Preferred Skin Color Enhancement of Digital Photographic Images

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Abstract

Reproducing skin colors pleasingly is essential for photographic color reproduction. Moving skin colors toward their preferred skin color center improves the skin color preference. Two main factors to successfully enhance skin colors are: a method to detect skin colors effectively and a method to morph skin colors toward a preferred skin color region properly. This paper starts with introducing a method to enhance skin colors using a static skin color detection model. It significantly improves the color preference for skin colors that are not far off from regular skin tones. To enhance a greater range of skin tones effectively, another method that automatically adapts the skin color detection model to the skin tone of each individual image is proposed. It not only enhances skin colors effectively, but also adjusts the overall image colors to produce more accurate white balance on the image.

Keywords: Skin Color Enhancement, Image Enhancement, Skin Tone, Preferred Color, Memory Color, Skin Color Model.

1. INTRODUCTION

Preferred color rendering is essential for enhancing the perceived image quality of photographic images. Previous research efforts for preferred color reproduction may be traced back to more than half a century ago. It has been reported that people prefer to see an image in which the color appearance of a familiar object agrees with its memory color rather than with the actual colorimetric content of the original scene, and certain memory colors such as skin, grass, and sky are preferred to be produced with slightly different hues and with greater purity [1]-[3]. Since the color sensations evoked by a reproduction are compared with a mental recollection of the color sensations previously experienced when looking at objects similar to the ones being appraised, observers are able to rate the quality of an image without the original object presented [4]-[6].

Reproducing skin tones pleasingly is critical in preferred color reproduction. Moving skin colors toward their preferred skin color center improves the color preference. Braun [7] proposed a method for preferred skin color enhancement by squeezing the hue angles of skin colors toward a preferred point over a limited chroma range while keeping chroma unchanged. The overall color preference is improved even if skin colors of non-skin objects are modified. Because the chroma is not adjusted, it does not enhance skin tones that are within the preferred hue range but are too pale or too chromatic. Kim et al. [8] applied adaptive affine transform in Yu’v’ to enhance skin color reproduction of video streams. Skin colors are defined within an ellipse, and preferred skin colors are set in a smaller ellipse within the skin color ellipse. An input skin color is converted into the preferred skin color by a linear transformation. Post-processing is required to fix contouring in the skin color boundary. Park et al. [9] developed a method to optimize memory colors in YCbCr color space for the color reproduction on digital TV. The skin color distribution is modeled with a bivariate Gaussian probability density function. The Mahalanobis distance is used to determine the skin boundary. A smaller region within the center of the skin color ellipse is determined as the preferred skin color region. Skin colors outside the small central color region are moved toward this color region. Because the preferred skin color center is usually different from the skin color distribution center, the skin color enhancement is not optimal. Xu and Pan [10] and Pan and Daly [11] applied a sigma filter to decompose an image into a primary image and a residue image. The primary image generated from a sigma filter contains limited details but maintains sharp edges, and the residue image contains details/noises/artifacts but relatively few sharp edges. To avoid amplifying noise and artifacts, the residue image that contains noise and artifacts are not modified. Skin colors in the primary image are adjusted and mapped from sRGB to an LCD display color space.

In all of these approaches, skin color models to detect skin pixels or face pixels are generated from statistical analysis of a larger number of images, and skin detection models are not adapted to different images in which skin tones may be shifted far away from the statistical skin center. If the skin color distribution of an image is far off from the general statistical skin color distribution (e.g. skin colors are very pale or over-saturated, or skin colors are shifted to very pinkish or very yellowish direction), skin colors may not be detected or probabilities of skin colors may be very low. Thus skin colors may not be adjusted or the adjustment may be insufficient. Increasing the skin color range of a skin color model enables the model to capture more skin tones, but the false detection rate is increased as well. Face feature detections may be applied to resolve the problem [12].

The skin color modeling and skin color preference were comprehensively studied by the authors for preferred skin color reproduction [13]. A skin color model that is trained with a large number of images is applied to detect skin colors. The detected skin colors are morphed toward a preferred skin color center. Although the method improves the skin color preference, it is not effective in enhancing low quality images in which skin tones are very different from normal skin tones. To enhance skin colors more effectively, an image-dependent skin color model is developed to detect skin colors. The method results in more effective and more accurate skin color detection and leads to more effective skin color enhancement.

The rest of the paper is organized as below: the skin color modeling is briefly introduced in the following section; preferred skin color regions for skin color enhancement is briefly described in Section 3; a skin color enhancement method based on a static skin color model is presented in Section 4; skin color enhancement using image-dependent skin color modeling is presented in Section 5; a new skin color morphing method is presented in Section 6; Section 7 briefly describes experimental result; and the last section is the conclusion.

2. SKIN COLOR MODELING

The cluster of skin colors may be approximated with an elliptical shape [14]-[15]. An elliptical model is applied for baseline skin color detection. Let X1, …, Xn be the distinctive colors of a training data set and f(Xi) (i=1, …, n) be the occurrence counts of a color, Xi. An elliptical boundary model is defined as

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

where Ψ is the elliptical center, and Λ is the covariance matrix.

Given a threshold ρ and an input color X of a pixel, X is classified as a skin color if $\Phi(X) < \rho$ and as a non-skin color otherwise. The threshold ρ trades off correct detections by false detections. As ρ increases, the correct detection rate increases, but the false detection rate increases as well. $\Phi(X) = \rho$ defines an elliptical boundary between skin and non-skin colors. The elliptical center is given by ψ and the principal axes are determined by Λ.

