by direct and indirect illuminations correspond to the diffuse reflection distribution $f_{i1}(\mathbf{x})$ and the interreflection distribution $f_{i2}(\mathbf{x})$. So we can further decompose the geometric factor of the self-luminescent component into the direct and indirect illumination component. The observed image is decomposed into five components of (1) reflection, (2) interreflection, (3) luminescence by direct illumination, (4) luminescence by indirect illumination, and (5) interreflection by fluorescent illumination as $[f_{i1}(\mathbf{x}) \;\; f_{i2}(\mathbf{x}) \;\; f_{i3}(\mathbf{x}) \;\; f_{i4}(\mathbf{x}) \;\; f_{i5}(\mathbf{x})]$.

Reference Geometric Factor Estimation

The geometric factors $f_{ij}(\mathbf{x})$ obtained from the spectral image decomposition depend on the illumination direction. First, we suppose a simple case of the geometric factors between two flat planes. The reference geometric factor is defined to be independent of illumination direction change, which are estimated from the observed geometric models for reflection, luminescence, and mutual illumination. The observations by diffuse reflection are modeled as

$$y_{1i}(\mathbf{x},\lambda) = f_{\mathrm{o}1}(\mathbf{x})(\mathbf{n}_i \cdot \qquad E(\lambda), \qquad \text{for Surface}\,i \tag{6}$$

where $\mathbf{n}_i$ are the unit vectors in the normal directions of Surfaces i, and $\mathbf{l}$ is the directional vector of the light source. The surface normals are estimated from multiple observations under different illumination directions, where the photometric stereo is applied to the first geometric factor $f_{i1}(\mathbf{x})$ under different direction. The symbol $f_{\mathrm{o}1}(\mathbf{x})$ represents the reference geometric factor, which is defined as the geometric factor at the vertical incidence to each surface. Next, the observations by the interreflection between two matte surfaces are modeled as (see [8])

$$y_{2i}(\mathbf{x},\lambda)=f_{o2}(\mathbf{x})(\mathbf{n}_i\cdot \quad S_2(\lambda)E(\lambda), \quad \text{for Surface} i \quad (7)$$

where $f_{o2}(\mathbf{x})$ represents the reference geometric factor at the case of incidence from the direction bisecting the two planes in contact with each other.

The reference geometric factors are estimated based on the above models. The reference geometric factors $f_{o1}(\mathbf{x})$ are calculated from the observed geometric factors as

$$f_{o1}(\mathbf{x}) = f_1(\mathbf{x})/(\mathbf{n}_i\cdot \quad \text{for Surface} i \quad (8)$$

where the vector **I** bisecting the two planes is described as

$$\mathbf{l}=(\mathbf{n}_1+\mathbf{n}_2)/\sqrt{2(1+\mathbf{n}_1\cdot} \quad (9)$$

The reference geometric factors for interreflection are calculated as

$$f_{o2}(\mathbf{x}) = f_2(\mathbf{x})\sqrt{1+\mathbf{n}_1\cdot} \quad \cdot \quad \text{for Surface} i \quad (10)$$

Concerning the fluorescent geometric factors, $f_{o3}(\mathbf{x})$ can be estimated in the same way in Eq.(8), and the geometric factors $f_{o4}(\mathbf{x})$ and $f_{o5}(\mathbf{x})$ by indirect illumination and interreflection are estimated in the same way as in Eq.(10).

Second, we consider the geometric factor estimation for mutual illumination between a cylinder and a plane. We should note that, even though the object surfaces are Lambertian, the mutual illumination effects by the cylinder onto the flat plane are dependent on illumination and viewing angles. Figure 2 demonstrates the spatial distribution of ($f_{12}(\mathbf{x}), f_{22}(\mathbf{x})$) under the illumination direction of upper right, where $f_{12}(\mathbf{x})$ on the plane is more dependent on the illumination angle than $f_{22}(\mathbf{x})$. Therefore, the reference geometric factors $f_{o2}(\mathbf{x})$, $f_{o4}(\mathbf{x})$ and $f_{o5}(\mathbf{x})$ for the second, fourth, and fifth components are determined based on the mutual illumination efforts when viewing from the normal direction of the cylinder.

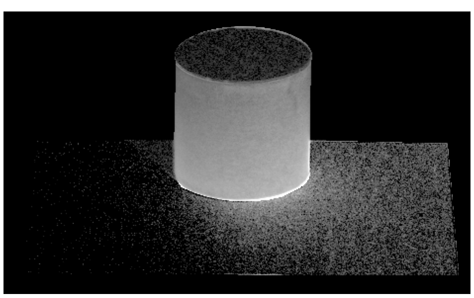

Figure 2. Spatial distribution of the geometric factors $f_{12}(\mathbf{x}), f_{22}(\mathbf{x})$ under the illumination direction of upper right.

