Skin Color Modeling of Digital Photographic Images

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Huanzhao Zeng and M. Ronnier Luo

Presented by Euiwon Nam

School of Electrical Engineering and Computer Science
Kyungpook National Univ.
Abstract

Three elliptical skin color models

- Single ellipse model
  - Using single ellipse ignoring lightness dependency
  - Simple, efficient and adequate accuracy
- Lightness-dependent ellipse model
  - Adapted to different lightness levels to fit shape
  - Complex to train and low computation efficiency
  - High accuracy considerably
- Ellipsoid skin color model
  - Simple to train, high accuracy and efficient in computation
Introduction

- Color rendering
  - Important factor
    - judging Quality of color reproduction of digital images
  - Skin tone
    - Important role in preferred color reproduction

- Skin color detection models
  - Simple method
    - Definition of range of color in specific color space
    - Computationally efficient and low in hardware cost
  - Another method
    - Estimating skin color distribution from training data
    - Quantized and represented using lookup table without skin color model
Assumption
- Spread skin color around center of skin color
  - Variation in physical condition
    - Skin types, capturing conditions, etc.
  - Approximated distribution of skin color with Gaussian-like function

Single Gaussian model
- Formulated model by multivariate normal distribution function
- Intolerable error in estimation
  - Using Gaussian mixture model

Gaussian mixture model
- Mixing finite number of Gaussian function
- Complex to train and expensive term of computation
Methods of skin color detection

- Combined RGB bands and near-infrared bands
  - Demonstrated result
    - Improving robustness over pure RGB
    - Generalized for skin color detection of multispectral image
    - Unfitting for general consumer imaging
- Applied ellipse distribution function
  - Expressing skin colors for face detection
- Using ellipse for modeling skin color cluster
Elliptical skin boundary model

Elliptical boundary model

\[ \Phi(X) = [X - \Psi]^T \Lambda^{-1} [X - \Psi] \]

where \( X \) is occurrence counts of color, \( \Psi \) is center of ellipse, \( \Lambda \) is principal axes, and \( \Phi(X) < \rho \) is in ellipse as skin color.

\[ \Psi = \frac{1}{n} \sum_{i=1}^{n} X_i \]

\[ \Lambda = \frac{1}{N} \sum_{i=1}^{n} f_i (X_i - \mu)(X_i - \mu)^T \]

where \( N = \sum_{i=1}^{n} f_i \) is total number of occurrences, \( \mu = (1 / N) \sum_{i=1}^{n} f_i X_i \) is mean of color vectors and \( f(X_i) = f(i = 1, \ldots, n) \).
- Ellipse skin color modeling
  - Ignoring the lightness coordinate
  - Two-dimensional chrominance space \( X = \begin{pmatrix} x \\ y \end{pmatrix} \)
  - Represented \( \Lambda^{-1} \) in matrix form

\[
\Lambda^{-1} = \begin{pmatrix} \lambda_{00} & \lambda_{01} \\ \lambda_{10} & \lambda_{11} \end{pmatrix}
\]  \hspace{1cm} (4)

- Elliptical boundary between skin and nonskin colors

\[
\Phi(X) = \lambda_{00}(x - x_0)^2 + (\lambda_{01} + \lambda_{10})(x - x_0)(y - y_0) + \lambda_{11}(y - y_0)^2
\]  \hspace{1cm} (5a)

or

\[
\Phi(X) = u_0(x - x_0)^2 + u_1(x - x_0)(y - y_0) + u_2(y - y_0)^2
\]  \hspace{1cm} (5b)

- Angle \( \theta \) to rotate \( x - y \) coordinates to principal axes

\[
\theta = 0.5 \arctan \left( \frac{2\lambda_{01}}{-\lambda_{00} + \lambda_{11}} \right)
\]  \hspace{1cm} (6)
• Two parameters related to principal axes

\[
a = \lambda_{00} \cos^2(\theta) - \lambda_{01} \sin(2\theta) + \lambda_{11} \sin^2(\theta),
\]
\[
b = \lambda_{00} \sin^2(\theta) + \lambda_{01} \sin(2\theta) + \lambda_{11} \cos^2(\theta)
\]

(7)

• Relationship between \( \Lambda \) and \( a \), \( b \) and \( \theta \)

\[
\begin{pmatrix}
\lambda_{00} & \lambda_{01} \\
\lambda_{10} & \lambda_{11}
\end{pmatrix} =
\begin{pmatrix}
\frac{b-a}{2} \sin(2\theta) & a \sin^2(\theta) + b \cos^2(\theta) \\
\frac{b-a}{2} \sin(2\theta) & a \cos^2(\theta) + b \sin^2(\theta)
\end{pmatrix}
\]

(8)
- Ellipsoid skin color modeling
  - Three-dimensional color space $X$

\[
X = \begin{pmatrix} x \\ y \\ z \end{pmatrix},
\]

and represented $\Lambda^{-1}$ in matrix form

\[
\Lambda^{-1} = \begin{pmatrix} \lambda_{00} & \lambda_{01} & \lambda_{02} \\ \lambda_{10} & \lambda_{11} & \lambda_{12} \\ \lambda_{20} & \lambda_{21} & \lambda_{22} \end{pmatrix}
\]