A 3-D modeling of skin colors using an ellipsoid function can be written as:

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

A 2-D modeling of skin colors in chrominance space (x, y) ignoring the lightness axis is expressed with an ellipse function:

$$\Phi(x,y) = u_0(x-x_0)^2 + u_1(x-x_0)(y-y_0) + u_2(y-y_0)^2 \quad (3)$$

To improve the accuracy of 2-D modeling, the ellipse model may be trained on a serial of lightness buckets to formulate a lightness-dependent ellipse model.

3. PREFERRED SKIN COLOR REGION

It is generally agreed that preferred skin colors are different from actual skin colors and preferred skin colors are within a smaller region of skin colors. While some reports conclude that preferred skin colors are not significantly different among observers with different culture backgrounds, others indicate that they are statistically different for preferred color reproduction [16]-[21]. In order to have a better understanding of skin color preference of digital photographic images, skin color preferences of different ethnic skin tones judged by mixed ethnic groups and by each of unique culture backgrounds were studied by the authors [22]-[23]. The psychophysical experimental results of the skin tone preference by ethnicity (the preferred African skin tone judged by Africans, the preferred Caucasian skin tone judged by Caucasians, and the preferred Oriental skin tone judged by Orientals) in CIELAB a*-b* coordinates with the D50 adapted white are shown in Figure 1. The orange, black, and green ellipses are the preferred skin color regions of Caucasian, African, and Oriental culture backgrounds, respectively. A large dot at each ellipse center is the preferred skin color center of the corresponding ethnical group. The blue ellipse is the overall preferred skin color region. The preferred hue angle in CIELAB adapted to the D50 white point is about 49^o in all three groups.

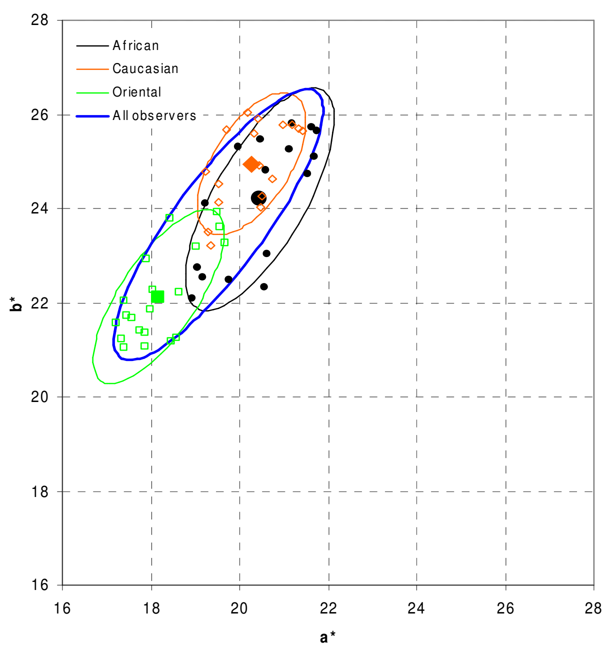


FIGURE 1: Preferred skin colors of African, Caucasian, and Oriental judged by African, Caucasian, and Oriental observers, respectively.

Statistical analysis of skin color preference among African, Caucasian and Oriental culture backgrounds reveals that all three preferred skin color centers are significantly different from each other in 5% significance level; Orientals prefer slightly less chromatic skin colors than Africans and Caucasians; the inter-observer variation of the skin color preference of Africans is larger than that of Caucasians and that of Orientals; Caucasians may prefer slightly more yellowish skin tones than Africans. In cross-culture preference, Orientals prefer slight less chromatic skin colors than Caucasians and Africans, and Africans prefer more chromatic Caucasian and Oriental skin colors than Caucasians and Orientals. The result of preferred skin colors are to be used for skin color enhancement presented in following sections.

4. PREFERRED SKIN COLOR ENHANCEMENT ALGORITHM

The ellipsoid skin color model is chosen for implementing skin color enhancement for the tradeoff of its efficiency in computation and its accuracy in skin color detection [15]. Equation (2) is used to calculate Mahalanobis distance of a point (x, y, z) to the ellipsoid center (x0, y0, z0). $\Phi(x, y, z) < \rho$ defines the region of skin tones.

Figure 2 is a sketch diagram for skin color adjustment (drawn in 2-D space for simplification). The large ellipse represents the skin color region, A is the center of the region (the statistical skin color center), and B is the preferred skin color center (PSCC). Skin colors (in the large ellipse) are morphed toward the preferred skin color region (in the smaller ellipse) for skin color enhancement.

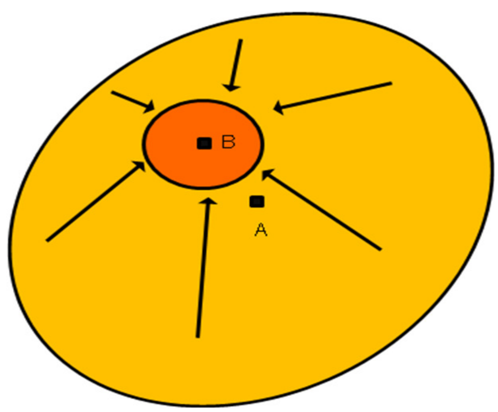


FIGURE 2: A Sketch Diagram for Skin Color Enhancement.

