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

Yu, Hengjun
Department of Communication Design Science, Kyushu University

Inoue, Kohei
Department of Communication Design Science, Kyushu University

Hara, Kenji
Department of Communication Design Science, Kyushu University

Urahama, Kiichi
Department of Communication Design Science, Kyushu University

出版情報：ICT Express. 4 (3), pp.134-137, 2018-09. Elsevier
バージョン：

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

Hengjun Yu, Kohei Inoue, Kenji Hara, and Kiichi Urahama

Department of Communication Design Science, Kyushu University
4-9-1, Shiobaru, Minami-ku, Fukuoka 815-8540, Japan

Abstract

This paper proposes a method for improving the saturation of colors in hue-preserving color image enhancement without gamut problem. Firstly, 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 the saturation. Then the projected color onto the plane is transformed into the 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 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 contents. Recently, Naik and Murthy [1] have proposed a hue-preserving color image enhancement method for enhancing the contrast of color images without the gamut problem, i.e., the enhanced colors may go outside the permitted color range. Han et al. [2] also proposed the equivalent method from a viewpoint of 3-D color histogram equalization. However, Naik and Murthy's method cannot only increase the saturation of colors to be enhanced, but also often decreases it. To overcome this problem, Yang and Lee [3] proposed a modified hue-preserving gamut mapping method that provides higher saturation than Naik and Murthy's one. In Yang and Lee's method, the range of luminance is equally divided into three parts that correspond to dark, middle and bright colors, and the saturation of dark and bright colors can be enhanced. However, the other colors falling into the middle range of luminance are handled in the same way as Naik and Murthy's method, and therefore, the saturation of those colors is not increased even if Yang and Lee's method is used.

Empirically, we observe that correctly exposed pictures have better saturation than under or over exposed pictures. Based on this observation, we consider that a candidate with the optimal saturation in hue-preserving color image enhancement is correctly exposed images. However, it is difficult to control the exposure of a picture after shooting it because the exposure is determined by three camera settings: aperture, ISO and shutter speed. To overcome such a difficulty, image processing-based approaches are taken as described above.

In this paper, we propose an improved method for hue-preserving color image enhancement where all chromatic colors have the potential to have their saturation increased. We experimentally compare the proposed method with Naik and Murthy's and Yang and Lee's methods, and demonstrate that the saturation of color images is improved by the proposed method better than the compared methods.

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

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

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 R (red), G (green) and B (blue) values of $\boldsymbol{p}$, respectively, and satisfy $0 \leq p_i \leq$

1 for $i = 1, 2, 3$. Then the intensity of $\boldsymbol{p}$ is 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]:

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

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 one. Then Naik's method [1] can be summarized as follows.

2.1. Naik and Murthy's method

If $\alpha(l) \leq 1$, 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 $i = 1, 2, 3$; or else $\boldsymbol{p}$ is transformed into the CMY (cyan, magenta and yellow) color vector $\boldsymbol{q} = (q_1, q_2, q_3) = \boldsymbol{1} - \boldsymbol{p}$ where $\boldsymbol{1} = (1, 1, 1)$. Then the modified CMY color vector is 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 pointed out that the saturation of the enhanced color image by Naik's method decreases compared with that of the original one, and proposed a modified hue-preserving gamut mapping method 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 $l = 2$: $l \leq 1$, $1 < l \leq 2$ and $2 < l$. For a dark color $\boldsymbol{p}$ with $l \leq 1$, the intensity of $\boldsymbol{p}$ is boosted up as $\tilde{\boldsymbol{p}} = \boldsymbol{p}/l$ whose intensity is 1, and then Naik's method is applied to $\tilde{\boldsymbol{p}}$. For a moderate color $\boldsymbol{p}$ with $1 < l \leq 2$, Naik's method is applied to $\boldsymbol{p}$ directly. Therefore, in this case, Yang's method outputs the same result as Naik's one which decreases the saturation of input colors. For a bright color $\boldsymbol{p}$ with $l > 2$, $\boldsymbol{p}$ is transformed into the CMY color vector $\boldsymbol{q} = \boldsymbol{1} - \boldsymbol{p}$, and then the intensity of $\boldsymbol{q}$ is dropped down as $\tilde{\boldsymbol{q}} = \boldsymbol{q}/(3-l)$ to have the RGB color vector as $\tilde{\boldsymbol{p}} = \boldsymbol{1} - \tilde{\boldsymbol{q}}$ whose intensity is 2. Finally, Naik's method is applied to $\tilde{\boldsymbol{p}}$.

