Spectral Reflectance-Based Modeling of Human Skin and Its Application

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Abstract

The analysis and model of human skin color is important in many research areas including computer graphics, medical imaging, and cosmetic development. The skin color is influenced with a variety of conditions, such as the mental condition of human's feelings, the physical condition of sunburn, and the medical condition of inflammation. The present paper describes an estimation method of surface-spectral reflectance based on a skin optics model and its application to image rendering of human skin. The human skin is modeled as two layers of turbid materials. The estimation algorithm is based on the Kubelka-Munk equations with unknown five parameters in the two-layers model. These parameters are the regular reflectance at skin surface and the four weights for spectral absorption of such different pigments as melanin, oxy-hemoglobin, deoxy-hemoglobin, and bilirubin. Moreover, the optical coefficients of spectral absorption and scattering for the two skin layers and the thickness values of these layers are used for the solution. Realistic three-dimensional images of a human hand are created using the estimated spectral reflectances and the Torrance-Sparrow reflection model. We execute some experiments for examining the estimation accuracy of skin spectral reflectances and evaluating the computer graphics images of a human hand created under the variety of conditions. The experimental results show the feasibility of the proposed method.

Introduction

The analysis and model of human skin color have attracted increasing attention in many fields including computer graphics, medical imaging, and cosmetic development. The skin color modeling is not easy because it is influenced with a variety of conditions, such as the mental condition of human's feelings, the physical condition of sunburn, and the medical condition of inflammation. There were several methods for modeling coloring formation within human skin. Most of the methods were based on the absorption analysis of main pigments such as melanin and oxy-hemoglobin by using the Lambert-Beer law.[1] However this law is available only for describing light transmission properties. Note that human skin color is caused by mostly based on strong back scattering within the skin layer and partly based on surface reflection at the interface between the skin surface and the air. Therefore the Lambert-Beer law is not always a tool enough to describe the optical analysis of human skin.

In a previous work,[2] we proposed an analysis method of human skin coloring using the Kubelka-Munk theory. The optical values of reflectance and transmittance within a layer consisting of turbid materials can be calculated using the Kubelka-Munk theory.[3] Therefore, the Kubelka-Munk theory is useful for modeling the skin surface reflectance because we can consider that the skin layers consist of turbid materials.

This paper describes an estimation method of surface-spectral reflectance based on a skin optics model and its application to image rendering of human skin. The human skin is modeled as two layers of turbid materials. The estimation algorithm is based on the Kubelka-Munk equations in the two-layers model. The estimation accuracy is examined using the real spectra-reflectance measured from human skin. Moreover we show an algorithm for image rendering of human skin under different conditions by using the estimated spectral reflectances.

Skin Optics Model

The spectral reflectance of skin is based on the influence by various pigments inside the skin tissue and scattering of the skin tissue. In order to determine a relation between skin spectral reflectance and these factors, we assume a simple optics model of skin as shown in Figure 1. The skin optics model has two layers including pigments. These layers are epidermis and dermis. The epidermis includes the pigments of melanin. The dermis includes the pigments of oxy-hemoglobin, deoxy-hemoglobin and bilirubin. The main pigments inside the skin are melanin and hemoglobin. The melanin makes the skin color darker. The hemoglobin is included in blood. The hemoglobin is distinguished into oxy-hemoglobin and deoxy-hemoglobin. Moreover, the skin includes bilirubin. This pigment makes the skin color yellowish.

The amounts of these four pigments have a strong influence on the color of the skin.

Under the dermis, there is hypodermis consisting of white fat Therefore, the reflectance of the hypodermis is set to 1. In this model, a part of incident light is reflected between the skin surface and the air. The remaining light penetrating the surface is absorbed and scattered in the layers. The light ray that reaches the hypodermis layer is reflected at interface between the two layers and return into the upper layer. It should be noted that the optical properties in each layer tissue, such as scattering, refracting, and absorption depend on wavelength.