Figure 3 is a flowchart for skin colors adjustment. P is an input color and P' is its corresponding output color. The source color of each pixel is converted to CIELAB (or another luminance-chrominance color space, such as YCbCr). A skin color detection model is applied to compute Mahalanobis distance, $\Phi(L, a, b)$. If $\Phi > \rho$, the color is not a skin color and no color adjustment is performed for the pixel. Otherwise, the color is a skin color, and a weight, w, is computed to adjust L*a*b*.

At the ellipsoid center, $\Phi(L, a, b) = 0$ and w is maximized; on the ellipsoid boundary, $\Phi(L, a, b) = \rho$ and w = 0. A weight for color adjustment may be calculated by

$$w = 1 - \Phi(L, a, b) / \rho. \quad (4)$$

Other linear or nonlinear formulae may be applied to calculate the weight. A basic concept is that the smaller Φ, the smaller w. Based on the desired strength for color enhancement, w may be further adjusted, i.e.,

$$w = w_0(1 - \Phi(L, a, b) / \rho), \quad (5)$$

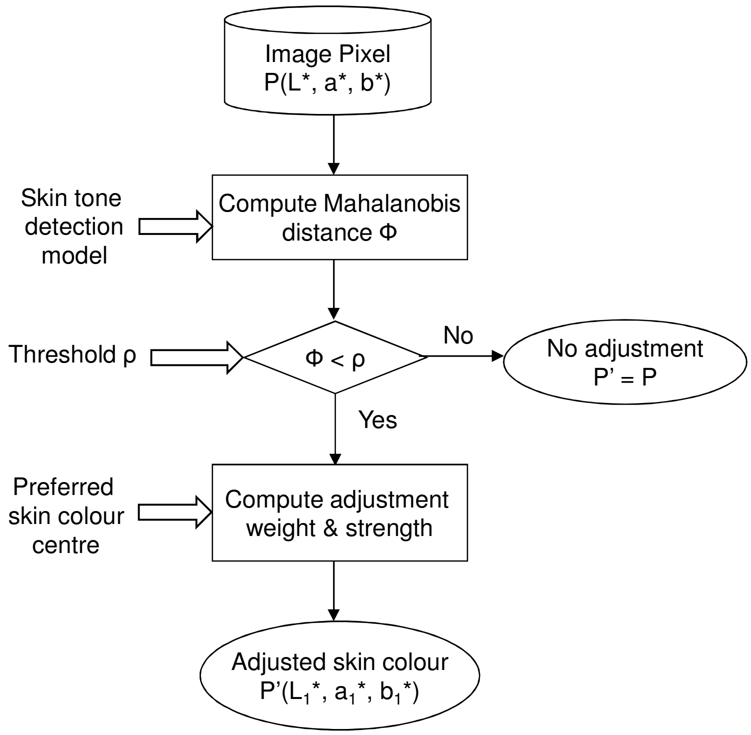


FIGURE 3: A Flow Chart for Skin Color Adjustment.

where w_0 is a strength factor for color adjustment. Without adjusting L*, a*, and b* are adjusted by equations:

$$\begin{aligned} a_{new} &= a + w \cdot (a_{center} - a) \\ b_{new} &= b + w \cdot (b_{center} - b) \end{aligned} \qquad (6)$$

where (a_{center}, b_{center}) is PSCC; (a, b) is a*b* of an original skin color, and (a_{new}, b_{new}) is a*b* of the corresponding enhanced skin color. The PSCC is an ellipse center shown in Figure 1. For preferred color reproduction of mixed culture backgrounds, a PSCC corresponding to mixed culture backgrounds is chosen.

The skin color enhancement presented by Park et al. [8] takes the statistical skin color center (the center of the skin color model) as the target color center for skin color adjustment. Because the objective is to morph skin colors toward a PSCC, which is different from the skin color center of the skin color model, (a_{center}, b_{center}) in Eq. (6) should be a PSCC.

Lightness dependency and highlight contrast are optimized with following implementations.

4.1. Lightness-Dependent Skin Color Enhancement

PSCCs are slightly different among different lightness. To enable different PSCCs for different lightness, three PSCCs (light, medium, and dark PSCCs) are determined. A PSCC at a given lightness is interpolated from these three PSCCs. In Figure 4, the large ellipsoid illustrates the skin color boundary; each of the three PSCCs is at the center of a preferred skin color region on a constant-lightness ellipse plane; and the red dash curve represents PSCCs at different lightness. A PSCC, (a_{center}, b_{center}), becomes a function of lightness. In each lightness level, skin colors are morphed toward its PSCC.

