Using Reflectance Models for Surface Estimation

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Abstract

We suggest dichromatic reflection models adequate for describing surface-spectral reflectances of a variety of materials. First we describe the standard dichromatic reflection model for inhomogeneous dielectric materials. Next the generalized models are shown for describing the spectral reflectances of the materials for which the standard model is inadequate. The reflection characteristics are analyzed on a chromaticity diagram. We demonstrate practical use of the reflectance models in computer graphics and color constancy.

Introduction

Modeling reflection properties of object surfaces is crucial in color measurement and in color applications. In computer graphics, reflectance models have been used for producing realistic images[1]. Machine vision applications often require reflectance models for image analysis and object recognition[2-3]. A reflectance model is used for classifying wood-surface features in wood products[4]. Moreover, a dichromatic linear model is used in realizing color constancy[5-6]. In color reproduction, a reflectance model is used for simulating the process color printings[7].

The surface-spectral reflectance of an object varies with the geometries of illumination and viewing. This function also depends on the object's material composition. The reflectance is usually decomposed into two parts: interface (specular) reflectance and body (diffuse) reflectance. The interface reflection occurs at the interface between the object's surface and the air. Reflection from homogeneous materials like metals is due mostly to the interface reflection. For inhomogeneous materials like plastics, the second reflectance component dominates. Shafer proposed the dichromatic reflection model for inhomogeneous materials[2,8]. The model suggests that under all illumination and viewing geometries the spectral reflectance function is described as the weighted sum of two functions of the constant interface reflectance and the body reflectance. We call this model the standard dichromatic reflection model. Tominaga et al.[9] and Lee et al.[10] examined the adequacy of the standard dichromatic reflection model. This model is valid for artificial objects like plastics and paints, and for natural objects like fruits and leave, but the model is inadequate for some cloths. Tominaga extended the standard model to describe surface-spectral reflectances of a variety of materials[11].

This paper reviews dichromatic reflection models adequate for describing surface-spectral reflectances of a variety of materials. In the following, first we describe the standard dichromatic reflection model for inhomogeneous materials. Next the generalized models are shown for describing the spectral reflectances of the materials for which the standard model is inadequate. The reflection characteristics are also analyzed on a chromaticity diagram. Moreover we demonstrate applications of the reflectance models in computer graphics and color constancy.

Standard Dichromatic Reflection Model

Model

Figure 1 sketches the reflection process, which applies to nonconducting materials called inhomogeneous dielectric materials. The radiance $Y(\theta, \lambda)$ of light reflected from a surface is a function of the wavelength λ and the geometric parameters θ, including the illumination direction angle, the viewing angle, and the phase angle. The dichromatic reflection model describes the reflected light as the sum of interface and body reflections

$$Y(\theta, \lambda) = c_I(\theta)\, L_I(\lambda) + c_B(\theta)\, L_B(\lambda)\ , \qquad (1)$$

where the terms $L_I(\lambda)$ and $L_B(\lambda)$ are the spectral power distributions of the interface and body reflection components, respectively. These components are unchanged as the geometric angles vary. The weights $c_I(\theta)$ and $c_B(\theta)$ are the geometric scale factors.

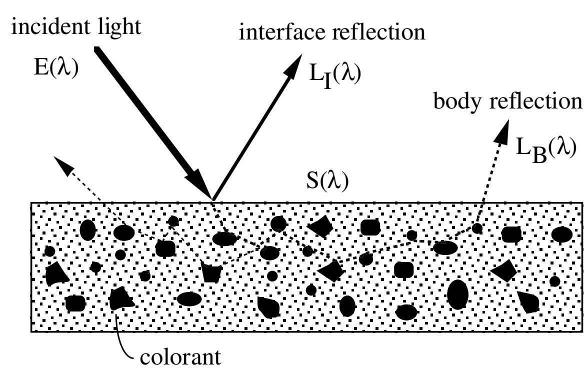

Figure 1. Reflection model in an inhomogeneous dielectric material

The body reflection occurs from light scattering among the pigment colorant layer. Therefore the spatial distributions of these two reflection components are quite different. Light scattered by the interface reflection is quite restricted in angle, and much as a mirror reflects incident rays. Conversely, the light scattered by the body reflection emerges equally in all directions.