3. Proposed method

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

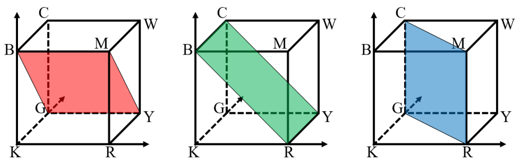


Figure 1: Three bisectors of RGB color cube.

Fig. 1 shows three bisecting planes or bisectors of RGB color cube. The horizontal, diagonal and vertical arrows in each figure denote R, G and B axes of 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 the color. The unit normal 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

$$i_{\boldsymbol{p}} = \arg \operatorname*{median}_{i \in \{1,2,3\}} (p_i), \qquad (2)$$

where 'median()' operator selects the median value from given values. For example, if $i_{\boldsymbol{p}} = 1$, 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 with the red plane in Fig. 1 before it goes outside the gamut of the RGB color cube. The equation of the plane with normal vector $\boldsymbol{u}_{i_{\boldsymbol{p}}}$ is given by $\boldsymbol{u}_{i_{\boldsymbol{p}}} \cdot \boldsymbol{p}_0 = \theta$, 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 go outside the gamut when $\alpha(l)$ is large. To avoid such a gamut problem, we first project $\boldsymbol{p}$ onto the above-mentioned plane with unit normal vector $\boldsymbol{u}_{i_{\boldsymbol{p}}}$, and then apply Naik's method to the projected color point. The detailed procedure is as follows:

i) If $\boldsymbol{u}_{i_{\boldsymbol{p}}} \cdot \boldsymbol{p} \leq \theta$ and $\boldsymbol{u}_{i_{\boldsymbol{p}}} \cdot \tilde{\boldsymbol{p}} \leq \theta$, 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 $\boldsymbol{u}_{i_{\boldsymbol{p}}}$ 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 $\boldsymbol{p}$.

ii) If $\boldsymbol{u}_{i_{\boldsymbol{p}}} \cdot \boldsymbol{p} \leq \theta$ and $\boldsymbol{u}_{i_{\boldsymbol{p}}} \cdot \tilde{\boldsymbol{p}} > \theta$, 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 $\boldsymbol{u}_{i_{\boldsymbol{p}}} \cdot \boldsymbol{p}_0 = \theta$, i.e., $\boldsymbol{x}_{\boldsymbol{p}} = \boldsymbol{p}/(p_{i_a} + p_{i_b})$, where $i_a = \{[(i_{\boldsymbol{p}} - 1) - 1 + 3] \bmod 3\} + 1$ and $i_b = \{[(i_{\boldsymbol{p}} - 1) + 1] \bmod 3\} + 1$ with the modulo operation $\bmod$. The intensity of $\boldsymbol{x}_{\boldsymbol{p}}$ is given by $l_{\boldsymbol{x}} = l/(p_{i_a} + p_{i_b})$, from which we have the modified color of $\boldsymbol{p}$ as

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

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

iii) If $\boldsymbol{u}_{i_{\boldsymbol{p}}} \cdot \boldsymbol{p} > \theta$ and $\boldsymbol{u}_{i_{\boldsymbol{p}}} \cdot \tilde{\boldsymbol{p}} \leq \theta$, then $\tilde{\boldsymbol{p}}$ is located on the same side of the plane as 'K', and $\boldsymbol{p}$ is located on the opposite side. In this case, we compute the intersection of the plane $\boldsymbol{u}_{i_{\boldsymbol{p}}} \cdot \boldsymbol{p}_0 = \theta$ and the line passing through $\boldsymbol{p}$ and $\boldsymbol{1}$, i.e., $\boldsymbol{y}_{\boldsymbol{p}} = \boldsymbol{p} + (1 - p_{i_a} - p_{i_b})(\boldsymbol{1} - \boldsymbol{p})/(2 - p_{i_a} - p_{i_b})$ whose intensity is given by $[3 + p_{i_{\boldsymbol{p}}} - 2(p_{i_a} + p_{i_b})]/(2 - p_{i_a} - p_{i_b})$, from which we have the modified color of $\boldsymbol{p}$ as

$$\boldsymbol{p}' = \frac{f(l)}{3 + p_{i_{\boldsymbol{p}}} - 2\left(p_{i_a} + p_{i_b}\right)} \boldsymbol{y}_{\boldsymbol{p}}. \tag{4}$$