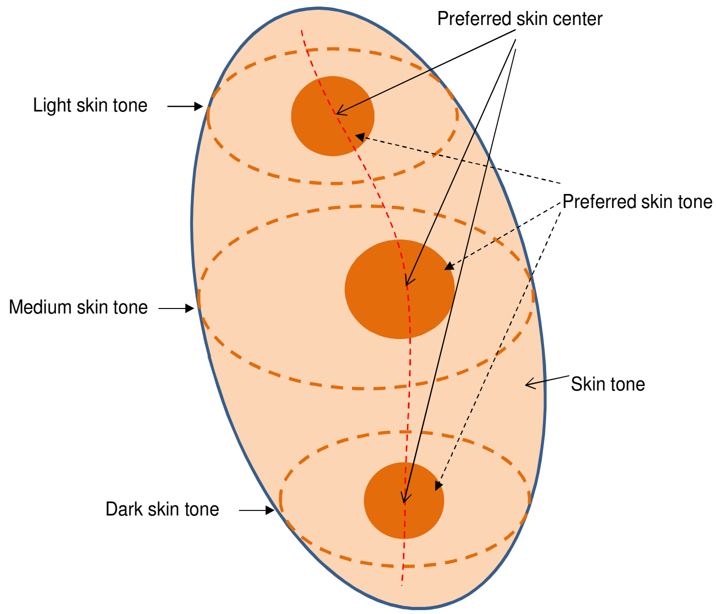


FIGURE 4: A Sketch Diagram for Skin Color Adjustment Using Three PSCCs.

4.2. Highlight Skin Color Enhancement

The perceptual contrast in the highlight skin color region may decrease after the skin color adjustment. This is due to the fact that low chroma skin colors in the highlight region may be moved toward more chromatic colors. If the adjusted colors are out of the device gamut or the encoding gamut, they are clipped to the gamut boundary. These effects result in a slight reduction in visual contrast. One approach to fix the problem is to reduce the amount of adjustment for highlight colors. The adjustment strength, w, in Eq. (6) is modulated with a factor, w_L, for lightness-dependent adjustment as shown in Eq. (7).

$$a_{new} = a + w \cdot w_{L} \cdot (a_{center} - a)$$
$$b_{new} = b + w \cdot w_{L} \cdot (b_{center} - b) \qquad (7)$$

w_L is 1 when L* is smaller than or equal to a threshold (it is set to 65 in our experiment). It gradually decreases as L* increases, and it becomes 0 at L*=100.

Another approach to fix the highlight problem is to preserve chroma and to only adjust hue of highlight skin colors. After applying Eq. (7) to calculate an adjusted skin color, its hue angle and chroma (h1 and C1) are computed. Chroma of the original color, C0, is computed as well. In order to have a smooth transition from medium to highlight skin tones, chroma adjustment is slowly adapted from mid-tone to highlight by Eq. (8).

$$C = C_0 + w_L \cdot (C_1 - C_0) \qquad (8)$$

Since the aim is to adjust the original hue toward a preferred hue and not to change chroma for highlight skin colors, chroma, C, and hue angle, h1, are used to compute a final skin color (a_{new}, b_{new}).

5. APPLYING FACE DETECTION INFORMATION FOR PREFERRED SKIN ENHANCEMENT

There are a few limitations in the skin color enhancement algorithm described in the earlier section. Because a static elliptical skin color model is the statistical modeling of a large set of images, it is suitable for detecting skin colors that are not distributed too far away from a statistically distributed skin color region. If skin color distribution of an image is too much biased toward a certain direction, skin colors may be out of the edge of the skin color boundary or the probability of the skin color may be very low. Thus skin colors will not be adjusted or will be adjusted insufficiently.

Nachlieli et al [14] proposed face-dependent skin color enhancement method to resolve the problem. Since faces that are not detected are not enhanced, the method is unreliable for enhancing images that contain multiple faces. Improper face detection (e.g. faces partially detected) may result in color artifacts after color enhancement. A new image-dependent skin color enhancement method proposed below is to resolve the problem and the problem using static skin color models. Face detection is applied to assist analyzing skin tones in the image and to adapt the skin color model to each scene. A scene-dependent (aka image-dependent) skin color model is then applied to detect skin colors and to compute skin color weighting factors for skin color adjustment.

First, a face detection method is applied to detect faces in an image [24]-[26]. Because of potential false face detections, a static skin color model is applied to verify each detected face. The order of these two operations may be exchanged or merged into a single step, depending on how the face detection algorithm is implemented. The skin color detection model at this step is relatively high tolerant for false skin color detection rates. Since an accurate skin detection model is not required in this step, the ellipse skin color model, which is more efficient in computation but less accurate than the ellipsoid model and the lightness-dependent ellipse model, is applied [29]. The threshold, ρ, can be larger than that used in a static skin color model. A subsequent step using information of face boxes is applied to modify the skin color model for accurate skin color detection on the image. The procedure for skin color enhancement is illustrated in Figure 5 and described below.

Step 0: Initialize a skin color detection model. In this study, the ellipse model in CIELAB a*b* space (adapted to D50) is selected for skin color modeling.

Step 1: Apply a face detection method to detect faces.

Step 2: Remove false detected face boxes. The skin color model formulated in Step 0 is applied to classify each pixel in a face box as a skin pixel or a non-skin pixel. If the ratio of skin pixels over all pixels within a face box is lower than a pre-determined threshold, this face is classified as a false detected face and is removed from the face list. A mean skin color is then computed from detected skin colors in each remaining face box. The histogram of skin colors in each face box is generated, and skin colors in the top 25% occurrence rates are applied to compute mean skin color, a*b*. If the color difference between the mean skin color and the statistical skin color center is larger than a tolerance threshold, this face is considered a false detected face and is removed from the face list.

Step 3: Compute a global mean skin color from the remaining face boxes. A global mean skin color is averaged from the mean skin colors of all remaining face boxes weighted with their skin pixel counts. The mean a*b* are compared with a preferred skin color. If the difference is less than a pre-determined threshold, the overall skin tone of the image is considered to be within the preferred color region, therefore no skin color adjustment is performed for the image and the skin color adjustment ends here. Otherwise, skin color adjustment on the whole image is performed by remaining steps below.