Appearance Reconstruction

A new appearance of the two fluorescent objects is reconstructed under the fixed viewpoint but the different conditions of fluorescent material, illuminant spectrum, and illumination direction. The geometric factors $f_1'(\mathbf{x}), f_2'(\mathbf{x}), f_3'(\mathbf{x}), f_4'(\mathbf{x}), f_5'(\mathbf{x})$ for the desired illumination direction **l'** are predicted from the reference geometric factors $f_{o1}(\mathbf{x}), f_{o2}(\mathbf{x}), f_{o3}(\mathbf{x}), f_{o4}(\mathbf{x}), f_{o5}(\mathbf{x})$ at the respective component levels. The geometric factors $f_1'(\mathbf{x})$ and $f_3'(\mathbf{x})$ for diffuse reflection and self-luminescent by direct illumination are predicted using the normal vector **n** at location **x** and the directional vector **l'** as

$$f_{11}'(\mathbf{x})=(\mathbf{n}_1\cdot \quad \cdot$$
$$f_{31}'(\mathbf{x})=(\mathbf{n}_1\cdot \quad \cdot \quad . \quad (11)$$

If **x** is on the cylinder surface, the geometric factors $f_{2i}'(\mathbf{x})$, $f_{4i}'(\mathbf{x})$, and $f_{5i}'(\mathbf{x})$ for mutual illumination by indirect illumination are predicted from the reference geometric factors $f_{o2}(\mathbf{x})$, $f_{o4}(\mathbf{x})$, and $f_{o5}(\mathbf{x})$ in the same way as the geometric factors in the case of two planes. If **x** is on the plane surface, the geometric factors $f_{2i}'(\mathbf{x})$, $f_{4i}'(\mathbf{x})$, and $f_{5i}'(\mathbf{x})$ are predicted from the reference geometric factors, determined in viewing from the normal direction of the cylinder.

The spectral image representing the new appearance is reconstructed by the linear sum of a set of spectral functions $(\mathbf{A}_1', \mathbf{A}_2')$ and a set of geometric factors $(\mathbf{f}_1', \mathbf{f}_2')$ at the respective component levels as

$$\mathbf{y}_1'(\mathbf{x})=\mathbf{A}_1'\mathbf{f}_1'(\mathbf{x}), \;\; \mathbf{y}_2'(\mathbf{x})=\mathbf{A}_2'\mathbf{f}_2'(\mathbf{x}), \quad (12)$$

where

$$\begin{aligned}
\mathbf{A}_1' &= [\mathbf{s}_1.*\mathbf{e} \quad \mathbf{s}_1.*\mathbf{s}_2.*\mathbf{e} \quad \mathbf{c}_{11}.*\boldsymbol{\alpha}_1 \quad \mathbf{c}_{12}.*\boldsymbol{\alpha}_1 \quad \mathbf{c}_{13}.*\mathbf{s}_1.*\boldsymbol{\alpha}_2] \\
\mathbf{A}_2' &= [\mathbf{s}_2.*\mathbf{e} \quad \mathbf{s}_1.*\mathbf{s}_2.*\mathbf{e} \quad \mathbf{c}_{21}.*\boldsymbol{\alpha}_1 \quad \mathbf{c}_{22}.*\boldsymbol{\alpha}_2 \quad \mathbf{c}_{23}.*\mathbf{s}_2.*\boldsymbol{\alpha}_1] \; . \\
\mathbf{f}_1'(\mathbf{x}) &= [f_{11}'(\mathbf{x}) \quad f_{12}'(\mathbf{x}) \quad f_{13}'(\mathbf{x}) \quad f_{14}'(\mathbf{x}) \quad f_{15}'(\mathbf{x})]^t \\
\mathbf{f}_2'(\mathbf{x}) &= [f_{21}'(\mathbf{x}) \quad f_{22}'(\mathbf{x}) \quad f_{23}'(\mathbf{x}) \quad f_{24}'(\mathbf{x}) \quad f_{25}'(\mathbf{x})]^t
\end{aligned} \quad (13)$$

Experimental results

Two objects of a cylinder and a flat plane shown in Figure 1 were used in the present experiment. The spectral images of the objects were captured at 5nm intervals in the visible range under the five illumination directions. The light source was an incandescent lamp, and the imaging system consisted of a monochrome CCD camera with 12-bit dynamic range and a VariSpec LCT filter. The spectral curves of reflectance, emission, and excitation functions for the two materials were shown in Figure 2 of [8]. Figure 3 shows a color image set of the observed spectral images under the five illumination directions. The observed spectral images were decomposed into the five components by using the spectral functions and the incandescent illuminant spectrum, so that a set of the geometric factors was obtained for each illumination direction. The surface normals were estimated using only the first geometric factor. The reference geometric factors were estimated from each set of the observed geometric factors, and then were averaged over all sets for five different illumination directions to get the reliable estimates.