We express the model in terms of surface-spectral reflectances. Let $S_I(\lambda)$ and $S_B(\lambda)$ be the surface-spectral reflectances for the two components, and let $E(\lambda)$ be the spectral power distribution of the incident light. Then by dividing the color signal $Y(\theta, \lambda)$ by $E(\lambda)$, the total spectral reflectance is described as

$$S(\theta, \lambda) = c_I(\theta)\, S_I(\lambda) + c_B(\theta)\, S_B(\lambda). \quad (2)$$

The standard model also incorporates an assumption called the Neutral Interface Reflection (NIR) (or Constant Interface Reflection) assumption, which is that the interface reflection component $S_I(\lambda)$ is constant and can be eliminated from Eq. (2):

$$S(\theta, \lambda) = c_I(\theta) + c_B(\theta)\, S_B(\lambda). \quad (3)$$

The NIR condition is approximately obeyed by many materials, such as plastics and oil- and water-based paints.

Test

The adequacy of the above standard model is examined based on Eq. (3) for the observed data of spectral reflectance. The check points are the two assumptions of two-dimensionality and constant interface reflectance.

(1) The total spectral reflectance $S(\theta, \lambda)$ is expressed as a linear combination of the two component vectors of surface reflectance $S_I(\lambda)$ and $S_B(\lambda)$. Since two vectors span a two-dimensional plane, all the observed reflectances should fall in this subspace. The first test is to examine whether all the observed curves of spectral reflectances are represented by only two basis vectors.

(2) The second assumption implies that one component for the observed reflectances should be a constant spectrum. The second test is to determine whether the constant spectral line is described by two basis vectors. For instance, let $\mathbf{u}_1$ and $\mathbf{u}_2$ be two basis vectors extracted from a set of the observed reflectance data, and let $\mathbf{i}$ be a vector of ones. Then we examine the validity of a linear combination $\mathbf{i} = a\,\mathbf{u}_1 + b\,\mathbf{u}_2$ with suitable weighting coefficients a and b.

Figure 2 shows a set of normalized curves of the surface-spectral reflectances measured from a blue plastic cup. Nearly straight lines correspond to the observations from a highlight area. The singular-value decomposition (SVD) was used for extracting principal components of a set of curves. The percent variance exceeded 0.999 for the first two principal components $\mathbf{u}_1$ and $\mathbf{u}_2$ only. The component vectors $\mathbf{u}_1$ and $\mathbf{u}_2$ were fit to the unit vector $\mathbf{i}$ using linear regression. A straight line with squares shows the fitting result. Thus the observed spectral reflectances satisfy the two conditions.

Example

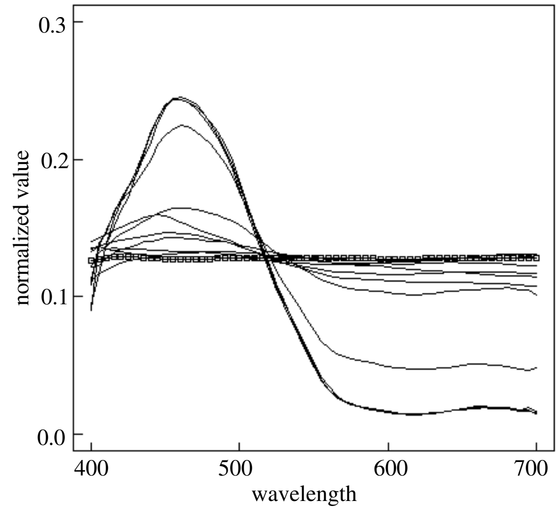

Figure 2. Normalized curves of the observed surface-spectral reflectances from a blue plastic cup

The standard dichromatic reflection model is valid for plastic, paints, ceramics, vinyls, tiles, fruits, leaves, and woods. The validity for some materials is also confirmed by Maristany et al.[4] and Lee et al[10]. However this model has difficulty in describing metals, some cloths and papers.