Step 4: Construct an image-dependent skin color ellipse model for skin color adjustment. It starts from the static skin color ellipse in Step 0. The center of the skin color ellipse is then replaced with the mean skin color of the image computed in Step 3. Because the skin color ellipse is to represent the skin color distribution of this image instead of the skin color distribution of a training image set, the size of the ellipse can be reduced. This skin color ellipse is applied to detect skin colors of the whole image.

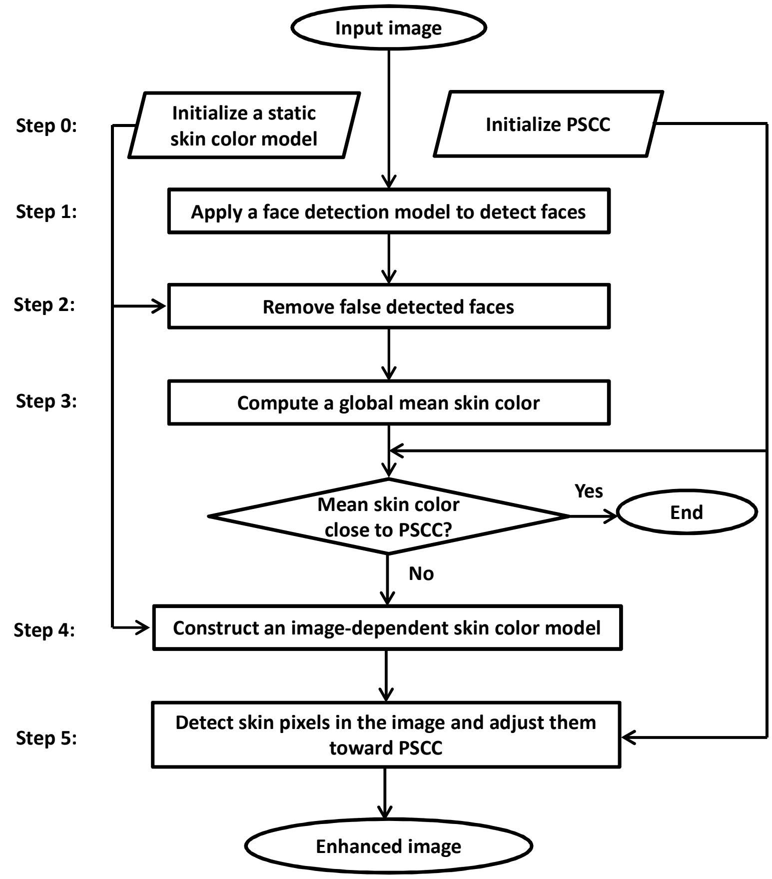


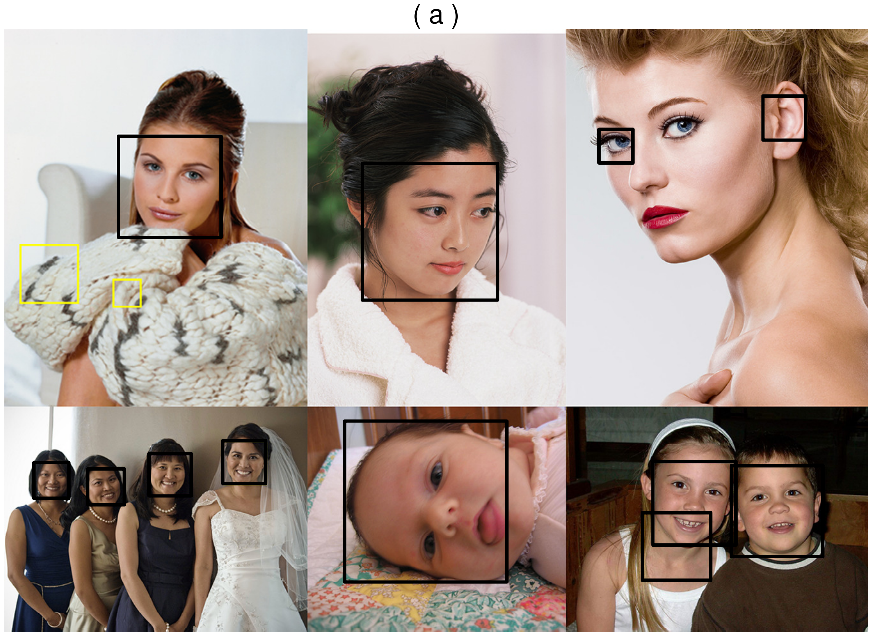
FIGURE 5: A Block Diagram for Skin Color Enhancement.

Step 5: Apply the image-dependent skin color model to adjust skin colors of the image. Instead of limiting to process skin colors within face boxes, all skin colors (skin color of any objects) in the whole image are adjusted. If the Mahalanobis distance of a pixel is smaller than a skin color threshold, the pixel is a skin color, and the Mahalanobis distance is applied to calculate a weight, w. Eq. (6) is applied to compute a preferred skin color, (a_{new}, b_{new}), corresponding to an original skin color, (a, b).

Large color adjustment on skin colors may have an effect that skin colors are not harmonized with the overall color balance of the image. If the mean skin color of an image is very different from the target PSCC, the adjustment is reduced. To further optimize the preferred skin color reproduction, the preferred skin color center, (a_{center}, b_{center}), may be optimized as a function of lightness using Eq. (7).