- Reorganized $X(\Phi)$ in Eq. (1)

\[
\Phi(x, y, z) = \lambda_{00}(x - x_0)^2 + (\lambda_{01} + \lambda_{10})(x - x_0)(y - y_0) \\
+ (\lambda_{02} + \lambda_{20})(x - x_0)(z - z_0) + \lambda_{11}(y - y_0)^2 \\
+ (\lambda_{12} + \lambda_{21})(y - y_0)(z - z_0) + \lambda_{22}(z - z_0)^2
\]
• According to Eq. (3)

\[
\Lambda = \frac{1}{N} \sum_{i=1}^{n} f(x_i, y_i, z_i) \times \left( \begin{array}{ccc}
(x_i - x_0)^2 & (x_i - x_0)(y_i - y_0) & (x_i - x_0)(z_i - z_0) \\
(x_i - x_0)(y_i - y_0) & (y_i - y_0)^2 & (y_i - y_0)(z_i - z_0) \\
(x_i - x_0)(z_i - z_0) & (y_i - y_0)(z_i - z_0) & (z_i - z_0)^2
\end{array} \right)
\]

(11)

• Rewriting ellipsoid function (10)

\[
\Phi(x, y, z) = u_0 (x - x_0)^2 + u_1 (x - x_0)(y - y_0) + u_2 (y - y_0)^2 + u_3 (x - x_0)(z - z_0) + u_4 (y - y_0)(z - z_0) + u_5 (z - z_0)^2
\]

(12)

where \( u_0 = \lambda_{00}, \ u_1 = \lambda_{01} + \lambda_{10}, \ u_2 = \lambda_{11}, \ u_3 = \lambda_{02} + \lambda_{20}, \ u_4 = \lambda_{12} + \lambda_{21}, \ \text{and} \ u_5 = \lambda_{22} \)

• Rewritten Eq. (1)

\[
\Phi(X') = X'^T M_r^T \Lambda^{-1} M_r X'
\]

(13)

where 3X3 diagonal matrix \( M = M_r^T \Lambda^{-1} M_r \), \( \Phi(X') = X'^T M X' \) for rotating \( X' \) to \( X' \)
Construction an image database to train skin models

- Aim of skin color detection
  - Capturing images using different digital cameras
    - Using various conditions for training skin color models
  - Development of skin color models
    - Preferred skin color enhancement in digital images
  - Using Halloween database
    - 2500 digital images
      » Caucasian, Asian, and African facial tones
  - Using Royal Photographic Society database
    - 626 photographic images including indoor and outdoor images
      » Different ethnic types
      » Sampling uniform resolution of 1200X1800
– Using SkinSelector tool

**Fig. 1.** A tool to label skin colors.
- Segmentation method in the tool
  - Used to construct skin database
    - Growing similar colors to other objects
    - Labeling skins of different persons
      » different color centers on image
      » Adding occurrences of skin colors to $256^3$ RGB LUT
        » Convenience for counting 8bit RGB images
    - Setting parameters
  - Removal noisy pixels and inaccurate skin pixels
    - Excluding lowest occurrences pixels
      » Removal 10% least occurrence pixels
  - Reason of Insignificant user selection bias
    - Removal small percentage of labeled skin pixels below threshold
    - Collecting large number of skin pixels
Results of the skin color modeling
- Halloween database in CIELAB color space

Fig. 2. 3D gamut of all labeled skin pixels of Halloween database.
Lightness-independent ellipse model (single)
  • Ignoring each color’s lightness value
    – 95% of labeled skin colors of Halloween database

Fig. 3. The trained skin color ellipse in CIELAB $a^*-b^*$ coordinates.
- Lightness-dependent ellipse model (multi)
  - Centers, sizes, and orientations of 2D chrominance ellipses
    - 90% of skin colors within bucket

Fig. 4. Skin color ellipses in different constant-lightness buckets.
• Skin color center
  - Plotted Chroma of each ellipse center
  - Plotted Hue angles of ellipse centers

Fitting equation of curve
\[ C^* = -0.00004L^3 - 0.000013L^2 + 0.4226L^* + 16.848 \]

Hue angle of 47.35° averaged

**Fig. 5.** Chroma of the skin color centers.

**Fig. 6.** Hue angles (deg) of the skin centers.
• Orientations and sizes of ellipses
  - Plotted orientations($\theta$) of the trained major axes

Equation of orientations $\theta = 49 - 0.26L^*$

Fig. 7. Orientations of the major axes.
- Plotted length of trained semimajor and semiminor axis in each $L^*$ level
- Plotted fitting curve of length of trained semimajor and semiminor axis

Length of semiminor axis

$$b = 65.452 \left( \frac{L^*}{100} \right)^3 + 67.657 \left( \frac{L^*}{100} \right)^2$$

$$- 5.2756 \left( \frac{L}{100} \right) + 5.5431$$

Equation of semimajor axes $a = 0.000004L^*^3$

$$- 0.0127L^*^2 + 1.3331L^* - 5.0139$$

Fig. 8. Semimajor axes of skin ellipses.

