Improved Color Reproduction by Hue Preservation in Integrated Multi-scale Retinex

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Abstract

Tone reproduction is now widely used in the field of HDR imaging and image enhancement, especially to provide the proper luminance, so that captured images give the same sensation as the real scene. As a result, a high contrast and naturalness of colors can be obtained. In recent studies on tone reproduction with the objective of reproducing natural looking colors in digital images, an integrated multi-scale retinex (IMSR) has produced great naturalness in the resulting images. Most methods, including IMSR, work in RGB or quasi-RGB color spaces, although some methods have adopted the use of luminance. As such, this produces hue distortion from the perspective of the human visual system, that is, hue distortion in CIELAB color space. Accordingly, this paper proposes an enhanced IMSR method in a device-independent color space, CIELAB, to preserve the hue and obtain a high contrast and naturalness. To achieve the desired objectives, a captured sRGB image is transformed into CIELAB color space. The IMSR is then applied to only the L^* values, thereby preserving the balance of the color components. However, since this process causes unnatural saturation, saturation adjustment is performed by applying the ratio of the chroma variation at the sRGB gamut boundary according to the corrected luminance. The adjusted CIELAB values are then transformed into sRGB using an inverse transform function. In experiments, the proposed method is shown to improve the visibility in dark shadows and bright regions in the resulting images and reduce any color distortion.

Introduction

Tone reproduction or tone mapping is achieved through an operator attempting to replicate the sensation of real-world luminance intensities in images from a regular digital camera. Most digital camera sensors are limited as regards capturing both the high and low luminance regions of a scene. In fact, such devices can only sense a dynamic range of about 10^2cd/m^2, whereas the dynamic range of a real scene is almost 10^8cd/m^2. Therefore, unless properly treated, images captured from regular digital cameras only present light or dark regions. Meanwhile, the dynamic range of the human eye is almost 10^5cd/m^2, which also does not cover the entire dynamic range of a scene, however, the human visual system uses a mechanism called “lightness adaptation” to perceive the light and dark areas of a scene simultaneously[7][8]. Thus, to obtain a similar perception when looking at digital images, tone reproduction methods are used.

There are two types of tone reproduction technique: TRC (spatially-invariant tone reproduction curve) and TRO (spatially-variant tone reproduction operator)[3]. TRC methods are based on the global adaptation mechanism of human vision and performed pointwise on the image data. However, while simple and efficient, these methods do not preserve the local contrast in the case of both light and dark regions. In contrast, TRO methods are based on a multi-resolution decomposition algorithm, such as Gaussian decomposition, and operate in a local way on the image data (e.g. by convolution). As a result, the local image contrast is preserved, although unwanted spatial artifacts sometimes occur.

Recently, various Retinex methods, which are TRO methods, have been widely used, due to their high local contrast and improved visibility, even given the presence of artifacts, such as halo effects. Jobson and others also developed the Retinex theory into the single-scale retinex (SSR) method and multi-scale retinex (MSR) method, as a combined form of the SSR method[5]. Initially, the MSR method had problems related to appropriate values for the parameters, chromatic unbalance, color distortion, noise, and graying out. Yet, a lot of work has been dedicated to improve these issues. A multi-scale retinex with color restoration (MSRCR) attempted to overcome the graying out phenomenon in large uniform areas of an image by adopting a color restoration function to control the saturation of the final rendition[6]. However, the output does not reproduce natural tones and colors when compared with the real scene. Meanwhile, an adaptive scale-gain Retinex algorithm was introduced to prevent halo artifacts and suppress chromatic unbalance and noise by synthesizing both the original image and the image processed by MSR[2]. In a recent paper, an integrated multi-scale retinex (IMSR) algorithm was introduced to improve the visibility in dark shadow areas of natural color images, while preserving a pleasing contrast without banding artifacts[1]. In this case, a Gaussian pyramid decomposition is used to reduce the computation time for generating a large-scale surround, while an integrated luminance surround value is applied to each channel to preserve the color balance in RGB color space. Other papers have also attempted to prevent color or chroma distortion by controlling the ratio of the RGB channels. However, regardless of such efforts, all existing methods lead to some perceived color distortion. Based on the assumption that the input images are directly acquired in sRGB, the execution of MSR in RGB color space does not preserve the perceived hue, that is, the hue of the original image in CIELAB color space is distorted.