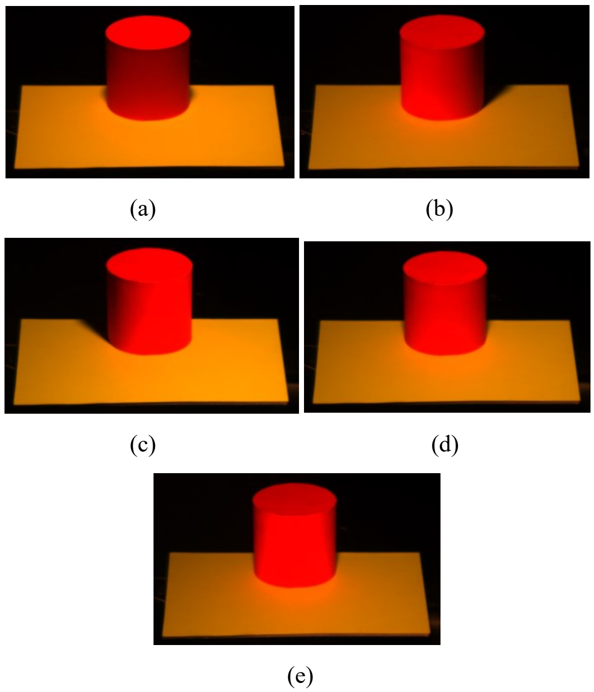

Figure 3. Color image set of the observed spectral images under the five illumination directions of (a) very upper, (b) upper left, (c) upper right, (d) middle upper, and (e) front.

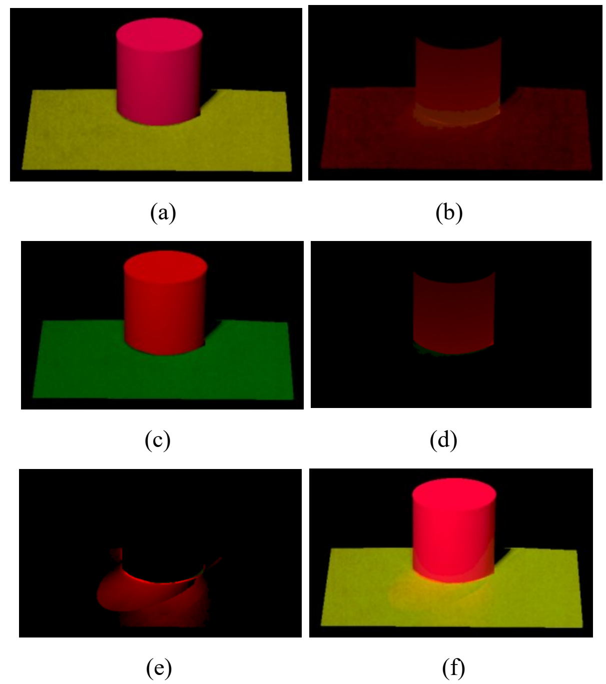

Figure 5. Component images (a)-(e) produced in the reconstruction process and the construction result (f). (a) Diffuse reflection, (b) interreflection, (c) luminescence by direct illumination, (d) luminescence by indirect illumination, and (e) interreflection by fluorescent illumination.

The feasibility of the proposed method was examined using a pair of different fluorescent materials with the same size as in Figure 1. The first object has the object color of pink and the fluorescent color of orange, and the second object has the object color of pale green and the fluorescent color of vivid green. Figure 4 shows the spectral curves of reflectance, emission, and excitation for these materials. We supposed that these objects were illuminated with the incandescent light source from the direction of upper left. The geometric factors were estimated at the new illumination direction. The component spectral images were produced by combining the geometric factors and the spectral functions at the respective component levels. Figures 5(a)-(e) show the color image set of the five component spectral images, where the cast shadows in the component images (a) and (c) were rendered additionally by the illumination direction and the cylinder size. Figure 5(f) shows the reconstructed appearance by the linear sum of the five component images (a)-(e). The reconstructed appearance in Figure 5 (f) is close to the real scene.