This case is schematically illustrated with Fig. 2(b), where a vector from $\boldsymbol{1}$ to $\boldsymbol{p}$ is elongated to $\boldsymbol{y}_{\boldsymbol{p}}$, to which Naik's method is applied. Then we have the color $\boldsymbol{p}'$ indicated by the blue point, which is more distant from the intensity axis than $\tilde{\boldsymbol{p}}$ which is also the output of Naik's method.

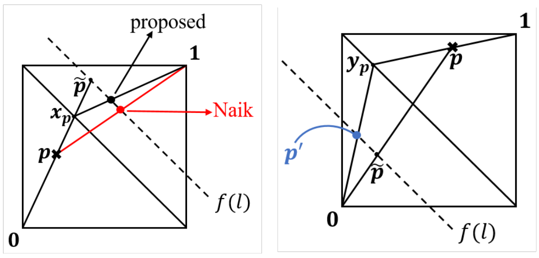
iv) If $\boldsymbol{u}_{i_{\boldsymbol{p}}} \cdot \boldsymbol{p} > \theta$ and $\boldsymbol{u}_{i_{\boldsymbol{p}}} \cdot \tilde{\boldsymbol{p}} > \theta$, then both $\boldsymbol{p}$ and $\tilde{\boldsymbol{p}}$ are located on the same side of the plane to 'W'. In this case, the modified color is given by

$$\boldsymbol{p}' = \boldsymbol{1} - \frac{3 - f(l)}{3 - l} (\boldsymbol{1} - \boldsymbol{p}). \tag{5}$$

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

4. Experimental results

We experimentally compared the proposed method with Naik's method [1] and Yang's method [3]. Fig. 3 shows the results of color image enhancement, where Fig. 3(a) shows three original images: Couple (underexposed), House (moderately exposed) and Tiffany (overexposed) arranged from left to right. Figs. 3(b), (c) and (d) show the results by Naik's, Yang's, and the proposed methods, respectively. In this example, we commonly used conventional histogram equalization for the intensity transformation $f(l)$ in the three methods, by which the contrasts are equally enhanced as shown in Figs. 3(b)-(d). Naik's method decreases the saturation compared with the original images in Fig. 3(a) as shown in Fig. 3(b), whose images become similar to their grayscale ones. On the other hand, Yang's method produces more colorful images than Naik's results as shown in Fig. 3(c). The results by the proposed methods shown in Fig. 3(d) is the most colorful among the compared methods.



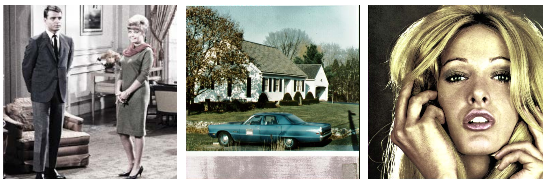
(a) Case ii) (b) Case iii)

Figure 2: Diagrams for cases ii) and iii) in proposed method.

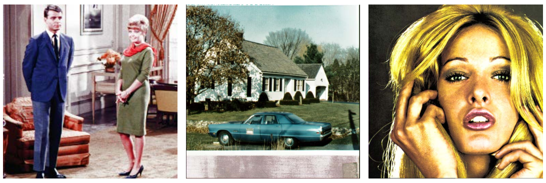
Fig. 4 shows the saturation images corresponding to the images in Fig. 3, where the brightness of each pixel in the saturation images is proportional to the value of saturation $S(\boldsymbol{p})$ in (1). For example, the regions of business suit in the left image and woman's face in the right image have brighter pixels in Fig. 4(d) than in Figs. 4(b) and (c). From the fact that the images in Fig. 4(d) are brighter than the corresponding images in Figs. 4(b) and (c), it is visually demonstrated that the proposed method improves the saturation compared with Naik's and Yang's methods.