Extended Dichromatic Reflection Models

Model for Cloth and Paper (Type II)

The cloth of satin is not described by the first type of the standard dichromatic model[11]. Recently Usui and Imamura[7] have investigated the surface reflection of printed papers. Figure 3 shows the reflectances observed from a cyan solid color patch at various geometric angles. The incident angle of illumination was fixed, and the viewing angle was changed from the mirrored direction to 65°. Note that the spectral reflectance curve at the viewing angle of the mirrored direction is not constant with respect to wavelength. No constant specular reflectance is observed at any angle. These spectral reflectance curves satisfy the first condition of two-dimensionality, but the second condition is not satisfied. Rayon satin and polyester satin exhibit the similar properties.

Surface reflectance for such a material is dichromatic, but the specular reflections at the interface include no illuminant color. The surface-spectral reflectance function is described as the generalized dichromatic reflection model of Type II

$$S(\theta, \lambda) = c_I(\theta)\, S_I(\lambda) + c_B(\theta)\, S_B(\lambda), \quad (4)$$

where the interface reflectance component $S_I(\lambda)$ is not necessarily constant on wavelength.

Model for Metals (Type III)

Metals have quite different reflection properties from inhomogeneous materials, because they have only interface reflection. If the surface is shiny and stainless, body reflection of the reflected light is negligibly small. A sharp specular highlight is observed at only the viewing angle of the mirrored direction. This type of reflection obeys Fresnel's law, and the surface-spectral reflectance function depends on the incident angle of illumination.

Figure 4 shows the surface-spectral reflectances observed from a plate of brass. The normalized curves of the spectral reflectances are depicted in a three-dimensional view to show the influence of changing the incident angle. The viewing angle is always set to the mirrored direction to measure only specular reflection. As the incident angle approaches the grazing angle of 90°, the shape of the spectral reflectance tends to be whitened. The SVD shows the surface-spectral reflectances of the brass are described by two interface reflectance components, one of which is the constant spectral reflectance. Some other metals showed the same properties.

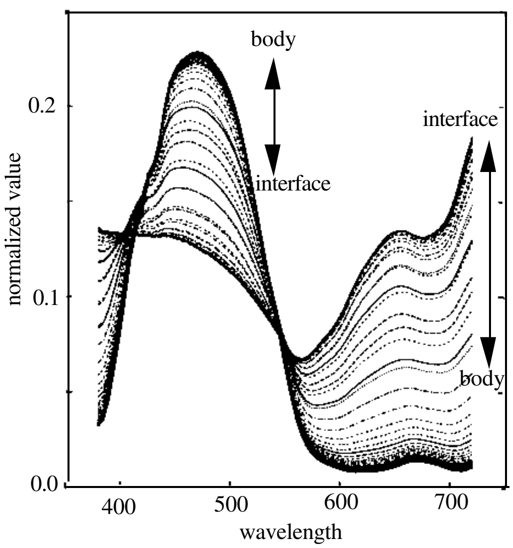

Figure 3. Normalized curves of the observed reflectances from a color patch with a cyan solid ink on an art paper[7].

The dichromatic reflection model of Type III is defined for approximating the surface-spectral reflectance function of a metal as

$$S(\theta, \lambda) = c_{I1}(\theta)\, S_I(\lambda) + c_{I2}(\theta)\ . \tag{5}$$

The right-hand side in Eq. (5) represents two interface reflection components. The first term corresponds to the specular reflection at the normal incidence. The second term is constant on wavelength, which corresponds to the grazing reflection at the horizontal incidence.