Estimation of Skin Spectral Reflectance

The skin spectrum is estimated as a solution to the differential equation of the Kubelka-Munk theory for radiation transfer in the absorbing medium. The object color of human skin is created from three kinds of spectral data of surface-spectral reflectances, illuminant spectrum, and spectral responses of a display device used for computer graphics. The proposed algorithm can predict the precise spectral shape of skin surface at different parts of human body by appropriately determining various model parameters. We control the weighting coefficients of the four pigments of melanin, bilirubin, oxy-hemoglobin, and deoxy-hemoglobin. Moreover we can change the thickness of skin layers on each body part as variable parameters.

First, we defined a set of equations for estimating spectral skin reflectances using the Kubelka-Munk theory as Equation 1.

$$R(\lambda) = (1 - R_s(\lambda))(R_e(\lambda) + \frac{T_e(\lambda)^2 R_{dt}(\lambda)}{1 - R_e(\lambda)R_{dt}(\lambda)}) + R_s(\lambda) \qquad (1)$$

The functions of λ in this equation are described as

$$R_e(\lambda) = \frac{1}{a_e(\lambda) + b_e(\lambda)\coth C_e(\lambda)}$$

$$T_e(\lambda) = \frac{b_e}{a_e(\lambda)\sinh C_e(\lambda) + b_e(\lambda)\cosh C_e(\lambda)}$$

$$a_e(\lambda) = \frac{S_e(\lambda) + K_{et}(\lambda)}{S_e(\lambda)}$$

$$b_e(\lambda) = \sqrt{a_e(\lambda)^2 - 1}$$

$$C_e(\lambda) = D_e b_e(\lambda) S_e(\lambda)$$

$$K_{et}(\lambda) = K_e(\lambda) + w_m K_m(\lambda)$$

$$R_{dt}(\lambda) = R_d(\lambda) + \frac{T_d(\lambda)^2}{1 - R_d(\lambda)}$$

$$R_d(\lambda) = \frac{1}{a_d(\lambda) + b_d(\lambda)\coth C_d(\lambda)}$$

$$T_d(\lambda) = \frac{b_d(\lambda)}{a_d(\lambda)\sinh C_d(\lambda) + b_d(\lambda)\cosh C_d(\lambda)}$$

$$a_d(\lambda) = \frac{S_d(\lambda) + K_{dt}(\lambda)}{S_d(\lambda)}$$

$$b_d(\lambda) = \sqrt{a_d(\lambda)^2 - 1}$$

$$C_d(\lambda) = D_d b_d(\lambda) S_d(\lambda)$$

$$K_{dt}(\lambda) = K_d(\lambda) + w_h K_h(\lambda) + w_{dh} K_{dh}(\lambda) + w_b K_b(\lambda)$$

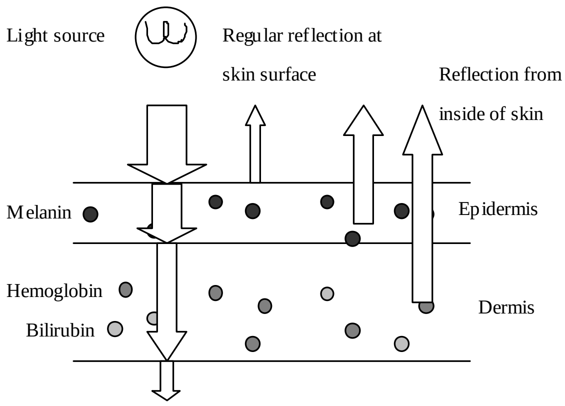

Figure 1. Skin optics model.

We note that the spectral reflectance $R(\lambda)$ is determined by the five parameters; the regular reflectance between the air and the skin surface $R_s(\lambda)$, weight w_m for the melanin absorption coefficient $K_m(\lambda)$, weight w_h for oxy-hemoglobin absorption coefficient $K_h(\lambda)$, weight w_{dh} for deoxy-hemoglobin absorption coefficient $K_{dh}(\lambda)$, and weight w_b for bilirubin absorption coefficient $K_b(\lambda)$. The thickness of epidermis D_e and dermis D_d are given, depending on the body part to be analyzed. The scattering coefficient of epidermis $S_e(\lambda)$, absorption coefficient of dermis $K_e(\lambda)$, scattering coefficient of dermis $S_d(\lambda)$ and absorption coefficient of dermis $K_d(\lambda)$ are constant. The numerical data for these scattering and absorption coefficients were taken by tracing the figures or numerical prediction on Refs. [4, 5]. Additionally, the decrease of reflectance in long wavelength range by lateral diffusion error is compensated in our method.