Fig. 9. Semiminor axes of skin ellipses.
• An alternative formulation of the ellipse model
  - Based on Eq. (5b)
    \[ u_0(x - x_0)^2 + u_1(x - x_0)(y - y_0) + u_2(y - y_0)^2 \leq \rho \]
  - Set to 1 for \( \rho \) to train \( u_0, u_1, \) and \( u_2 \)
  - 90% of skin colors in database

\[
\begin{align*}
  u_0 &= 0.005 + 0.006 \left( \frac{L^* - 60}{30} \right)^2, \\
  u_1 &= 0.0218 \left( \frac{L^*}{100} \right)^3 - 0.0678 \left( \frac{L^*}{100} \right)^2 + 0.0684 \left( \frac{L^*}{100} \right) - 0.0258, \\
  u_2 &= \left( \frac{L^*}{100} \right)^3 - 0.0055 \left( \frac{L^*}{100} \right)^2 - 0.0184 \left( \frac{L^*}{100} \right) + 0.0108
\end{align*}
\]

**Fig. 10.** \( u_0, u_1, \) and \( u_2 \) of skin color ellipses.
Ellipsoid skin color model

- Modeling ellipsoid to fit skin color boundary
  - Simplifying Modeling and training process
  - Ellipsoid center: (59, 19, 20)
  - Principal axis parameters: \([a, a/b, a/c]=[38, 1.4, 2.5]\)

Matrix \(\Lambda = \begin{bmatrix} 1404.6 & -110.2 & -125.8 \\ -110.2 & 349.1 & 223.7 \\ -125.8 & 223.7 & 656.0 \end{bmatrix}\)

Fig. 11. An ellipsoid to cover 90% of skin colors.
- Constant-lightness slices of ellipsoid covering 90% of skin colors

Fig. 12. Constant-lightness slices of the ellipsoid covering 90% of skin colors.
– Skin color detection accuracy
  • Evaluation of skin color detection accuracy of skin model
    – Using true and false positive detection rates
    – Plotted relationship between true positive and false positive
      » Receiver operating characteristic curve
  • Using database of 106 image instead of Halloween image
    – Analyzing skin color detection accuracy of three elliptical models
    – Different skin types and different capturing conditions

Fig. 13. ROC curves of three skin elliptical models.

Fig. 14. ROC curves of three elliptical skin models tested on dark skin images.
Discussion

- Three important factors for results of elliptical modeling
  - Skin types, image database, and color space
- Skin color modeling of different skin types
  - Royal photographic society database
    - 285 Asian images, 28 African images, 302 Caucasian images

Table 1. Comparison of ellipse coefficients for three different skin types

<table>
<thead>
<tr>
<th>Skin center</th>
<th>a</th>
<th>a/b</th>
<th>θ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caucasian</td>
<td>(17, 16)</td>
<td>29</td>
<td>1.7</td>
</tr>
<tr>
<td>Asian</td>
<td>(18, 21)</td>
<td>31</td>
<td>1.9</td>
</tr>
<tr>
<td>African</td>
<td>(21, 29)</td>
<td>35</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Fig. 15. Caucasian, oriental, and African skin ellipses in CIELAB $a^*-b^*$ coordinates.
• Comparison of Caucasian, Asian, and African skin color ellipsoids
  - 95% of skin colors in CIELAB color space

Fig. 16. Caucasian (color), oriental (black), and African (green) skin color ellipsoids in CIELAB color space (left) and their projection in $a^*-b^*$ coordinates (right).
Training with different image databases

- Results of different image databases
- Using Halloween and Royal photographic society database

**Fig. 17.** Skin color ellipses trained using two different databases.
– Skin color modeling with different color spaces
  • Aimed preferred color enhancement of digital images
    − Chosen CIELAB color space for workflow
    − Uniform color space CAM02-UCS
    − Comparing skin color modeling in CIELAB and CAM02-UCS

Fig. 18. ROC curves of the ellipsoid modeling in CIELAB and CAM02-UCS color spaces.
Conclusions

- Three elliptical models
  - Single ellipse model
    - Simple in training and efficient in computation
      - Covering high Chroma skin colors in midtone region
  - Lightness-dependent ellipse model
    - Lightness-dependent to adjust skin color ellipses
      - Fitting skin colors in different lightness levels
  - Ellipsoid skin color model
    - Representing compromise
      - Among complexity, computation efficiency, and detection accuracy
Results of skin color ellipses

- Trained with two different databases
- Separate training of Caucasian, Asian, and African skin color
  - Similar skin type of Caucasian with Asian
  - More Yellowish and chromatic for Asian than Caucasian
  - Dark African skin color region
    - Chromatic in Center of African skin color
- Results of skin color ellipsoids in CIELAB and CAM02-UCS
  - More uniform in skin color area and accurate in CAM02-UCS