Accordingly, this paper proposes an enhanced IMSR method in a device-independent color space, namely CIELAB, to preserve the hue. First, a captured sRGB image is transformed into CIEXYZ color space and then into CIELAB color space to calculate the lightness, hue, and saturation. The IMSR is then only applied to the lightness values, thereby preserving the balance of the color components. Thereafter, the L^* values produced by the IMSR are mapped to displayable values by means of a cumulative distribution function to preserve the luminance in the high valued regions. However, since this process results in an unnatural saturation, a saturation adjustment according to the changed luminance is applied to the a^* and b^* channels. Based on an analysis of the chroma value variation with the IMSR, the ratio of the chroma variation is adjusted at the sRGB gamut boundary depending on the luminance variation to achieve color naturalness. Finally, the adjusted CIELAB values are transformed into sRGB using an inverse transform function. In experiments with real scene images, the results show a high visibility in both dark and bright regions, and natural colors without any hue distortion. Furthermore, in the case of an observer preference test, most observers perceived the images from the proposed method as more natural than previous results.

Previous Integrated Multi-scale Retinex Method

The IMSR method proposed by Wang[1] is based on the adaptive scale-gain retinex developed by Kotera et al[2] with certain differences. First, the IMSR adopts a linear space without a logarithmic conversion to avoid any uncertainty for noise and the output range spreading in dark shadows. Second, the IMSR only uses the luminance channel to form the surround image, and then applies this result to each color channel to maintain the color balance. As such, the main difference is the use of an integrated multi-scale luminance surround from multiple luminance surround images using Gaussian filters with a different standard deviation. The whole process is illustrated in Figure 1.

Preserving the color balance is achieved by applying the integrated surround images Ssum to each channel in the IMSR. The following equation describes the IMSR process:

$$SSR_{sum}(x,y,\sigma_m) = A\frac{I_i(x,y)}{S_{sum}(x,y,\sigma_m)}, \tag{1}$$

where I is the input RGB image, SSR_{sum} is the image calculated by the Retinex, i is the index indicating the RGB channel, A is the gain coefficient, and S_{sum} is the integrated surround image. S_{sum} is calculated by integrating the different surround images $S_m(x, y, \sigma_m)$ with different adaptive weights $w(\sigma_m)$ as follows:

$$S_{sum}(x,y,\sigma_m) = \sum_{m=1}^{M} w(\sigma_m) S_m(x,y,\sigma_m). \tag{2}$$

Also, Eq. (3) shows the calculation of the surround images performed by convolution between the luminance Y images using Gaussian filters $G_m(x, y)$ with a different standard deviation σ_m.

$$S_m(x,y,\sigma_m) =< G_m(x,y) \otimes Y(x,y) > \tag{3}$$

$$\sum_{m=1}^{M} w(\sigma_m) = 1 \tag{4}$$

The optimum gain coefficient A and weights w are obtained by the Trial and Error method based on human vision[1]. As such, the optimum gain coefficients and weights used in this study were based on those determined for the IMSR.

For the IMSR results shown in Figure 2, there is less banding than with the MSR. Also, the visibility is increased with the naturalness of the colors. Nonetheless, although this algorithm can preserve the color balance in RGB color space, the perceived hue is not preserved. Thus, if the original image is a sRGB image, the perceived hue can be thought as the hue value in CIELAB color space. Sometimes, the hue values in the IMSR results are changed by almost 180°, as shown in Figure 2(c).

