for $1 \leq I \leq K, 0 \leq n \leq I-2$. For the case when $J = K$ and $n = I-1$, we only need to show $F_{0,I+K} \leq F_{1,I+K-1}$, which is obvious as $F_{1,I+K-1} = 1+F_{0,I+K-1}^2+F_{0,I+K-2}^2 \geq 1+F_{0,I+K-1}^2 = F_{0,I+K}$. Therefore, (21) holds for $1 \leq I \leq J = K$ and $0 \leq n \leq I-1$, which completes the proof of (16). Replacing both I and J in (16) with $J-1$ and letting $n = 0$ yield $F_{J-2,J} \leq F_{J-1,J-1}$.

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Background Adjustment and Saturation Enhancement in Ancient Chinese Paintings

Soo-Chang Pei and Yi-Mei Chiu

***Abstract*—This work presents a color enhancement scheme to virtually restore ancient Chinese paintings in electronic form. Two degradations result in color contrast loss in ancient Chinese paintings: paper aging and pigment fading. The proposed enhancement scheme comprises two subsequent methods: background adjustment and saturation enhancement. The former method, based on the Von Kries color conversion in the CIE xyY color space, retrieves the original color of the paint paper by modifying colors based on their similarity to the background color. The proposed saturation enhancement method makes colors more vivid and bright, and also improves the image contrast.**

***Index Terms*—Background adjustment, color contrast, color enhancement, gamut mapping and saturation enhancement.**

I. INTRODUCTION

Classical Chinese artists often leave extensive empty background spaces in their paintings to give the viewers more room for imagination. However, since ancient Chinese paintings were painted on handmade paper, those unpainted regions generally turn yellowish owing to long-term exposure to light. Consequently, the contrast between unpainted and painted parts of an ancient painting may decrease. Furthermore, traditional pigments used in Chinese painting were extracted from minerals or vegetables. They could easily fade as time goes by. Color degradation, thus, is inevitable.

This study applies a two-step method to virtually restore the appearance of ancient Chinese paintings. Each ancient Chinese painting is processed using the proposed background adjustment followed by saturation enhancement. The proposed background adjustment is adopted from the color correction in [1] and aims to virtually recover the original color of the paper. Gamut mapping [2] provides a means of increasing the overall contrast of an image by fully utilizing the dynamic range of the display device. Nevertheless, gamut mapping does not remove the effects of pigment fading and yields unnatural pictures. However, a pigment-fading model of ancient Chinese paintings would be rather complex, since the physical and chemical properties of color pigments in different times and places might be dramatically different. In this paper, we simply assume that only the saturation of classic pigments fades away with time. This kind of pigment fading could be cancelled out using saturation enhancement.

Lucchese *et al.* [3] and Pei *et al.* [4] developed saturation enhancement schemes by first saturating chromatic colors and then desaturating them using the center of gravity law for color mixture. However, without considering the display gamut constraints, the resultant colors of the above schemes might not be correctly displayed on any monitor. Additionally, only one global parameter tunes the performance and the result cannot be predicted before processing. This study proposes an improved saturation enhancement method with more freedom and manageability than the existing ones.

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Fig. 1. Example of an ancient Chinese painting. The distinction between painted and unpainted regions in the circled area is subtle.

The remainder of this paper is organized as follows. Sections II and III describe the methods of background adjustment and saturation enhancement, respectively. Section IV presents some experimental results. Finally, Section V draws the conclusions.

II. Background Adjustment

The most intuitive method of restoring the original contrast between unpainted and painted parts is to make the unpainted regions more achromatic. However, the distinction between these regions is not always very clear, due to some Chinese painting skills. For example, in the region circled by a white line in Fig. 1, the distinction between painted and unpainted regions is subtle. Segmentation is indeed a hard problem. Thus, we propose a background adjustment, which makes pixels more achromatic based on their similarity to the background of the image.

A. Similarity to Dominant Color

Generally, the dominant color of a Chinese painting is its background color and the background color is rather achromatic. After hundreds of years of exposure to light, the paint paper turns yellowish. Three-dimensional histogram in the Lab color space can determine the dominant color (L_D, a_D, b_D) of a Chinese painting. This dominant color is assumed to be the background color of the deteriorated painting.