Fig. 5 shows the mean saturation values per pixel of the images in Fig. 4. The vertical and horizontal axes denote mean saturation and the names of images, respectively. The colors of bars denote the compared methods, i.e., cyan, green, yellow and orange denote the original image, Naik's, Yang's and the proposed methods, respectively. This figure shows graphically and numerically that Naik's method (green bar) decreases the mean saturation

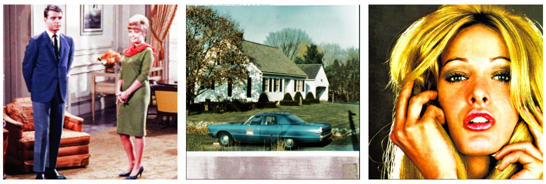
(a) Original images



(b) Naik's method [1]



(c) Yang's method [3]



(d) Proposed method

Figure 3: Color image enhancement results.

(a) Original images

(b) Naik's method [1]

(c) Yang's method [3]

(d) Proposed method

Figure 4: Saturation images.

from the original images (cyan bar), Yang's method (yellow bar) gives higher saturation than Naik's method, and the proposed method (orange bar) boosts up the mean saturation values further than Yang's method. Compared with the under and over exposed images (Couple and Tiffany), the increase in the mean saturation value in the moderately exposed image (House) is small because the moderately exposed image has nearly optimal saturation, and therefore, has only a few room for improvement.

Additionally, we compared the mean saturation values for twelve images selected from the USC-SIPI Image Database (`http://sipi.usc.edu/database/`) as shown in Table 1 where the proposed method achieved higher values than Naik's and Yang's methods.

5. Conclusion

We have proposed a method for hue-preserving color image enhancement with saturation improvement. The proposed method overcomes the drawback of conventional methods which may decrease the saturation of colors depending on the situation. Experimental results show that the proposed method increases the saturation of given color images better than conventional methods.

Acknowledgments

This work was supported by JSPS KAKENHI Grant Number JP16H03019.

[1] S. K. Naik, C. A. Murthy, Hue-preserving color image enhancement without gamut problem, IEEE Trans. Image Process. 12 (12) (2003) 1591–1598. doi:10.1109/TIP.2003.819231.

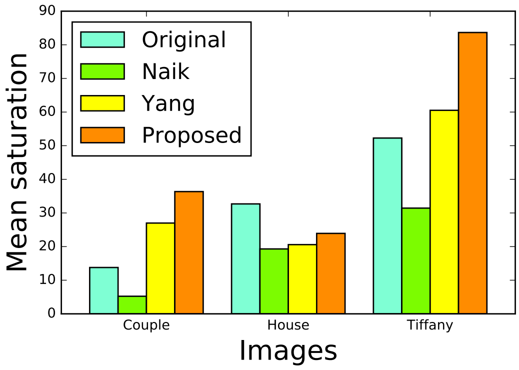


Figure 5: Mean saturation.

Table 1: Comparison of mean saturation values.

	Naik	Yang	Proposed
Aerial	14.50	14.50	**15.10**
Airplane	4.71	5.98	**8.46**
Balloon	13.03	13.03	**13.16**
Couple	5.23	26.99	**36.35**
Earth	23.18	23.18	**23.31**
Girl	13.22	26.90	**32.88**
Lenna	44.56	44.56	**46.14**
Mandrill	31.19	31.19	**32.16**
Milkdrop	58.23	58.23	**58.88**
Parrots	28.56	28.56	**33.40**
Peppers	52.30	52.30	**54.73**
Sailboat	27.27	28.18	**29.82**

[2] J.-H. Han, S. Yang, B.-U. Lee, A novel 3-d color histogram equalization method with uniform 1-d gray scale histogram, Trans. Img. Proc. 20 (2) (2011) 506–512. `doi:10.1109/TIP.2010.2068555`.
URL `http://dx.doi.org/10.1109/TIP.2010.2068555`

[3] S. Yang, B. Lee, Hue-preserving gamut mapping with high saturation, Electronics Letters 49 (19) (2013) 1221–1222. `doi:10.1049/el.2013.0221`.

[4] R. C. Gonzalez, R. E. Woods, Digital Image Processing (3rd Edition), Prentice-Hall, Inc., Upper Saddle River, NJ, USA, 2006.