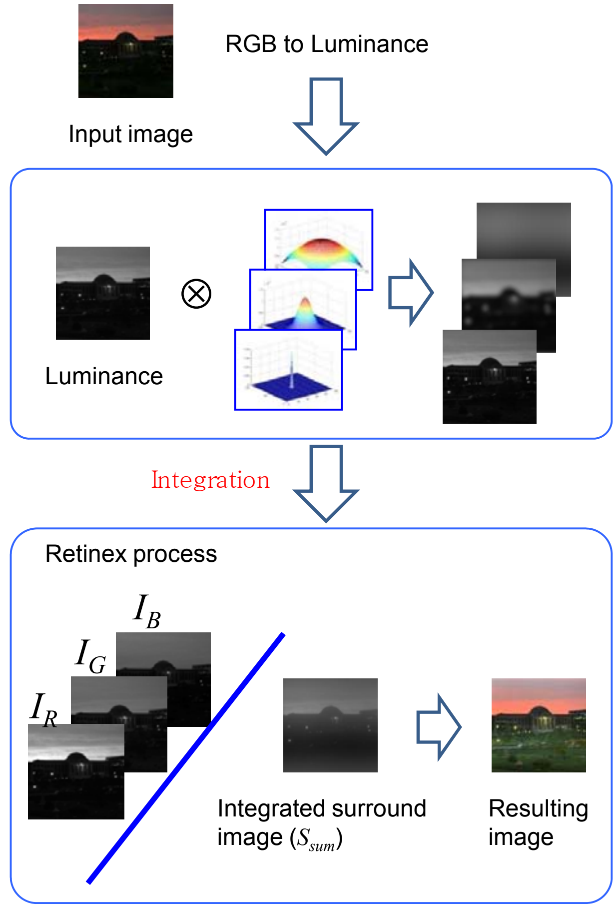
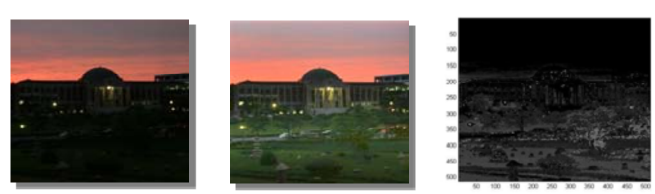


***Figure 1**. Flowchart for IMSR using integrated surround.*

Proposed Tone Reproduction Method

As mentioned above, the main objective of the proposed method is to preserve the perceived hue, and the process is explained in Figure 3. To consider the hue values, the proposed method adopts CIELAB color space. Therefore, the first process is the transformation of the sRGB values into CIELAB values. Then,



(a) (b) (c)

***Figure 2**. Result of IMSR and hue difference in CIELAB. (a) is the original image, (b) is the resulting image by IMSR, and (c) is the hue difference between the original and resulting image.*