The Euclidean distance between two colors in the Lab color coordinate system is often used as a measure of color difference. The similarity between two colors is inversely related to the distance between them. Hence, colors distant from the dominant color are considered to have lower probability of being similar to the dominant color. Colors with distances exceeding an empirical threshold Dth to the dominant color are considered not similar to the dominant color. The similarity between two colors (L,a,b) and (L_D, a_D, b_D) is defined as (1), shown at the bottom of the next page, where d_{Lab} [(L,a,b),(L_D, a_D, b_D)] is the Euclidean distance from (L,a,b) to (L_D, a_D, b_D) in the Lab color space, and β and D_{th} are the empirical values that determine the shape of the soft boundary.

Fig. 2(a) shows some exemplary similarity curves with several combinations of β and D_{th}. Fig. 2(b) illustrates the degree of similarity between pixels and the dominant color. For large β, the similarity of a color decreases slowly as its distance to the dominant color increases.

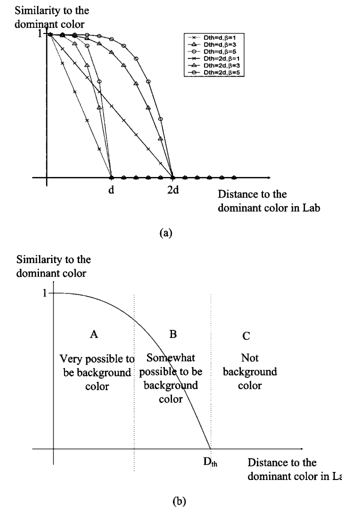

Fig. 2. (a) Several color similarity curves with different combinations of β and D_{th}. (b) Illustration of the degree of similarity between pixels and the dominant color.

In this case, a color that is not very close to the dominant color but with a distance to the dominant color less than D_{th} is still deemed to be somewhat similar to the dominant color. On the other hand, while β is a small number, only colors extremely close to the dominant color are regarded as colors similar to the dominant color. The similarity curve in the region A of Fig. 2(b) is generally chosen to be rather flat in order to make colors close to the dominant color have large similarity value. Besides, the similarity curve in the region B should not be steep. Otherwise, the similarity decision reduces to quasi-hard decision; this may result in some noticeable contour effect.

B. Adjust Color Pixel According to Color Similarity α

The model of Von Kries [1] can modify the color from the initial tristimulus (X_i, Y_i, Z_i) to the final tristimulus (X_f, Y_f, Z_f) with two reference neutral colors through (2), shown at the bottom of the page, where $(x_{\mathrm{ref1}}, y_{\mathrm{ref1}})$ and $(x_{\mathrm{ref2}}, y_{\mathrm{ref2}})$ are the initial and final reference chromaticity values, respectively, and $z_{\mathrm{ref1}} = 1 - x_{\mathrm{ref1}} - y_{\mathrm{ref1}}$ and $z_{\mathrm{ref2}} = 1 - x_{\mathrm{ref2}} - y_{\mathrm{ref2}}$. If $(x_{\mathrm{ref1}}, y_{\mathrm{ref1}})$ and $(x_{\mathrm{ref2}}, y_{\mathrm{ref2}})$ are close to each other, the change in tristimulus values would be slight, and vice versa.

Color pixels are adjusted in different ways based on their similarity to the dominant color. Color pixels close to the dominant color in the perceptual sense are considered background pixels and made more achromatic. Otherwise, they are regarded as the pixels belonging to the foreground. Since the proposed background adjustment aims to recover the color of paper, pixels belonging to the foreground should be modified slightly or not modified at all. This modification can be

$$\alpha = \begin{cases} 1 - \left(\frac{d_{\mathrm{Lab}}((L,a,b),(L_D,a_D,b_D))}{D_{\mathrm{th}}}\right)^{\beta}, & \text{if } d_{\mathrm{Lab}}((L,a,b),(L_D,a_D,b_D)) < D_{\mathrm{th}} \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

$$\begin{pmatrix} X_f \\ Y_f \\ Z_f \end{pmatrix} = \begin{pmatrix} x_{\mathrm{ref2}} y_{\mathrm{ref1}} / x_{\mathrm{ref1}} y_{\mathrm{ref2}} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & z_{\mathrm{ref2}} y_{\mathrm{ref1}} / z_{\mathrm{ref1}} y_{\mathrm{ref2}} \end{pmatrix} \begin{pmatrix} X_i \\ Y_i \\ Z_i \end{pmatrix} \tag{2}$$

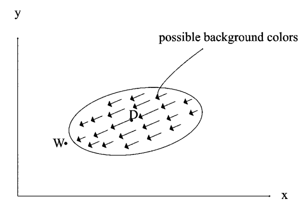

Fig. 3. Color shift owing to background adjustment. W represents the white point of a display. D stands for the dominant color of a given Chinese painting. The elliptic contour is the fuzzy boundary of possible background colors controlled by D_{th}. Colors outside the elliptic contour are not modified at all.