Figure 6 shows a few test images and the enhancement result. All square boxes (black and yellow boxes) are the faces detected at Step 1. Yellow boxes are the faces removed in Step 2. Although an eye and an ear in the upper-right image are detected as faces, a mean skin color computed from these two boxes still represents the face tone of the image. Therefore, the algorithm still works well in adjusting skin colors. This demonstrates that the image-dependent skin color enhancement is more robust than face-dependent skin color enhancement. Since the skin color enhancement adjusts pixels that are skin colors regardless of their object types, it modifies the overall color balance, i.e., it adjusts the white balance of the image. Therefore it produces more accurate color balance and fixes inaccurate illuminant detection on the image. This can be seen in the bottom-left image where the wall in the back is adjusted as well.

(a)



(b)

FIGURE 6: A Block Diagram for Skin Color Enhancement.

Because the skin color detection model in Step 0 is set to detect a larger region of skin colors than that for the skin color enhancement using a static skin color model, the new method adjusts a wider range of skin colors that deviate more seriously from normal skin colors. Since the ellipse used in Step 3 and Step 4 is adapted to a specific image, this method adjusts skin colors more effectively than those approaches using a static skin color model.

This algorithm works well in a uniform luminance-chrominance color space, such as CIELAB or CIECAM02 even if a single PSCC is applied to all lightness levels. Replacing the working color space with YCbCr improves the computation efficiency for processing RGB images and videos for display color enhancement. However, chroma coordinates (CbCr) of preferred skin colors are changed significantly among different luma values, Y. CbCr of preferred skin colors and skin color ellipses should be adapted to different luma for skin color enhancement.

A few cases explaining the improvement of the approach over approaches utilizing static skin color models are discussed in Appendix.

6. SKIN COLOR MORPHING BY TRIANGULAR SUB-DIVISION

Once a weight is computed for a skin color and a target preferred color is determined, Eq. (6) is applied to adjust the skin color. To avoid contouring, the weight, w in Eqs. (4-5), should be less than 1 [29]. In this section, an alternative color adjustment method is proposed. Figure 7 shows a skin color ellipse that is divided into a set of triangles [30]. Each triangle connects two neighbor points on the skin color ellipse boundary and the central point A. The more triangles are used, the more accurate the ellipse is represented. As the statistical skin color center, A, is moved toward a PSCC, B, all colors in each triangle (e.g. A-C0-C1) are morphed to its corresponding triangle (e.g. B-C0-C1). Since gamut boundary colors are not changed, it guarantees smooth color adjustment.

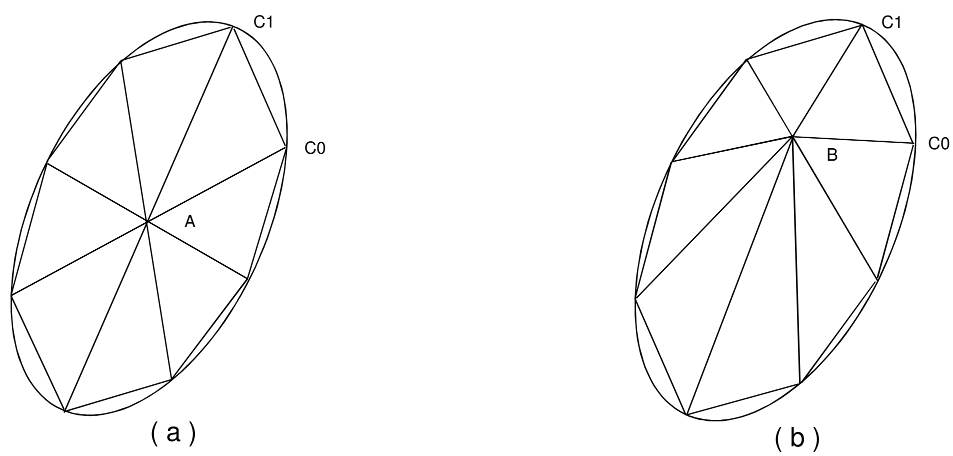


FIGURE 7: A skin color ellipse is approximated with a set of triangles for color adjustment. The statistical skin center (A) in (a) is mapped to a PSCC (B) in (b).

To adjust a skin color, a triangle that contains the color is found and a triangle-based interpolation is performed. Let's assume a skin color, P, is within the triangle A-C0-C1, as shown in Figure 8. As the mean skin color, A, is morphed to a PSCC, B, while C0 and C1 stay unchanged, P is mapped to P'. A method to preserve area ratio of three sub-triangles may be used to compute the adjusted color P'. Areas of triangles A-P-C0, A-P-C1, and P-C0-C1 are noted SA-P-C0, SA-P-C1, and SP-C0-C1, respectively. They are computed using three known colors, A, C0, and C1, and the original skin color P. P' is computed by the following equation:

$$p = \frac{\left(C0 \cdot S_{A-P-C1} + C1 \cdot S_{A-P-C0} + B \cdot S_{P-C0-C1}\right)}{\left(S_{A-P-C1} + S_{A-P-C0} + S_{P-C0-C1}\right)} \qquad (9)$$

An advantage of this method over the method described in earlier sections is that the statistical color center of the original skin colors A is exactly mapped to a target preferred skin color B and all other colors are morphed smoothly.