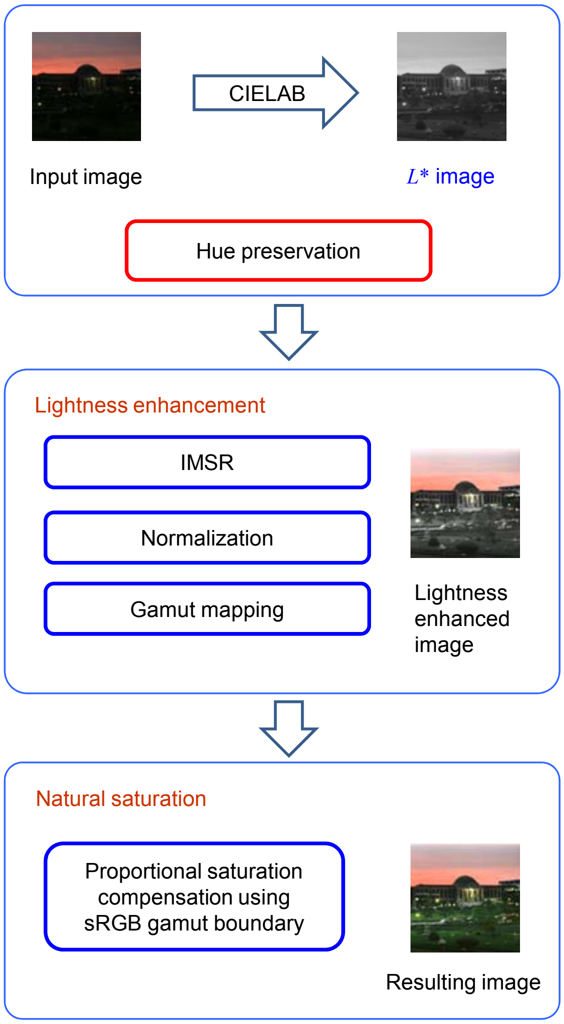


***Figure 3**. Procedure of the proposed tone reproduction method.*

only the lightness values are enhanced using the IMSR. However, normalization is a problem in the last IMSR process. Usually, the maximum value of lightness is applied to each channel as the denominator, yet this dulls the lightness values in bright regions. Therefore, to deal with this problem, the information of a cumulative distribution function (cdf) using enhanced values is applied. Next, the values of the sRGB gamut are clipped to the sRGB gamut boundary using a gamut mapping algorithm, resulting in a lightness-enhanced image. However, the dark regions in the original image look like a black-and-white image, as they have low saturation values, therefore, the enhanced regions still have low saturation values. Thus, the saturation is also enhanced based on proportional control using the sRGB gamut boundary information as the last process.

Lightness enhancement

To obtain the lightness, hue, and saturation values respectively, the original image, which has sRGB values, is first transformed into CIEXYZ values using the following equation[9]:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix} \begin{bmatrix} R_{sRGB} \\ G_{sRGB} \\ B_{sRGB} \end{bmatrix} \tag{5}$$

The CIEXYZ values are then transformed into CIELAB values using the following equation [9]:

$$L^* = \begin{cases} 116\left(\dfrac{Y}{Y_n}\right)^{1/3} - 16 & if \ \dfrac{Y}{Y_n} > 0.008856 \\ 903.3\left(\dfrac{Y}{Y_n}\right) & if \ \left(\dfrac{Y}{Y_n}\right) < 0.008856 \end{cases} \tag{6}$$

$$a^* = 500\left(f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right) \tag{7}$$

$$b^* = 200\left(f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right) \tag{8}$$

$$where \ f(x) = \begin{cases} x^{1/3} & if \ x > 0.00856 \\ 7.787x + \dfrac{16}{116} & if \ x < 0.00856 \end{cases} \tag{9}$$

Thereafter, only the lightness values obtained by the IMSR are used to preserve the hue values as follows:

$$L^*_{sum}(x, y, \sigma_m) = A\frac{L^*(x, y)}{S'_{sum}(x, y, \sigma_m)} \tag{10}$$

$$S'_{sum}(x, y, \sigma_m) = \sum_{m=1}^{M} w(\sigma_m) S'_m(x, y, \sigma_m) \tag{11}$$

$$S'_m(x, y, \sigma_m) = < G_m(x, y) \otimes L^*(x, y) > \tag{12}$$

This is actually the same process performed using RGB values in the IMSR, yet using $L^*(x, y)$ instead of $I_i(x, y)$. Thus, $L^*_{sum}(x, y, \sigma_m)$ is the enhanced lightness value, and the enhanced lightness is shown in figure 4(b). Next, normalization is performed

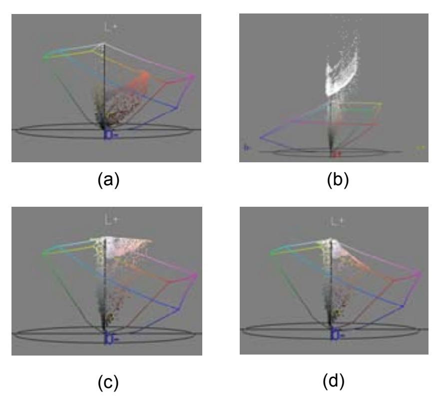


***Figure 4**. Gamut data of each step. (a) is the input image, (b) is the gamut data after IMSR in CIELAB color space, (c) is the gamut data after normalization, and (d) is the gamut data after HPMINDE gamut mapping method.*