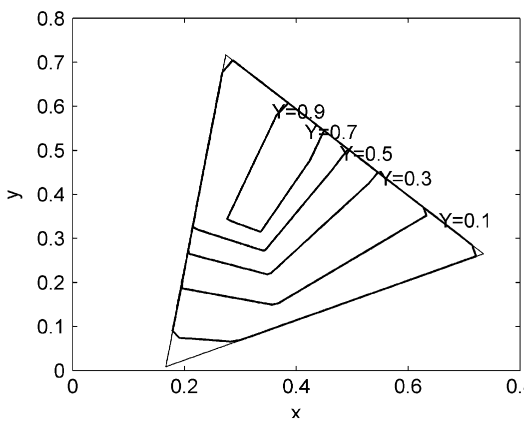

Fig. 4. Several producible color gamuts of a display for Y=0.1, 0.3, 0.5, 0.7, and 0.9 in CIE xy diagram. Some colors on the triangular edge are outside the producible gamut.

achieved by setting (x_{ref1}, y_{ref1}) to (x_D, y_D), the xy chromaticity value of the dominant color, and setting (x_{ref2}, y_{ref2}) as

$$\begin{pmatrix} x_{\mathrm{ref2}} \\ y_{\mathrm{ref2}} \end{pmatrix} = (1-\alpha)\begin{pmatrix} x_D \\ y_D \end{pmatrix} + \alpha \begin{pmatrix} x_w \\ y_w \end{pmatrix} \tag{3}$$

where (x_w, y_w) denotes the xy chromaticity value of the white of the display device. The color shift owing to the background adjustment is roughly illustrated in Fig. 3. Colors that are very different from the background color are altered less, and vice versa.

III. Saturation Enhancement

The best way to enhance the saturation contrast of a given image is to histogram equalize the saturation distribution of the image. However, the image resulting from applying saturation histogram equalization could be rather unnatural. The color enhancement methods proposed by [3] and [4] are implemented by saturating all the chromatic colors and then desaturating them using the center of gravity law for color mixture. Nevertheless, an issue in [3] and [4] deserves mention here. Fig. 4 illustrates the color gamut of a display at several luminance values in the xy chromaticity diagram. Clearly, not all the producible colors at any luminance level cover the whole color gamut triangle. Consequently, for a specific fully saturated color, a color at the edge of the gamut triangle in the CIE xyY space might be outside the producible parallelepiped. In [3] and [4], mixing a fully saturated color with a neutral color (white) does not always yield a producible color and an extra gamut clipping process, as in [5], is required. This problem mainly produces artifact pixels in the resultant image.

The above problem primarily arises from the incomplete separation of chromaticity and luminance components. Thus, this study proposes a color enhancement which considers the physical constraints of displays. The two steps mentioned in the following sections achieve the proposed color enhancement. First, the enhancement procedure finds the most saturated color, which is producible while preserving the hue and the luminance. Second, the saturation ratio of color is defined and adjusted according to a specified saturation ratio transfer function.

A. Step 1: Finding the Most Saturated Color

Saturating a color $C = (x, y, Y)$ to $S = (x_s, y_s, Ys)$ while preserving its hue can be expressed as

$$\begin{pmatrix} x_s \\ y_s \end{pmatrix} = \begin{pmatrix} x \\ y \end{pmatrix} + k \begin{pmatrix} x - x_w \\ y - y_w \end{pmatrix}. \tag{4}$$

The scalar k is termed the saturation gain here. It is generally accepted that as k increases, the saturation of the resultant color also increases. Since no luminance components are modified, Ys equals Y. The saturated color S is converted back to the RGB space through

$$\begin{aligned} \begin{pmatrix} R_s \\ G_s \\ B_s \end{pmatrix} &= T^{-1}\begin{pmatrix} X_s \\ Y_s \\ Z_s \end{pmatrix} \\ &= T^{-1}\begin{pmatrix} X_s \\ Y \\ Z_s \end{pmatrix} \\ &= T^{-1}\frac{Y}{y_s}\begin{pmatrix} x_s \\ y_s \\ z_s \end{pmatrix} \end{aligned} \tag{5}$$

where T represents the conversion matrix from RGB to XYZ and $z_s = 1 - x_s - y_s$.

