Spectral Reflectance Estimation of Human Skin and Its Application to Image Rendering

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Abstract

Proposed method

- Method for estimating the surface spectral reflectance of human skin based on an optics model
  - Human skin model → two layers for epidermis and dermis
  - Kubelka-Munk theory → estimation algorithm for two layers
  - Determination of parameters based on spectral reflectance
    - Parameters representing concentration of pigments
- Technique for rendering realistic skin image of a skin surface as a 3D object
  - Torrance-Sparrow model for rendering process
Introduction

- Depending on some histological variables
  - Melanin, Hemoglobin, Bilirubin and so on
- Skin coloration model
  - Lambert-Beer law → only the light absorption
  - Monte Carlo technique → random walks of photons
  - Cotton et al. → mathematical model of color formation
  - Kubelka-Munk theory
    - Formulated optical radiation transfer involving absorption and scattering in a turbid medium
    - Applying to two skin layers
      - Consisted of epidermis and dermis
      - Parameters based on spectral reflectance measurements
Application for rendering realistic skin images

- Decomposition of reflected light from human skin
  - Diffuse reflection component based on absorption and scattering in the skin layers
    - Description by the Lambertian model
  - Specular reflection component occurring at the interface between the outer skin layer and air
    - Description by Torrance-Sparrow

- Essential points of the proposed method
  - Not estimation of RGB color model for describing human skin
  - Using two layers model and Kubelka-Munk theory
  - 3D reflection model with the estimated surface reflectance and the rendering algorithm
Skin optics model

- Dichromatic reflection model

$$R(\lambda) = R_b(\lambda) + R_s(\lambda)$$

where

- $R_b(\lambda)$: diffuse reflection component
- $R_s(\lambda)$: specular reflection component

- Diffuse reflectance component from inside of the skin
  - Independent of the viewing angle
- Specular reflectance component occurring at the interface of skin and air
  - Observing within limited range of the viewing angle
Example of surface spectral reflectance

Fig. 1. Surface spectral reflectances of real skin. (a) Measurements at different skin surfaces of the human body. (b) Measurements with different lighting directions at a skin surface.
◆ Relationship between light and pigments in two skin layers
  
  - Epidermis
    - Melanin pigments
  
  - Dermis
    - Oxy-hemoglobin, Deoxy-hemoglobin
  
  - Hypodermis
    - Under the dermis
    - White fat
      - Reflectance of unity

Fig. 2. Skin optics model.
Kubelka-Munk theory

- Convenient method for calculating the optical values of reflectance and transmittance within a layer

Kubelka-Munk equations for a single layer

\[
\frac{dI}{dx} = -SI - KI + SJ
\]

\[-\frac{dJ}{dx} = -SJ - KJ + SI\]  \hspace{1cm} (2)

where

- S : coefficient of back-scattering

- K : coefficient of absorption
Reflectance $R$ and transmittance $T$

- Some mathematical approximations

\[ R = \frac{J_0}{I_0} = \frac{1}{a + b \coth(bSD)} \]

\[ T = \frac{I_D}{I_0} = \frac{1}{a \sinh(bSD) + b \coth(bSD)} \]  \hspace{1cm} (3)

where $D$ : thickness of layer

\[ a = \frac{S + K}{S}, \quad b = \sqrt{a^2 - 1} \]
Consideration for multiple reflections

- Because of the two layer model
- Reflections at the interface between the Layer1 and Layer2

Fig. 4. Different paths of the diffused light for the two layered model.
– Total reflectance

\[ R_{1,2} = R_1 + T_1^2 R_2 (1 + R_1 R_2 + \cdots) \]

\[ = R_1 + \frac{T_1^2 R_2}{1 - R_1 R_2} \]  