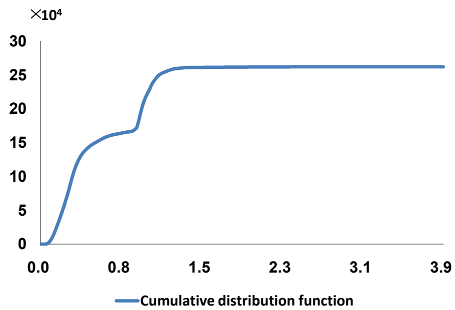


***Figure 5**. CDF of the enhanced lightness value.*

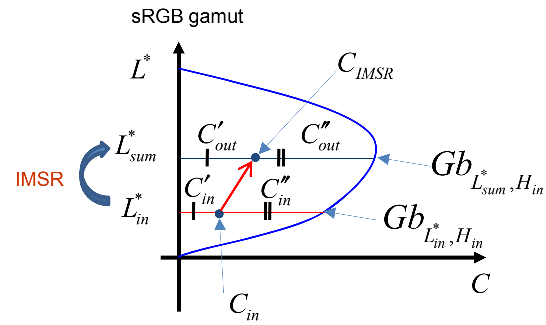


***Figure 7**. Saturation compensation.*

to produce displayable values. In this case, if the maximum value is used, only a small number of pixels will be involved in the normalization, as only a few pixels have the highest values, thereby resulting in a dull image. Thus, to reproduce bright regions correctly, cdfs of the enhanced lightness values are used. Figure 5 shows one of the cdfs. The cdf has the maximum value, as there are only a small number of highest values.

As a result, the value with an almost zero gradient in the cdf is used as the normalization value. Figure 4(c) depicts the result of normalization. Nonetheless, this method leads to the existence of values outside the display gamut. Therefore, a hue preserving minimum delta E clipping algorithm (HPMINDE) is applied to the values outside the gamut[10]. The final result of the IMSR using lightness values is shown in figure 4(d).

Saturation compensation in CIELAB

As described above, saturation compensation is needed for dark regions in the original image. As the process of the IMSR with lightness values does not change any chroma values, a^* and b^*, in the case of dark regions, which are significantly enhanced, the low chroma values are preserved. Before the saturation compensation, the variation of the chroma values by the IMSR with RGB values was observed using some test patches. Figure 6 illustrates the variation of the chroma values in CIELAB. As shown in Figure 6, the chroma variation showed a linear relationship with the lightness correction. The IMSR in RGB space showed a better visibility for areas that were only moderately corrected, while oversaturation was observed in dark regions.

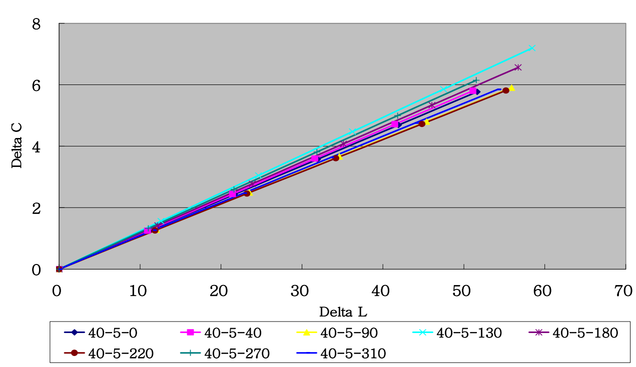


***Figure 6**. The variation of chroma values by IMSR using some patches.*

***Figure 8**. Comparison of saturation between IMSR and proposed method. (a) is the input image, (b) and (c) are resulting images by IMSR and by proposed method, respectively.*

To solve the problem of oversaturation, pixel values with originally small chroma values in dark areas need to be significantly improved during a large variation of lightness by the IMSR, whereas pixel values with originally large chroma values should be minimally improved during a small variation of lightness. Therefore, in the proposed method, the ratio of the sRGB gamut boundary is applied to the enhancement of the chroma values, as shown in Figure 7, which allows a low improvement of the chroma value for a small variation of lightness and vice versa. Therefore, this method can prevent oversaturation in light regions. In the proposed procedure, the initial step is finding the sRGB gamut boundary values corresponding to the input hue(H_{in}), input lightness(L^*_{in}), and result lightness(L^*_{sum}), respectively. The ratio of these boundary values is then applied to the input chroma value. Eq. (13) shows the saturation compensation for a pixel at position (x, y):

$$C_{IMSR}(x,y) = \frac{Gb_{L^*_{sum},H_{in}}(x,y)}{Gb_{L^*_{in},H_{in}}(x,y)} \times C_{in}(x,y) \tag{13}$$

where C is the chroma value and Gb is the gamut boundary value corresponding to the lightness, L^*_{in} and L^*_{sum}, with the input hue, H_{in}. In Figure 8 shows the effect of the saturation compensation using ratio of the sRGB gamut boundary.

