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Saturation improvement in hue-preserving color image enhancement without gamut problem

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Abstract

This study proposes a method to improve the saturation of colors during hue-preserving color image enhancement without the gamut problem. First, the color of each pixel in an input image is projected onto one of three bisecting planes or bisectors of an RGB color cube to increase saturation. Then, that projected color is transformed into a target color with a designated luminance and the same hue as the original color. Experimental results show that the proposed method can enhance color images better than can recent hue-preserving color image enhancement methods.

Keywords: Color image enhancement; Gamut mapping; Hue; Saturation

1. Introduction

In color image enhancement, hue-preserving techniques are often required to preserve the appearance of image content. Recently, Naik's and Murthy [1] proposed a hue-preserving color image enhancement method (hereafter "Naik's method") for enhancing the contrast of color images without the gamut problem (i.e., when the enhanced colors may appear outside the permitted color range). Han et al. [2] proposed a similar method from the viewpoint of 3D color histogram equalization. However, Naik's method can not only increase the saturation of colors to be enhanced but also decrease it. To overcome this problem, Yang and Lee [3] proposed a modified hue-preserving gamut mapping method (hereafter "Yang's method") that provides higher saturation than does Naik's method. In Yang's method, the range of luminance is divided equally into three parts corresponding to dark, middle, and bright colors, and the saturation of dark and bright colors can be enhanced. However, those colors that fall into the middle range of luminance are handled in the same manner as in Naik's method and, therefore, the saturation of those colors is not increased even when Yang's method is used.

Empirically, we observe that correctly exposed pictures have better saturation than those that are underexposed or overexposed. Based on this observation, we consider that a candidate having the optimal saturation in hue-preserving color image enhancement correctly exposes images. However, controlling the exposure of a picture after capturing it is difficult because the exposure is determined by three camera settings: aperture, ISO, and shutter speed. To overcome this difficulty, the aforementioned image processing-based approaches are considered.

In this study, we propose an improved method for hue-preserving color image enhancement in which it is possible for the saturation of all chromatic colors to be increased. We experimentally compare the proposed method with those of Naik and Murthy and Yang and Lee, and demonstrate that the proposed method improves the saturation of color images.

2. Previous methods for hue-preserving color image enhancement without gamut problem

In this section, we briefly summarize the methods proposed by Naik and Murthy [1] and Yang and Lee [3].

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Let $\boldsymbol{p} = (p_1, p_2, p_3)$ be an RGB color vector in RGB color space, where $p_1 = r$, $p_2 = g$ and $p_3 = b$, and r, g and b denote the red (R), green (G), and blue (B) values of $\boldsymbol{p}$, respectively, and satisfy $0 \le p_i \le 1$ for $i = 1, 2, 3$. The intensity of $\boldsymbol{p}$ is then defined by $l = \sum_{i=1}^{3} p_i \in [0, 3]$ [1], and the saturation of $\boldsymbol{p}$ is the distance from the intensity axis to $\boldsymbol{p}$ [4]:

$$S(\boldsymbol{p}) = \sqrt{\frac{(r-g)^2 + (g-b)^2 + (b-r)^2}{3}}. \tag{1}$$

Let $\alpha(l) = f(l)/l$, where $f(l)$ is a function of l for transforming the intensity of a grayscale image into the modified version. Naik's method [1] can thus be summarized as follows.

2.1. Naik and Murthy's method

If $\alpha(l) \le 1$, then the modified color $\boldsymbol{p}' = (p'_1, p'_2, p'_3)$ of $\boldsymbol{p}$ is given by $\boldsymbol{p}' = \alpha(l)\boldsymbol{p}$ or $p'_i = \alpha(l)p_i$ for $i = 1, 2, 3$; otherwise, $\boldsymbol{p}$ is transformed into the cyan, magenta, and yellow (CMY) color vector $\boldsymbol{q} = (q_1, q_2, q_3) = \boldsymbol{1} - \boldsymbol{p}$ where $\boldsymbol{1} = (1, 1, 1)$. The modified CMY color vector is then given by $\boldsymbol{q}' = \frac{3-f(l)}{3-l}\boldsymbol{q}$. Finally, $\boldsymbol{q}'$ is transformed back into the RGB color vector as $\boldsymbol{p}' = \boldsymbol{1} - \boldsymbol{q}'$.