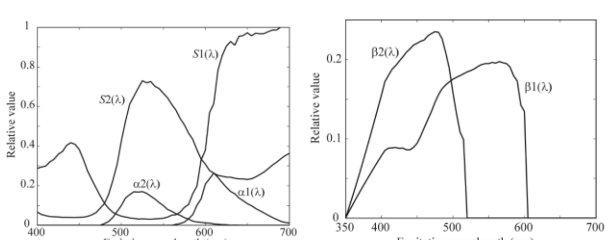

Figure 4. Spectral curves of reflectance and emission functions (left), and excitation functions (right) for the two fluorescent objects.

Conclusions

Appearance reconstruction of objects under different conditions of (1) material properties, (2) different illumination directions, (3) different illuminant spectra, are often necessary in daily life settings. Creation of plausible novel object appearances under different conditions is sometimes called appearance control or appearance editing. Previous studies had been focused more on the mutual illumination considered the non-fluorescent objects without much consideration on fluorescent objects.

In this paper, we have considered appearance reconstruction of 3D fluorescent objects with mutual illumination effect. We analyzed the mutual illumination between flat plane and curved objects. Especially we supposed that a cylinder was placed on a flat plane. First, the spectral images of the fluorescent objects were acquired under different illumination directions. The respective observed images were then decomposed into five components on the basis of the spectral compositions and the spatial distributions of geometric factors. The surface normal vectors were estimated by utilizing the photometric stereo method. Second, the reference geometric factors were defined as geometric factors independent of illumination direction. The reference geometric factors for mutual illumination were determined based on viewing from the normal direction of the cylinder. A new appearance of the two fluorescent objects was constructed under different conditions of fluorescent material, illuminant spectrum, and illumination direction. The total appearance of the reconstructed image predicted well the real scene.

Acknowledgements

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Author Biography

Shoji Tominaga received the Ph.D. degrees in electrical engineering from Osaka University, Japan, in 1975. In 2006, he joined Chiba University, Japan, where he was a Professor (2006-2013) and Dean (2011-2013) at Graduate School of Advanced Integration Science. He is now a Specially Appointed Researcher, Chiba University, and a Professor at NTNU, Norway. His research interests include multispectral imaging and material appearance. He is a Fellow of IEEE, IS&T, SPIE, and OSA.

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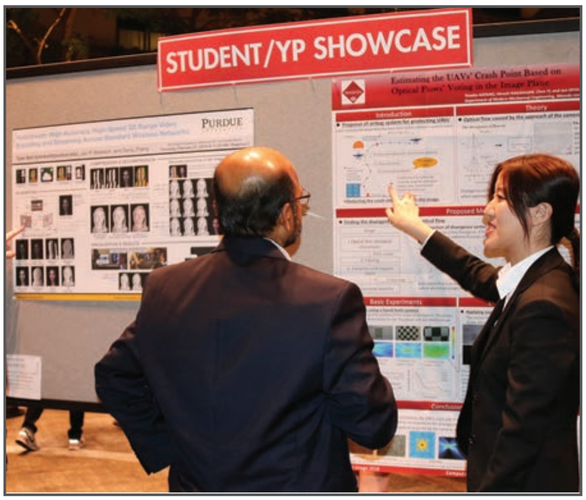

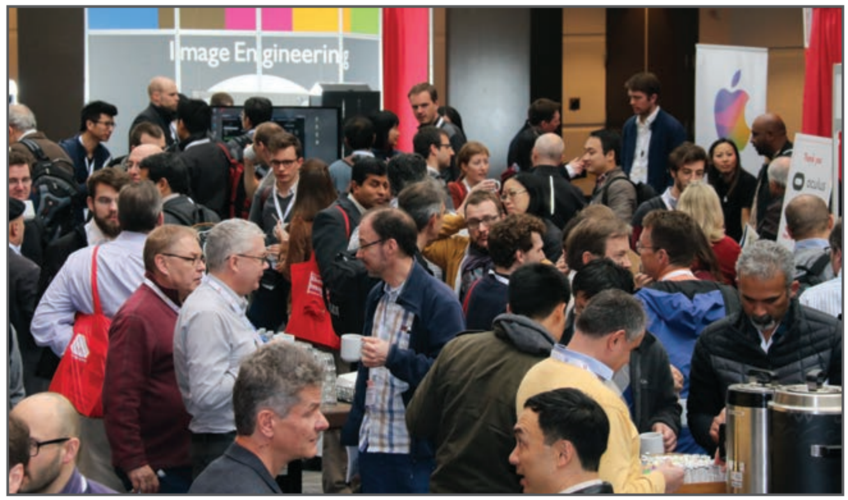

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