Second, the weights for pigment absorption and reflectance on the skin surface are determined so that the estimated reflectances can be fitted to the direct measurements in the sense of least squared error between the estimated reflectances and the measured ones. Then, the skin color spectra in various conditions are generated by controlling these five parameters.

Rendering of Human Skin

The image of human skin is created on a calibrated display device by using the estimated surface-spectral reflectances of human skin and a rendering algorithm. We use the Torrance-Sparrow model[6,7] as a light reflection model for 3D image rendering.

Figure 2 shows the reflection geometry in the Torrance-Sparrow model. In this model, a specular surface is assumed to be an isotropic collection of planar microscopic facets. In Figure 2, **N** represents the normal vector of a macroscopic surface, **L** is the incident light vector, **V** is the view vector and **Q** is the vector bisector of an **L** and **V** vector pair (i.e. the normal vector of a microfacet).

The spectral radiance distribution $Y(\lambda)$ from a reflective object surface is described as

$$Y(\lambda) = \alpha(\mathbf{N}\cdot\mathbf{L})R(\lambda)E(\lambda) + \beta\frac{D(\varphi,\gamma)F(\theta_Q,n)G(\mathbf{N},\mathbf{V},\mathbf{L})}{\mathbf{N}\cdot\mathbf{V}}E(\lambda) \quad (2)$$

where the first and second terms represent the body and specular reflection components, respectively. Parameters of α and β are their weighting coefficients. $R(\lambda)$ is the spectral reflectance calculated by the skin surface-spectral reflectance estimation algorithm using the Kubelka-Munk theory. $E(\lambda)$ is the spectral distribution of illumination. $D(\varphi,\gamma)$ is the distribution of the microfacet orientation as the function of angle φ and surface coarse parameter γ. $F(\theta_Q,n)$ is the Fresnel spectral reflectance of the microfacets with the parameter of the reflective index n. $G(\mathbf{N},\mathbf{V},\mathbf{L})$ is the geometrical attenuation factor representing the mutual masking and shadowing effects of the microfacets. These functions are defined as follows;

$$D(\varphi,\gamma) = \exp\{-\ln(2)\varphi^2/\gamma^2\} \quad (3)$$

$$F(\theta_Q,n) = \frac{1}{2}\frac{(g-\cos\theta_Q)^2}{(g+\cos\theta_Q)^2}\{1+\frac{[\cos\theta_Q\cdot(g+\cos\theta_Q)-1]^2}{[\cos\theta_Q\cdot(g-\cos\theta_Q)+1]^2}\},$$
$$g = \sqrt{n^2+\cos^2\theta_Q-1} \quad (4)$$

$$G(\mathbf{N},\mathbf{V},\mathbf{L}) = \min\{1, \frac{2\cos\varphi\cos\theta_r}{\cos\theta_Q}, \frac{2\cos\varphi\cos\theta_i}{\cos\theta_Q}\} \quad (5)$$

Then, we use the ray-tracing algorithm for creating realistic images of 3D objects in a natural scene.

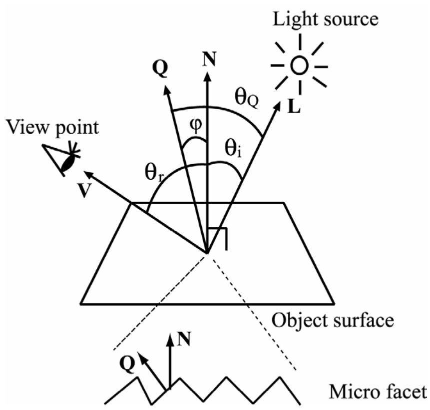

Figure 2. Reflection geometry in the Torrance-Sparrow model.