Experiments and Results

In the experiments, sRGB images were acquired using a Cannon 10D camera. The results from the proposed method were compared with those from the MSR and IMSR methods. The parameters used for the IMSR and proposed methods were the same as those previously reported for Wang's algorithm[1].

Figure 9. Comparison of resulting image by the proposed method and other tone reproduction methods. First row: Input images. Second row: Resulting images by MSR. Third row: Resulting images by IMSR. Fourth row: Resulting images by proposed method.

Table 1. Average hue angle difference between an input and a resulting images.

	MSR	IMSR	Proposed
Sunset	56.05	2.00	1.20
Night	50.30	1.85	0.27
Car	28.74	3.74	3.56

Figure 9 shows the experimental results. In the first column, Figure 9 (a) Sunset, while the visibility of the MSR image (second row) is improved, the sunset area appears as bright as day, giving a very artificial feeling. Meanwhile, the IMSR image (third row) and proposed method image (fourth row) appear similar to the real scene for a sunset. However, the proposed method shows an improved visibility and contrast when compared to the IMSR results. In the second column, Figure 9 (b) Night, while the MSR image has a better visibility than the other methods, the picture is perceived as artificial due to excessive illuminant color removal. Meanwhile, the proposed method shows an improved contrast in the buildings when compared to the IMSR results. In the third column, Figure 9 (c) Car, the colors in the second row image

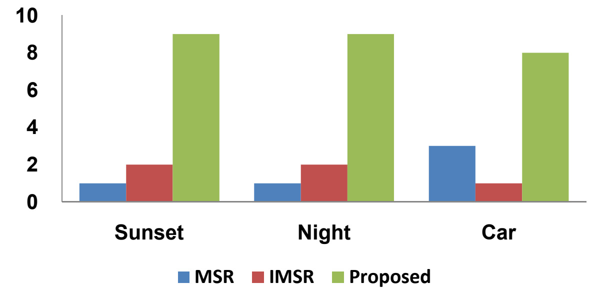


Figure 10. Resulting data of preference evaluation.

(MSR) are faded out, especially the lawn and car (red wine color). Meanwhile, the IMSR images are enhanced quite well, although the dark area around the tire seems to be noisy due to lightness over-enhancement. However, the fourth row image (proposed method) shows a better color rendition and reduced noise around the tire.

An objective evaluation of the hue difference is shown in Table 1, where the proposed method has the smallest average hue difference. As a final experiment, an observer preference test was performed. In this experiment, twelve observers, 4 females and 8 males aged 24-33, were involved. The observer's eyesight was either normal or had been corrected with eyeglasses. At each time four images were shown on the screen: the input image on the top left as reference, the resulting images by MSR, IMSR, and proposed method in clockwise order. The observers were asked to rank the images from the most natural looking to the least natural looking. As shown in Figure 10, most observers found the proposed method to have the best visibility and naturalness.

Conclusion

This paper proposed an enhanced IMSR method in CIELAB. The main goal of the proposed method is the preservation of the perceived hue, which means maintaining a constant hue from the original image in CIELAB color space (which has a linear property for the human visual system). Therefore, the IMSR method is executed in CIELAB color space with only lightness values. In addition, to ensure the appearance of a bright area, information from a cdf is used to perform lightness mapping. As a result, the hue is preserved, yet unnatural saturation occurs. Thus, to correct this phenomenon, based on the results from the IMSR, saturation compensation is performed according to the luminance variation by applying the ratio of the chroma values at the sRGB gamut boundary with the same luminance variation during the IMSR. In experiments with test images, the hue values were preserved. Also, by using the ratio of the chroma for the saturation compensation, oversaturated areas are prevented and pleasing natural colors maintained. In an observer preference test, most observers perceived that the resulting images from the proposed method had a higher visibility and naturalness.

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