Yang and Lee revealed that the saturation of an enhanced color image when using Naik's method decreases as compared to that in the original image, and proposed a modified hue-preserving gamut mapping method described as follows [3].

2.2. Yang and Lee's method

First, the RGB color space is divided into three parts by two equi-intensity planes $l = 1$ and $l = 2$: $l \le 1$, $1 < l \le 2$ and $2 < l$. For a dark color $\boldsymbol{p}$ with $l \le 1$, the intensity of $\boldsymbol{p}$ is increased to $\tilde{\boldsymbol{p}} = \boldsymbol{p}/l$, whose intensity is 1, and then Naik's method is applied to $\tilde{\boldsymbol{p}}$. For a moderate color $\boldsymbol{p}$ with $1 < l \le 2$, Naik's method is applied to $\boldsymbol{p}$ directly. Therefore, in this case, Yang's method outputs the same result as Naik's, that is, it decreases the saturation of input colors. For a bright color $\boldsymbol{p}$ with $l > 2$, $\boldsymbol{p}$ is transformed into a CMY color vector $\boldsymbol{q} = \boldsymbol{1} - \boldsymbol{p}$, and the intensity of $\boldsymbol{q}$ is then reduced to $\tilde{\boldsymbol{q}} = \boldsymbol{q}/(3 - l)$ so that the RGB color vector is $\tilde{\boldsymbol{p}} = \boldsymbol{1} - \tilde{\boldsymbol{q}}$, whose intensity is 2. Finally, Naik's method is applied to $\tilde{\boldsymbol{p}}$.

3. Proposed method

As previously described, Yang's method [3] is equivalent to Naik's method [1] when $1 < l \le 2$. In this case, both methods decrease the color saturation. In this section, we propose a hue-preserving color image enhancement method that yields higher saturation than the aforementioned two methods.

Fig. 1 shows three bisecting planes or bisectors of an RGB color cube. The horizontal, diagonal, and vertical arrows in each figure denote R, G, and B axes of the RGB color space, respectively. The origin $\boldsymbol{0} = (0, 0, 0)$ is denoted by "K" (black), whereas "W" denotes white with the coordinate $\boldsymbol{1}$. The colors of the planes indicate that the planes from left to right in Fig. 1 are parallel to the R, G, and B axes of the RGB color space, respectively. The projection of any color onto one of the three planes can increase the saturation of that color. The unit normal

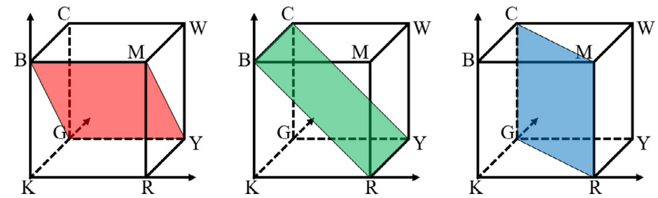

Fig. 1. Three bisectors of an RGB color cube. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

vectors of those planes are given by $\boldsymbol{u}_1 = (0, 1, 1)/\sqrt{2}$, $\boldsymbol{u}_2 = (1, 0, 1)/\sqrt{2}$ and $\boldsymbol{u}_3 = (1, 1, 0)/\sqrt{2}$. For a color $\boldsymbol{p}$, we select one of the three planes by

$$i_p = \arg \underset{i \in \{1,2,3\}}{\text{median}} (p_i), \tag{2}$$

where the "median()" operator selects the median value from given values. For example, if $i_p = 1$, then $p_1 = r$ is the median value among r, g and b. In this case, g or b is the maximal value, and therefore, the extension of $\boldsymbol{p}$ intersects the red plane in Fig. 1 before it appears outside the gamut of the RGB color cube. The equation of the plane with a normal vector $\boldsymbol{u}_{i_p}$ is given by $\boldsymbol{u}_{i_p} \cdot \boldsymbol{p}_0 = \theta$, where $\boldsymbol{p}_0$ denotes a point on the plane, $\theta = 1/\sqrt{2}$ is half the length of a diagonal line of a square with a side length of 1, and "$\cdot$" denotes the dot product of vectors.