Moreover, the images are displayed on a calibrated color monitors. The tristimulus values [XYZ] of each pixel are the calculated by the equation.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \int Y(\lambda)\begin{bmatrix} \bar{x}(\lambda) \\ \bar{y}(\lambda) \\ \bar{z}(\lambda) \end{bmatrix} d\lambda \quad (6)$$

where $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ are the color matching functions. These XYZ values are transformed into to the RGB values of the monitor used.

Experiments

We executed some experiments for examining the estimation accuracy of skin spectral reflectances and evaluating the computer graphics images of a human hand created under the variety of conditions with different light sources.

In order to examine the accuracy of the estimated skin spectra, the estimated spectral reflectance was compared with the direct measurement results of human skin by using a spectro-radiometer PHOTO RESEARCH PR-650 and a standard reference white. Figure 3 shows comparison between the estimate and the direct measurement, that shows a good coincidence.

For the rendering, we measured the three-dimensional surface shape of a human hand. A laser range finder of Minolta Vivid 910 was used for measurement. We obtained five sets of the range data of different parts of the hand, and unified these into an entire hand shape. Then, realistic three-dimensional images of the human hand are created using the estimated surface-spectral reflectances and the rendering algorithm.

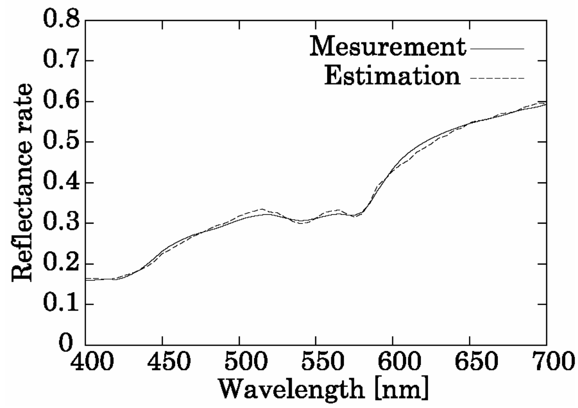

Figure 3. Estimation results for the skin spectral reflectance.

Figure 4 shows the image under different light sources of CIE D65 and A. The comparison with real observation shows good appearance of these skin colors.

Next, we created a set of hand images by changing the weighting coefficients of the pigments. The increase of melanin corresponds to sunburn. The increase of oxy-hemoglobin corresponds to inflammation. The increase of bilirubin corresponds to jaundice. Figure 5 shows the rendered images with the changed weights for melanin and hemoglobin. The images with large weights of the melanin (x4) show that the influence of hemoglobin is very weak. This means that the color of the lower layer of skin was hidden by the melanin pigments in the upper layer. Figure 6 shows the rendered images with the changed weights of bilirubin. In Figures 5-6, the light sources are CIE D65. These experimental results show good appearance of three-dimensional images of a human hand that are close to the real one. These images suggest that human skin color is controllable easily by changing weights for the component pigments.

Conclusions

The present paper has described an estimation method of surface-spectral reflectance based on a skin optics model and its application to image rendering of human skin. The human skin was modeled as two layers of turbid materials. The estimation algorithm was based on the Kubelka-Munk equations with unknown five parameters in the two-layers model. These parameters were the four weights for spectral absorption of such different pigments as melanin, oxy-hemoglobin, deoxy-hemoglobin, and bilirubin. Moreover, the optical coefficients of spectral absorption and scattering for the two skin layers and the thickness values of these layers were used for the solution. Realistic three-dimensional images of a human hand were created using the estimated spectral reflectances and the Torrance-Sparrow reflection model. The experimental results on the estimation accuracy and image rendering show the feasibility of the proposed method.

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Biography

Motonori Doi received his B.E. degree in Control Engineering from Osaka University in 1993. He received his M.E. and Ph.D. degrees in Information Science from Nara Institute of Science and Technology in 1995 and 1998 respectively. He was a research associate in Graduate School of Information Science at Nara Institute of Science and Technology during 1998-2001. Since 2001, he has been a lecturer in the Department of Telecommunication and Computer Networks at Osaka Electro-Communication University. His research interests include computational color vision, image recognition, and computer graphics. He is a member of IS&T and IEEE.