If lightness is modified together with chrominance, the morphing method must be expanded to a 3-D space. The original central color, A, in each sampled lightness level is mapped to a corresponding PSCC, B, in which lightness may be different. A set of sampling points to represent the boundary of the skin color gamut defined with a skin color model are generated. The boundary sampling points and the lightness-dependent points, A and B, are used to construct a set of tetrahedrons. Tetrahedral interpolation is applied to map each original skin color to a corresponding preferred skin color.

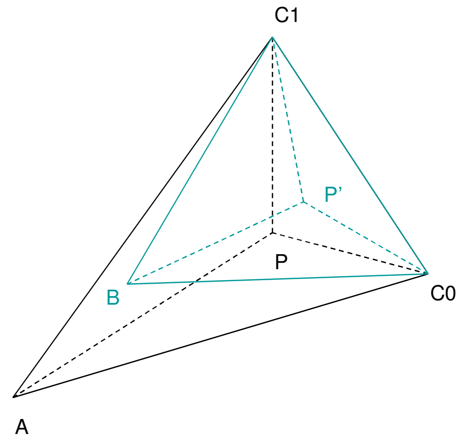


FIGURE 8: An original skin color, P, on a triangle A-C0-C1 is mapped to P' on another triangle B-C0-C1.

7. EXPERIMENTAL RESULT AND DISCUSSION

A psychophysical experiment was conducted to validate the effectiveness of the skin color enhancement algorithm. A calibrated monitor was used to display samples. 50 Caucasian images and 50 Oriental images were selected for testing. Most of images were captured with consumer digital cameras. 25 Caucasian observers and 25 Asian observers, who had normal visions, judged Caucasian images and Oriental images, respectively.

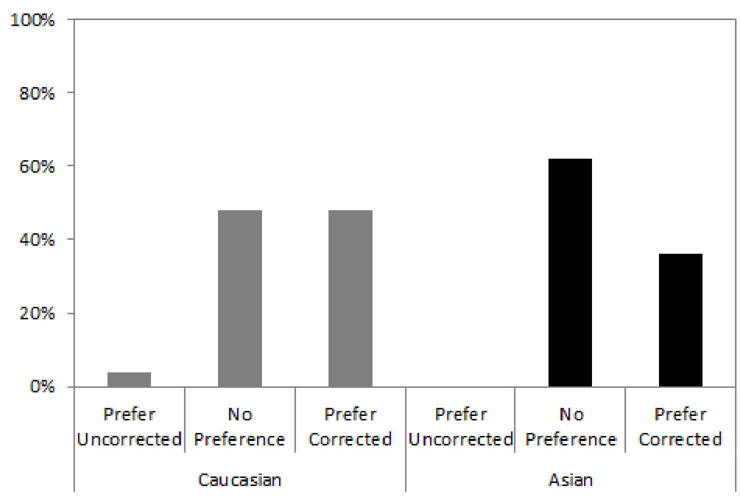


FIGURE 9: Psychophysical Experimental Result.

The result is plotted in Figure 9. For Caucasian images, 48% of images are significant improved while 4% have negative impact and the rest have no visual impact. For Asian images, 36% are significantly improved and the rest are visually not changed. The original images with skin tones close to optimal are mostly not changed visually. It verifies that the skin color enhancement method effectively improves skin color preference and does not damage good skin tones.

We also compared our method with skin color enhance using static skin color models. Our method is able to enhance images captured under more extended range of conditions. Skin color enhancement on each detected face, although able to process skin colors captured under a white range of conditions, is much less reliable than our method because of higher requirement on the accuracy of face detection and less number of pixels for statistical analysis of face tones.

8. CONCLUSION

A new skin color enhancement method is introduced for preferred skin color reproduction. If face detection is not enabled, it applies a statistical skin color model to detect skin colors and morphs skin colors toward a preferred skin color center. Preferred skin colors are adapted to different lightness to improve skin color preference. The highlight region is processed differently to maintain the contrast.

If skin colors are far away from the regular skin color distribution, applying a static skin color model for skin color enhancement is not able to detect skin colors effectively and therefore the method will not effectively enhance skin colors. With face detection, a skin color model adapted to the scene is constructed to resolve the limitation of the algorithm using statistical skin color models. By applying the scene-dependent skin color model, skin colors that are far away from normal skin colors are detected more effectively and the result of skin color enhancement is greatly improved. In addition, the result of the skin color analysis is applied to adjust overall color balance of the image, and therefore the method produces more accurate white balance on the image.

The current method is not able to enhance face tones of different culture backgrounds in a single image differently. This is a direction for further research. Another area for further research is to study the effectiveness of the method working on different color spaces, especially in YCbCr space to improve the computation efficiency.

9. APPENDIX: CASE STUDY OF SKIN COLOR ENHANCEMENT UTILIZING SCENE-DEPENDENT SKIN COLOR MODEL

A few cases illustrating the benefit of utilizing image-dependent skin color model for skin color enhancement are discussed below.