(4)

where \( R_1 \): reflectance of layer 1, \( R_2 \): reflectance of layer 2

\( T_1 \): transmittance of layer 1, \( T_2 \): transmittance of layer 2

\( R_{1,2} \): total reflectance
Estimation algorithms

◆ Application to skin optics model
  – Solution of the Kubelka-Munk equations
    • Estimation of surface spectral reflectance

\[
R_b(\lambda) = R_e(\lambda) + \frac{T_e(\lambda)^2 R_{dt}(\lambda)}{1 - R_e(\lambda) R_{dt}(\lambda)} \tag{5}
\]

where \( R_e(\lambda) \) : reflectance of epidermis, \( T_e(\lambda) \) : transmittance of epidermis
\( R_{dt}(\lambda) \) : reflectance of dermis, \( R_b(\lambda) \) : body reflectance

\[
R_{dt}(\lambda) = R_d(\lambda) + \frac{T_d(\lambda)^2 R}{1 - R_d(\lambda) R} \tag{6}
\]

where \( R_d(\lambda) \) : reflectance of dermis, \( T_d(\lambda) \) : transmittance of dermis
\( R = 1 \) : reflectance of hypodermis
◆ Spectral reflectances and transmittances of the respective layers

- Epidermis

\[
R_e(\lambda) = \frac{1}{a_e(\lambda) + b_e(\lambda) \coth(C_e(\lambda))} \\
T_e(\lambda) = \frac{b_e(\lambda)}{a_e(\lambda) \sinh(C_e(\lambda)) + b_e(\lambda) \coth(C_e(\lambda))} \\
a_e(\lambda) = \frac{S_e(\lambda) + K_{et}(\lambda)}{S_e(\lambda)} \\
b_e(\lambda) = \sqrt{a_e(\lambda)^2 - 1} \\
C_e(\lambda) = D_e(\lambda) b_e(\lambda) S_e(\lambda)
\]
– Dermis

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

\[ T_d(\lambda) = \frac{b_d(\lambda)}{a_d(\lambda) \sinh(C_d(\lambda)) + b_d(\lambda) \coth(C_d(\lambda))} \]

\[ a_d(\lambda) = \frac{S_d(\lambda) + K_{d_t}(\lambda)}{S_d(\lambda)} \]

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

\[ C_d(\lambda) = D_d(\lambda) b_d(\lambda) S_d(\lambda) \]

(8)
◆ Spectral absorption coefficients

- Scattering by the pigments $\rightarrow$ relatively small
  - Determination by the media
- Determination of absorption coefficient by the pigments

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

$$K_{dt}(\lambda) = w_h K_h(\lambda) + w_{dh} K_{dh}(\lambda)$$ (9)

where $K_m(\lambda)$: absorption coefficient of melanin
$K_h(\lambda)$: absorption coefficient of oxyhemoglobin
$K_{dh}(\lambda)$: absorption coefficient of deoxyhemoglobin
$w_m$, $w_h$, $w_{dh}$: weightings of pigment absorption coefficients
◆ Spectral curves of the absorption coefficients
  – Neglecting the light absorption by other medium

Fig. 5. Spectral absorption coefficients of pigments.
Spectral curves of the scattering coefficients
- Scattering in the epidermis

Fig. 6. Spectral scattering coefficients of skin.
Color image rendering

- Computer graphics images creating
  - Using the estimates obtained from the surface spectral reflectance

- Original Torrance-Sparrow model
  - Spectral distribution of radiance from skin surface

\[
Y(\lambda) = \alpha(N \cdot L)R_b(\lambda)E(\lambda) + \beta \frac{DF}{N \cdot V} E(\lambda)
\]  

(10)

where \( \alpha, \beta \) : weighting coefficients
\( N \) : normal vector, \( L \) : incident light vector, \( V \) : view vector
\( R_b(\lambda) \) : body spectral reflectance
\( E(\lambda) \) : spectral distribution of illumination
\( D \) : function of distribution of microfacet orientations, \( F \) : fresnel reflectance
Creating procedure color image of human

- Spectral power distribution of light reflected from the skin surface
- Computing over the visible range
- Sampling 5nm intervals
  - 61-dimensional vectors
- Determining pixel’s color in term of the tristimulus values CIE-XYZ
- Generating on a calibrated display device
- Creating a variety of images by controlling parameters
Experiments

- Experiments conditions
  - Under the light source of a halogen lamp
    - Angle of illumination → 45°
  - Measurements of the radiance with spectroradiometer
    - Visual field → 1°
    - Distance from the surfaces → 1.2m
    - Normal direction from the surfaces
  - Thickness data for the skin layers

Table 1. Thickness of Skin Layers at Different Parts of the Human Body in a Unit mm.