Figure 4. Hand images under different illuminations.

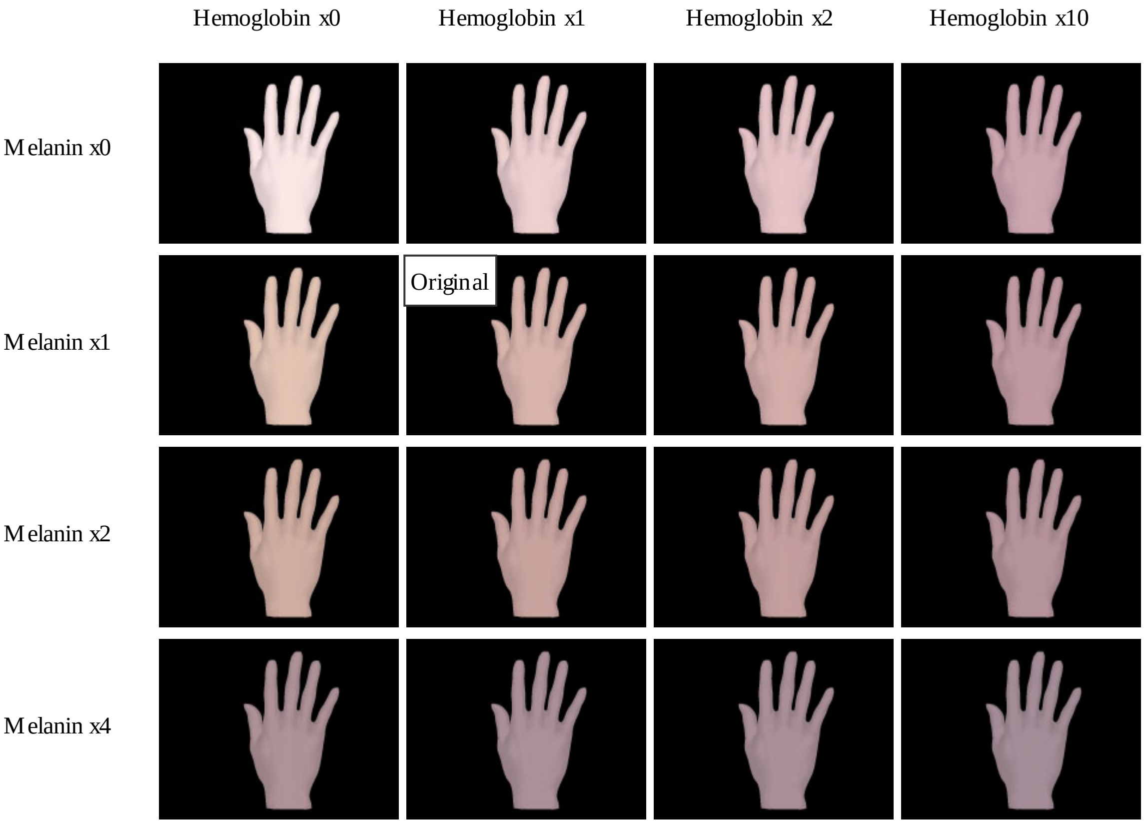

Figure 5. Hand images with the changed weights for melanin and hemoglobin under illumination of CIE 65.

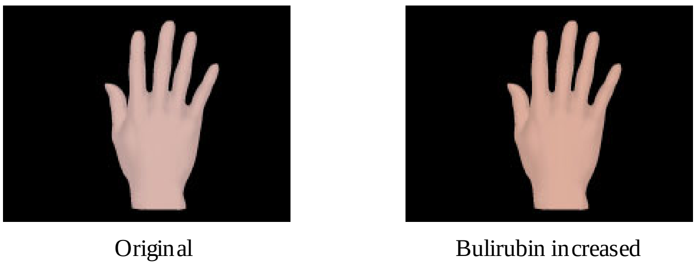

Figure 6. Hand images with the changed weights for bilirubin under illumination of CIE D65.