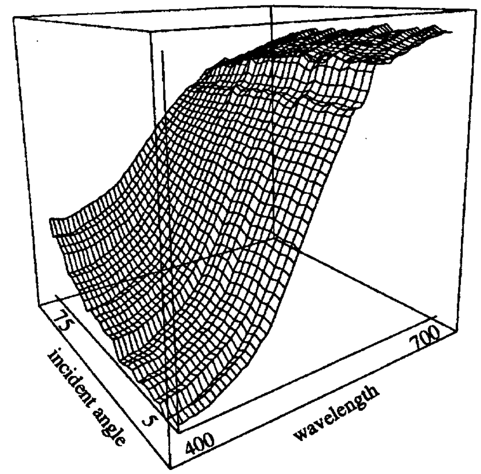

Figure 4. 3D view of the observed reflectances from a metal plate of brass

Chromaticity Analysis of Models

The reflection properties that are represented in a high dimensional vector space, hold true in a low dimensional color space. The chromaticity coordinates for a reflective object is a function of the geometric parameters θ. The coordinates (x(θ), y(θ)) on the xy chromaticity diagram are classified as follows:

Type I: The chromaticity coordinates of the standard dichromatic reflection model for an inhomogeneous material are described as

$$(x(\theta), y(\theta)) = c_I(\theta)\,(x_S, y_S) + c_B(\theta)\,(x_B, y_B), \tag{6}$$

where (x_S, y_S) and (x_B, y_B) represent, respectively, the fixed chromaticity coordinates of a light source and the body reflection component.

Type II: The chromaticity coordinates of the generalized dichromatic reflection model are described as

$$(x(\theta), y(\theta)) = c_I(\theta)\,(x_I, y_I) + c_B(\theta)\,(x_B, y_B), \tag{7}$$

where (x_I, y_I) represents the extreme coordinates for the interface reflection component.

Type III: The chromaticity coordinates of the dichromatic reflection model for a metal are described as

$$(x(\theta), y(\theta)) = c_{I1}(\theta)\,(x_I, y_I) + c_{I2}(\theta)\,(x_S, y_S), \tag{8}$$

where (x_I, y_I) and (x_S, y_S) represent, respectively, the interface reflection component at the normal incidence and the coordinates of a light source.

All the weighting coefficients of $c_I(\theta)$ and $c_B(\theta)$ take positive numbers that cannot exceed one. Therefore the chromaticity coordinates for any object color move on a straight line combining two extreme coordinates.

Figure 5 shows the chromaticity loci for three objects that obey Type I - III. These variations of chromaticity are obtained under a flood lamp for daylight. Open squares represent the chromaticity variation for the blue plastic cup of Type I. The loci with crosses and diamonds represent, respectively, the green cloth of rayon satin of Type II and the brass of Type III. A circle at the center indicates the chromaticity coordinates of the flood lamp. Note that the chromaticity coordinates of the plastic lie on a straight line passing through the light source chromaticity. The extension of the chromaticity coordinates for the brass also passes the light source. However, for the cloth the light source is not on the extension of the line.

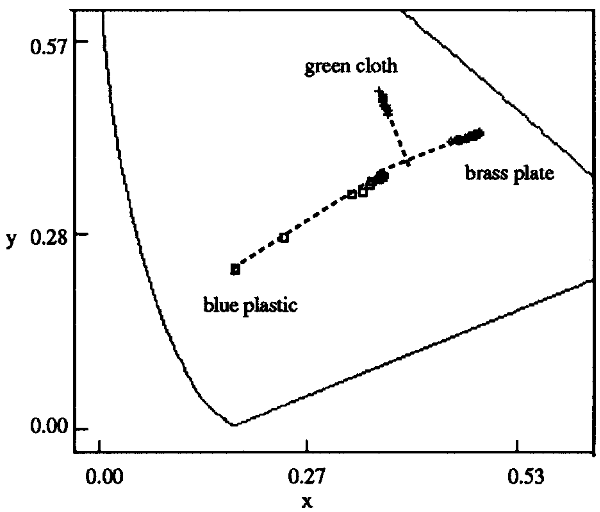

Figure 5. Chromaticity loci of three objects of blue plastic, green cloth, and brass plate