Case 1: Skin tones are highly chromatic. In Figure A1, the thick-black ellipse is the skin color region of an elliptical skin color model and the dash ellipse is derived from the skin colors of an image. If the static skin color model is applied to detect skin colors, skin colors that are out of the thick-black elliptical region will not be adjusted, and the adjustment strength of each skin color is proportional to the Mahalanobis distance calculated using the static skin color model. A color at location A has the highest adjustment strength and colors around B that are close to the boundary of the thick-black ellipse are adjusted very weakly. With the image-dependent skin color modeling, the ellipse skin color model is adjusted to center at the mean skin color of the face boxes of image. The gray ellipse becomes the elliptical model for skin color detection. The strength for skin color adjustment is proportional to the Mahalanobis distance calculated using the gray ellipse. A color at location B has the highest adjustment strength, and a color on the boundary of the gray ellipse is not adjusted. Because the image-dependent skin color ellipse (the gray ellipse) is adapted to colors of the skin pixels of the image, the size of the ellipse may be reduced. It is clear that the image-dependent skin color modeling is more effective for skin color adjustment.

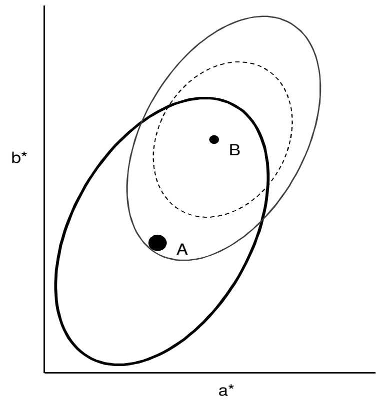


FIGURE A1: A sketch diagram illustrating effective adjustment of highly chromatic skin colors.

Case 2: Skin hues are very different from regular skin hues. In Figure A2, the large solid-black ellipse illustrates an elliptical skin color model and the dashed ellipse illustrates the skin tones of an image. Skin colors are very yellowish. Again, the strength of the skin color adjustment is proportional to the Mahalanobis distance computed using the skin color model. With the static skin color model, a color at location A has the highest adjustment strength and a color on the boundary of the black elliptical region or out of the ellipse has zero strength (no adjustment). Thus, the yellowish skin colors that are out of the black skin color ellipse are not adjusted. With the image-dependent skin color model, the ellipse skin color model is adjusted to center at the mean skin color of the face boxes of the image. Thus the skin color detection ellipse is shifted to the gray ellipse. Skin colors to be adjusted are detected using this gray ellipse and the strength of adjustment is proportional to the Mahalanobis distance computed using the gray ellipse. A color at location B has the highest adjustment strength, and a color on the boundary of the gray ellipse is not adjusted. Because the image-dependent skin color ellipse (the gray ellipse) is adapted to skin colors of the image, the size of the ellipse may be reduced. In this case, it is very likely that the illuminant detection on the image is incorrect and the entire image is shifted to the yellowish direction. Because the method of skin color enhancement adjusts all colors within the gray ellipse, all yellowish colors in the image are adjusted. Therefore, an additional benefit of the method is that it removes the yellow cast. The relative location of B and A can actually be used to assist illuminant detection and white balance.

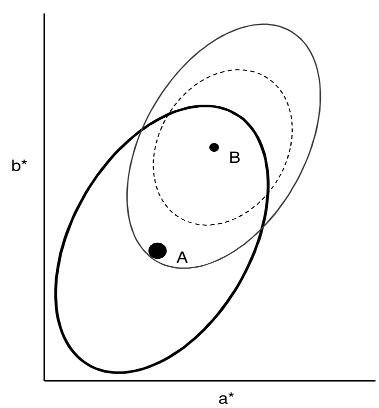


FIGURE A2: A sketch diagram illustrating the effective adjustment of yellowish skin tones.

Case 3: Bright and dark skin colors. Figure A3 shows an elliptical skin color model in a large solid-black ellipse and the skin color region of an image in a small dash ellipse. Very bright and very dark skin colors in digital photographic images tend to have lower chroma. If a skin color model is not adapted to very bright (or overexposed) and very dark (or underexposed) images, the skin elliptical model tend to have a mean chroma higher than the mean skin chroma of the image. With a static skin color model, high chroma skin colors close to the center, A, of the skin color model is adjusted the most. And very low chroma skin colors that are close to the boundary of the black ellipse or out of the ellipse are adjusted very weakly or are not adjusted. With the image-dependent skin color modeling, an ellipse skin color model is adjusted to have the ellipse centered at the mean skin color of the face boxes. The skin color detection ellipse is moved from the solid-black ellipse to the gray ellipse. Skin colors to be adjusted are detected using this gray ellipse and the strength of the adjustment is computed based on the Mahalanobis distance to the center B instead to the point A. It is clear that the image-dependent method adjusts skin colors more properly and more effectively. In this case, the skin color ellipse may be reduced because color gamut in highlight or shadow is smaller than that in medium tones.

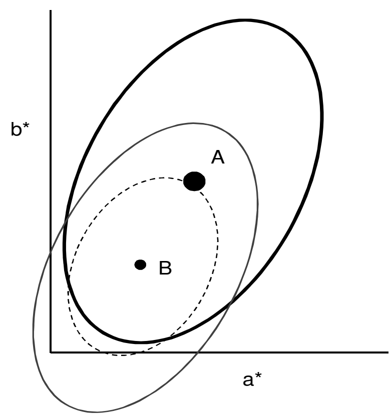


FIGURE A3: A sketch diagram illustrating effective and proper adjustment of pale skin tones.

In summary, a skin color model adapted to face tones of an image can be constructed by utilizing the face detection information. It models skin tones of the image more accurately than a static skin color model, and results in more effective skin color detection and skin color enhancement.

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