The dynamic range of the red, green, and blue channels of a given display is assumed to be constrained in [0, 1]. Consequently, given a color C, the most saturated color of the same hue and with the same luminance must satisfy

$$0 \le \begin{pmatrix} R_s \\ G_s \\ B_s \end{pmatrix} = T^{-1}\frac{Y}{y_s}\left(\begin{pmatrix} x \\ y \\ z \end{pmatrix} + k\begin{pmatrix} x - x_w \\ y - y_w \\ z - z_w \end{pmatrix}\right) \le 1. \tag{6}$$

Otherwise, this saturated color cannot be correctly produced on the display. The producible color with the largest saturation has k equal to the maximum value in the intersection of the three solution intervals of the inequalities in (6). Replacing the largest k satisfying the inequalities (6) into (4) yields the most saturated color $S = (x_s, y_s, Y)$, which is producible.

B. Step 2: Adjusting the Saturation Ratio

Step 1 obtains the most saturated color S, which can be displayed without hue shift. Adapted from the definition of colorimetric purity, in Fig. 5, we define an argument called the saturation ratio of a color C as

$$r = \frac{\overline{\mathrm{CW}}}{\overline{\mathrm{SW}}} \tag{7}$$

where W denotes the reference white of the display in the CIE xy diagram. While the colorimetric purity of a color indicates the amount of white mixed with the spectral color, the saturation ratio represents the

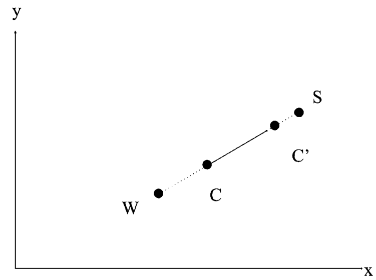

Fig. 5. C and C′ have the same hue and luminance. C is enhanced to C′ with larger saturation ratio than C by using the color gamut constraint.

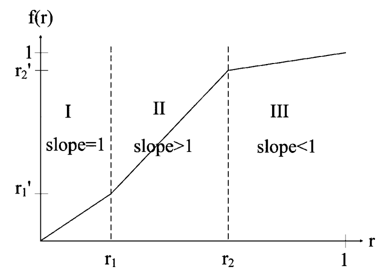

Fig. 6. Possible choice of the saturation ratio transfer function for saturation enhancement.

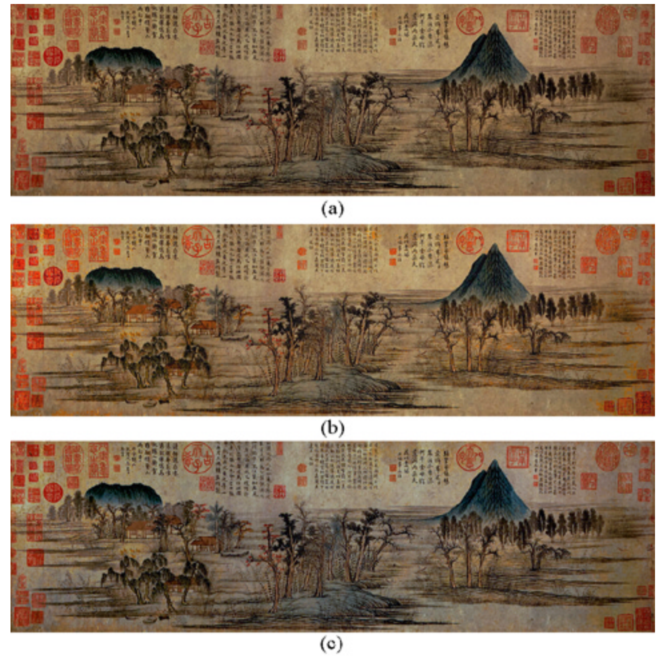

Fig. 7. (a) Original image. (b) Pei's method [4] applied to (a). (c) Application of the proposed method to (a) $D_{th} = 25, \beta = 5$, and the saturation transfer function $f(r)$ as Fig. 6 with $r_1 = 0.3, r_2 = 0.4, r_1' = 0.3$, and $r_2' = 0.6$.

quantity of white mixed with the color which could be displayed on a given display device with the maximum saturation of its hue.