Applications of Reflectance Models

Computer Graphics

Reflectance models are sometimes called illumination models or shading models. The Phong model[12] is known as a practical illumination model that shades three-dimensional object surfaces with combination of specular and diffuse reflection components. Therefore this illumination model corresponds to Type I of the standard dichromatic reflection models. Suppose that ϕ is the angle of incidence of light, and ρ is the angle between the viewing direction and the mirrored direction of incident light. The interface reflection is the strongest at the mirrored direction, and as the angle ρ increases, it falls off sharply. This rapid falloff is approximated by $(\cos \rho)^n$, where the index n is a measure of surface roughness. A small value of n=1 provides a broad and gentle falloff, whereas higher values simulate a sharp and focused highlight. On the other hand, the body reflection is assumed to obey Lambert's law. The intensity is proportional to $(\cos \phi)$ of the angle.

The reflected light $Y(\theta, \lambda)$ can be described as

$$Y(\theta, \lambda) = (\cos \phi)\, S_B(\lambda)\, E(\lambda) + (\cos \rho)^n\, E(\lambda). \quad (9)$$

The above equation corresponds to Eq. (3). The second and third terms of the right-hand side represent the body and interface reflection components.

Color Constancy

Computational color constancy has two difficulties: estimation of both the illuminant and surface reflectance is nonlinear, and the problem is underdetermined. A commonly used approach to reduce the number of parameters is to describe spectral functions using finite-dimensional linear models[13]. We can identify specular highlights or glossy surfaces in the image. Because specularities of an inhomogeneous material reflect directly the illuminant, information about the illumination can be obtained from the sensor responses to glossy surfaces[9,14].

By assuming a fixed imaging geometry, we replace the geometric parameters θ with the location parameter x. The standard dichromatic reflection model suggests that the color signal at spatial location x is expressed in the form

$$Y(x, \lambda) = c_B(x)\, S_B(\lambda)\, E(\lambda) + c_I(x)\, E(\lambda) \quad (10)$$

The sensor outputs $\rho_k(x)$ at x are described as

$$\rho_k(x) = \int Y(x, \lambda)\, R_k(\lambda)\, d\lambda, \quad k=1, 2, ..., K, \quad (11)$$

where $R_k(\lambda)$ is the spectral sensitivity function for the k-th sensor. Substituting the finite-dimensional model expressions into (11) permits us to express the relationship between the sensor outputs and the scene parameters as

$$\bar{\rho}(x) = c_B(x)\, \bar{\Lambda}_\varepsilon\, \bar{\sigma} + c_I(x)\, \mathbf{H}\, \bar{\varepsilon}, \quad (12)$$

where $\bar{\rho}(x)$ is a column vector formed from K sensor responses. The matrices Λ_ε and **H** are the weight matrices, and the vectors $\bar{\sigma}$ and $\bar{\varepsilon}$ represent the weight vectors for surface reflectance and illuminant.

The problem of recovering the illuminant and surface-spectral reflectance functions is reduced to estimating the illuminant vector $\bar{\varepsilon}$ and the reflectance vector $\bar{\sigma}$ from the sensor output vectors $\bar{\rho}(x)$ of the image data for object surfaces. A method for solving the estimation in two steps is proposed[6].

Conclusion

We have suggested three types of dichromatic reflection models for surface-spectral reflectances of a variety of materials. The standard dichromatic reflection model (Type I) assumes that surface reflection consists of two additive components, the body reflection and the interface reflection that is independent of wavelength. This model is adequate for many surface materials of both natural objects and artificial ones. The generalized dichromatic reflection model of Type II allows the interface reflection component to be a function of wavelength. The reflectance functions of cloths and papers can be approximated with this generalized model A dichromatic reflection model (Type III) specialized for only the specular reflection is defined to approximate the observed spectral reflectances of a metal. The reflection characteristics can be analyzed on the xy chromaticity diagram. The dichromatic reflection models are applied to computer graphics and color constancy.

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