<table>
<thead>
<tr>
<th></th>
<th>Cheek</th>
<th>Back of hand</th>
<th>Outside of arm</th>
<th>Inside of arm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epidermis $D_e$ (mm)</td>
<td>0.027</td>
<td>0.035</td>
<td>0.036</td>
<td>0.041</td>
</tr>
<tr>
<td>Dermis $D_d$ (mm)</td>
<td>1.491</td>
<td>1.190</td>
<td>1.403</td>
<td>1.294</td>
</tr>
</tbody>
</table>
Reflectance estimation results

- Determination by spectral reflectance function $R_b(\lambda)$
  - Pigment absorption coefficients $w_m$, $w_h$, $w_{dh}$
- Fitted to the measured spectral reflectance with the least squared error

Table 2. Pigment Absorption Weights Estimated for Subject A.

<table>
<thead>
<tr>
<th>Location</th>
<th>Melanin $w_m$</th>
<th>Oxyhemoglobin $w_h$</th>
<th>Deoxyhemoglobin $w_{dh}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cheek</td>
<td>454</td>
<td>278</td>
<td>50</td>
</tr>
<tr>
<td>Back of hand</td>
<td>384</td>
<td>152</td>
<td>222</td>
</tr>
<tr>
<td>Outside of arm</td>
<td>276</td>
<td>152</td>
<td>170</td>
</tr>
<tr>
<td>Inside of arm</td>
<td>234</td>
<td>84</td>
<td>264</td>
</tr>
</tbody>
</table>
Fig. 7-1. Estimation results of the skin spectral reflectances for Subject A.
Fig. 7-2. Estimation results of the skin spectral reflectances for Subject A.

(c) Outside of arm  
(d) Inside of arm
### Table 3. Least Squared Errors between the Estimated Reflectances the Measured Ones

<table>
<thead>
<tr>
<th>Subject</th>
<th>Proposed</th>
<th>Back of hand</th>
<th>Outside of arm</th>
<th>Inside of arm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject A</td>
<td>0.075</td>
<td>0.030</td>
<td>0.063</td>
<td>0.047</td>
</tr>
<tr>
<td></td>
<td>0.352</td>
<td>0.117</td>
<td>0.204</td>
<td>0.161</td>
</tr>
<tr>
<td>Subject B</td>
<td>0.031</td>
<td>0.015</td>
<td>0.016</td>
<td>0.021</td>
</tr>
<tr>
<td></td>
<td>0.130</td>
<td>0.090</td>
<td>0.086</td>
<td>0.106</td>
</tr>
<tr>
<td>Subject C</td>
<td>0.097</td>
<td>0.058</td>
<td>0.069</td>
<td>0.049</td>
</tr>
<tr>
<td></td>
<td>0.263</td>
<td>0.163</td>
<td>0.248</td>
<td>0.260</td>
</tr>
<tr>
<td>Average</td>
<td>0.068</td>
<td>0.034</td>
<td>0.049</td>
<td>0.039</td>
</tr>
<tr>
<td></td>
<td>0.248</td>
<td>0.123</td>
<td>0.179</td>
<td>0.176</td>
</tr>
</tbody>
</table>
Image rendering results

- Requirement of optical data of the surface reflection and geometric data of the surface shape
  - Measurement of the 3D shape of the human hand by using laser range finder
- Measurement of specular reflection component
  - Determination of specular function in the Torrance-Sparrow model
  - Observation of surface reflectances by changing the illumination direction and by fixing the viewing direction to about 60°
  - Extraction of the specular term by using polarizing filter
  - Empirically determining specular term of Eq (10)
Images of a human hand rendered under the CIE standard illumination D65 and A

- Illumination and viewing directions → normal direction

Fig. 8. Hand images under two illuminants.
Different images of the same hand by changing the angles of illumination and viewing.

Fig. 9. Hand images by changing the angles of illumination and viewing; (a) (0/0); (b) (30/0); (c) (60/0); and (d) (60/60).
Different appearances of the human hand by changing the weighting coefficients

Fig. 10. Hand images with the different weights for melanin and hemoglobin.
Conclusions

◆ Estimation algorithm
  – Applying the Kubelka-Munk theory to the two layer model
  – Including pigment absorption coefficients
    • Determination based on spectral reflectance measurements

◆ Technique for rendering realistic images
  – Using Torrance-Sparrow model as a 3D light reflection model

◆ Future works
  – Rendering for complicated structures