The saturation ratio of an achromatic color is close to zero. Meanwhile, colors which are almost saturated have saturation ratios very close to one. Hence, the saturation of a color is altered by tuning its saturation ratio. By increasing the saturation ratio, the color becomes more saturated.

The adjustment over the saturation ratio r is somewhat arbitrary. However, reversing or changing the saturation relationship among pixels of a painting is undesirable. For instance, after the saturation enhancement is applied, a pixel that is originally pale blue should not be more saturated than a pixel that is originally blue. A monotonically increasing saturation ratio transfer function is used to maintain the saturation relationship among image pixels. Besides, it is not advisable to saturate colors close to the reference white, since such achromatic colors belong to a region of hue ambiguity.

Fig. 6 shows the suggested saturation transfer function. For colors with small saturation ratio, below the threshold r_1, the saturation remains unchanged owing to hue ambiguity at low saturation. The colors in the middle saturation region, with saturation ratio below r_2, but larger than r_1, are enhanced more than the colors with low or high saturation.

Resorting to a certain saturation transfer function $f(r)$, saturating a pixel $C = (x, y, Y)$ with original saturation ratio r to $C' = (x', y', Y)$ can be represented as

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = (1 - f(r)) \begin{pmatrix} x_w \\ y_w \end{pmatrix} + f(r) \begin{pmatrix} x_s \\ y_s \end{pmatrix} \tag{8}$$

where (x_s, y_s) is the most saturated color from step 1. The proposed saturation enhancement can be easily controlled by $f(r)$.

IV. Experimental Results

Digital images of several ancient Chinese paintings have been processed using the two-step procedure proposed in this study. The experimental results demonstrate that the proposed approach can enhance the colors of Chinese paintings more vividly.

Figs. 7(b), 8(b), and 9(b) show the images obtained by applying Pei's saturation enhancement [4] to the original images Fig. 7(a), 8(a), and 9(a), respectively. 7(c), 8(c), and 9(c) show the images obtained by using the proposed method with different empirical parameters listed in the captions. We set $\beta = 5$ in all the experiments in accordance with the rule of thumb described in Section II. For the paper with nonuniform aging degradations, it is desired to set D_{th} large to capture the background pixels far from the dominant color in a perceptual sense. However, a large value for D_{th} might result in misclassifying some foreground pixels, not far from the dominant color, as background pixels. On the other hand, setting D_{th} to a small value can keep some background pixels not very close to the dominant color from being modified by the proposed background adjustment.

The empirical threshold r_1 is chosen to be in [0.2, 0.3], and the color with saturation less than r_1 is considered with low saturation. To fix the saturation of colors with low saturation, r_1' equals r_1. The effect of magnifying the color contrast of middle saturation is determined by the difference between r_2 and r_2'. Hence, at least they must differ from each other by 0.2; otherwise, the contrast enhancement could be unnoticeable. However, that difference cannot be too large to make the resultant image over saturated or to let the contrast between colors of high saturation diminish. That is, r_2' could not be too close to one. Hence, with the above constraints, r_2 and r_2' are suggested to be numbers in [0.4,0.5] and in [0.6, 0.7], respectively.