Let $\tilde{\boldsymbol{p}} = \alpha(l)\boldsymbol{p}$. Then, $\tilde{\boldsymbol{p}}$ may project outside the gamut when $\alpha(l)$ is large. To avoid this gamut problem, we first project $\boldsymbol{p}$ onto the aforementioned plane with a unit normal vector $\boldsymbol{u}_{i_p}$, and then apply Naik's method to the projected color point. The procedure is detailed as follows:

(i) If $\boldsymbol{u}_{i_p} \cdot \boldsymbol{p} \le \theta$ and $\boldsymbol{u}_{i_p} \cdot \tilde{\boldsymbol{p}} \le \theta$, then the modified color of $\boldsymbol{p}$ is given by $\boldsymbol{p}' = \tilde{\boldsymbol{p}}$. This condition means that both $\boldsymbol{p}$ and $\tilde{\boldsymbol{p}}$ are located on the same side of the plane with the unit normal vector $\boldsymbol{u}_{i_p}$ as $\boldsymbol{0}$.

In this case, if $\alpha(l) > 1$, then the saturation is improved because $\boldsymbol{p}' = \tilde{\boldsymbol{p}}$ is more distant from the intensity axis than is $\boldsymbol{p}$.

(ii) If $\boldsymbol{u}_{i_p} \cdot \boldsymbol{p} \le \theta$ and $\boldsymbol{u}_{i_p} \cdot \tilde{\boldsymbol{p}} > \theta$, then $\tilde{\boldsymbol{p}}$ is located on the opposite side of the plane to $\boldsymbol{p}$. In this case, we compute the intersection of the extension of $\boldsymbol{p}$ and the plane $\boldsymbol{u}_{i_p} \cdot \boldsymbol{p}_0 = \theta$ (i.e., $\boldsymbol{x_p} = \boldsymbol{p}/(p_{i_a} + p_{i_b})$), where $i_a = \{[(i_p - 1) - 1 + 3] \bmod 3\} + 1$ and $i_b = \{[(i_p - 1) + 1] \bmod 3\} + 1$ by the modulo operation $\bmod$. The intensity of $\boldsymbol{x_p}$ is given by $l_x = l/(p_{i_a} + p_{i_b})$, from which we derive the modified color of $\boldsymbol{p}$ as

$$\boldsymbol{p}' = \boldsymbol{1} - \frac{3 - f(l)}{3 - l_x}\left(\boldsymbol{1} - \boldsymbol{x_p}\right). \tag{3}$$

This case is schematically illustrated in Fig. 2(a), where the RGB color cube is orthogonally projected onto the G–B, B–R, and R–G planes for the left, middle, and right cases in Fig. 1, respectively. A color vector $\boldsymbol{p}$ is elongated to $\boldsymbol{x_p}$, to which Naik's method is applied. The proposed method then outputs the color indicated by the black point, which is more distant from the intensity axis connecting $\boldsymbol{0}$ to $\boldsymbol{1}$ than is the red point given by Naik's method.

(iii) If $\boldsymbol{u}_{i_p} \cdot \boldsymbol{p} > \theta$ and $\boldsymbol{u}_{i_p} \cdot \tilde{\boldsymbol{p}} \le \theta$, then $\tilde{\boldsymbol{p}}$ is located on the same side of the plane as "K", and $\boldsymbol{p}$ is located on the

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