Despite the saturation of Fig. 7(b) being enhanced globally, the saturation contrast of Fig. 7(b) is not enhanced. Instead, the proposed background adjustment improves the contrast between unpainted and painted regions. The proposed saturation enhancement retains the background achromatic and enhances the saturation of objects. The hues of objects, for example, flowers, roof, and mountains, in Fig. 7(c) are more easily recognized than those in Fig. 7(b). Moreover, in Fig. 8(c), the objects with color close to blue or green are more distinct than those in Fig. 8(a) and (b). Although the saturation of Fig. 8(b) exceeds that of the original image Fig. 8(a), the saturation of the background color is also enhanced. Consequently, Fig. 8(c)

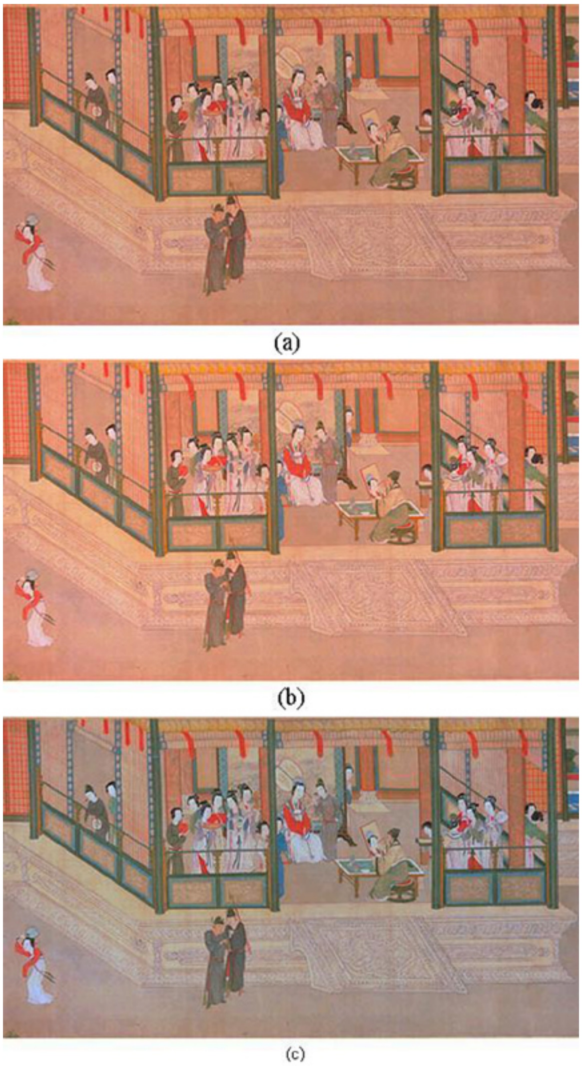

Fig. 8. (a) Original image. (b) Pei's method [4]. (c) Proposed method with $\mathrm{D_{th}} = 20, \beta = 5$, and the saturation transfer function $f(r)$ as Fig. 6 with $r_1 = 0.3, r_2 = 0.4, r_1' = 0.3$, and $r_2' = 0.7$

appears more natural and less reddish than Fig. 8(b). In Fig. 9, since the background color is roughly the complementary to the color of the lotus, compared with Fig. 9(c), the color of the lotus in Fig. 9(b) appears somewhat dark, despite the saturation of the whole image being enhanced.

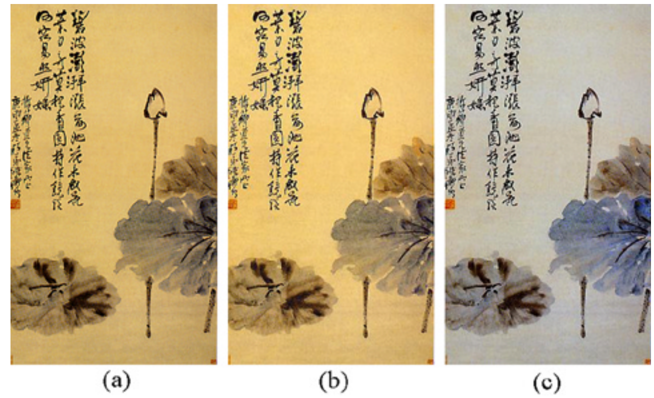

Fig. 9. (a) Original image. (b) Pei's method [4]. (c) Proposed method with $\mathrm{D_{th}} = 30, \beta = 5$, and saturation transfer function as Fig. 6 with $r_1 = 0.2, r_2 = 0.4, r_1' = 0.2$, and $r_2' = 0.7$.

V. Conclusion

This study presents an effective algorithm with high manageability for the virtual restoration of ancient Chinese paintings. The proposed method comprises two phases: background adjustment and saturation enhancement. Background adjustment and saturation enhancement aim to restore the color of background and foreground, respectively. Several experiments are also performed to demonstrate that the proposed scheme is satisfactory.

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