Estimation and Simulation of Color Temperature in Complex Images Using Gamut Extremes

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Abstract

In this paper, we proposed an accurate method to estimate the color temperature directly from a captured natural image, and further develop a simulation method in which the color tone of an image can be adjusted according to give color temperature. To avoid the ambiguity causing from the metamerism of illuminant lights and reflective objects, the illuminant light source is constraint as the daylight; moreover, The extreme points of the color gamut of capture devices is used as the references in our estimation, which is very different from the traditional algorithm of white balance. A simulation method of an image under the illuminant daylight specified is also derived to further evaluate the performance of the estimation proposed. It is expected that the color temperature estimation in a complex image will be well solved and the digital composting of high quality will be more efficient and effective.

Introduction

The color temperature is very important information about the illuminant light source in captured images for many applications, including digital compositing, video processing, virtual studio, photography, and cinematography [1]. The inconsistency of color temperatures of illuminants may lead to unnatural results when compositing images or videos captured from different environments under various lighting conditions. The color balance according to the color temperature of an image is necessary before its post processing. The influence of color temperature make gamut to change that color appearance will change by color temperature [2]. Although the color temperature can be detected at the moment of the capture of images or videos, it is unfortunate that people sometimes have no chance to obtain the value accurate enough, or even without the standard color checkers on hand, for the later color correction needed. Thus, a method to directly estimate the accurate color temperature in a complex capture image that correlation based approaches such as

There are some previous works devoted to this color temperature estimation of an image. *Color adaptation model solved illuminant estimation based on the image gamut comparison [3]. A known illuminant was usually needed to evaluate the gamut of an image [4]. The Forsyth's approach derived a gamut mapping algorithm to estimate illuminants based on the concept of color constancy [5]. Juge also derived an algorithm, named hue-non-segment color temperature loci estimation, as a color temperature adjustment method for image synthesis [6]. In this paper, we improve the Juge's method with the modifications of the different reference loci and better computational precision.*

The basic concept of our estimation is mainly relied on the loci of the reference points in a color space, the

L*a*b* space was taken here. Traditional algorithms of white balance considered the locus of white point under various daylight illuminants as the indicator of their color temperatures. The white balance is essential a gamut mapping to locate the white points in an image and move these points to the reference one. We extend this idea with multiple reference points as the indicators of color temperature of an image. Green, cyan, magenta, and yellow are also selected beside white point. These reference colors in the sRGB color space are the extreme points, and also the extreme ones in a color gamut, named gamut extremes. Such an extreme property and the constraint of the daylight illuminant are adopted to avoid the ambiguity of the possibility of metamerism causing from various object reflectance and illuminant.

The simulation of an image from the virtual lighting process under the daylight environment with a different color temperature is also derived in this paper. The colors of all pixels in the simulated image are obtained from the fundamental definition of tristimulus by changing the illuminant spectrum after the determination of the object reflectance in the original image. Some images derived are used to illustrate the performance of this simulation.

The rests of this paper are organized as follows. Section 2 is the modeling and derivation of our method. Section 3 is the experimental results of our studies. Some conclusions and discussions are given in Section 4.

Modeling

All the derivations in this study are based on the fundamental definition of tristimulus values, defined by formula (1).

$$X = k\int_{vis} R(\lambda)P(\lambda)\bar{x}(\lambda)d\lambda$$
$$Y = k\int_{vis} R(\lambda)P(\lambda)\bar{y}(\lambda)d\lambda, \qquad (1)$$
$$Z = k\int_{vis} R(\lambda)P(\lambda)\bar{z}(\lambda)d\lambda$$

where k is the normalization constant that

$$k = \frac{100}{\int_{vis} P(\lambda)\bullet \bar{y}(\lambda)d\lambda},$$

$\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ are the color matching functions, *R(λ)* is the spectral reflectance of the reflector, *P (λ)* is the spectral power distribution of the illuminant. Moreover, all our evaluations of color differences are calculated in the L*a*b* color space, defined by formula (2).

$$L^* = 116\left[\left(\frac{Y}{Y_w}\right)^{\frac{1}{3}} - \frac{16}{116}\right]$$
$$a^* = 500\left[\left(\frac{X}{W_w}\right)^{\frac{1}{3}} - \left(\frac{Y}{Y_w}\right)^{\frac{1}{3}}\right], \qquad (2)$$
$$b^* = 200\left[\left(\frac{Y}{Y_w}\right)^{\frac{1}{3}} - \left(\frac{Z}{Z_w}\right)^{\frac{1}{3}}\right]$$

where X, Y, Z are the tristimulus values of a pixel in an image, and X_w, Y_w, Z_w are the tristimulus values of reference white.

The estimation of color temperature is according to the loci of some reference colors of a certain reflector in the L*a*b* space with respect to the daylight illuminant of various temperature values. Different from the Juge's work that used 20 reference colors, we take 5 high chroma colors, that is, green (G), cyan (C), magenta (M), yellow (Y), and white (W), which is the extreme points in the sRGB color space used by most capture devices. The referred colors mentioned in her work may lead to the metameric ambiguity of various combinations of spectral reflectance and illuminants. Those points in our research are nearly considered as the extreme values of a gamut of an image captured from any input device; theoretically, no confusion will happen there.

The color temperature estimate of an image is modeled by the weighted average of the color temperature values of all pixels in this image, defined by formula (3).

$$\hat{t} = \frac{1}{N}\sum_{i=1}^{N} w(i)\hat{t}(i), \qquad (3)$$

where $\hat{t}(i)$ is the estimate of color temperature of pixel i, defined by the formula (4) shown below, N is the pixel number of an image, and $w(i)$ is the weight of pixel i.

$$\hat{t}(i) = \arg\min_t \{\arg\min_k \|l(k,t) - p(i)\|\}, \quad (4)$$

where $l(k, t)$ is the locus of the k-th reference color from t=2000 to t=25000, that is, t is the indicator of the color temperature to be estimated, and $p(i)$ denotes pixel i.

The weight $w(i)$ is a function of distance between the pixel color and the nearest locus of reference colors in L*a*b* space. The larger the weight comes weaker, and the smaller the weight comes stronger. It is noted that the daylight is considered as the only environmental illuminant.

The spectral reflectance of objects captured into an image is the key point of both the computation of reference loci and the simulation of the virtual environmental lighting. In our study, the spectrum of object reflectance is modeled by the Bernstein polynomial of degree n [7], which is defined by the formula (5) shown below.

$$B_n(h) = \sum_{v=0}^{n} \binom{n}{v} c_v h^v (1-h)^{n-v}, \quad (5)$$

where h is from 0 to 1, $\binom{n}{v}$ is the binomial coefficient, $c(v)$ is the control coefficient to determine the shape of this polynomial, and n=4 in this research, that is, a polynomial of degree 4 of the following form is used as the spectral reflectance of an individual pixel in an image.

$$\begin{aligned} &B_4(h) = \\ &c_0(1-h)^4 + 4c_1 h(1-h)^3 + 6c_2 h^2 (1-h)^2 + \\ &4c_3 h^3 (1-h) + c_4 h^4, \end{aligned} \quad (6)$$

where h is from 0 to 1 to present the wavelength of the visible light from 380nm to 780nm.The control coefficients is further constrained by setting c_0=0 and c_4=0 to simplify the estimation in our evaluation.

The estimation of the spectral reflectance of a pixel $p(i)$ with color $(Ri,Gi,Bi)^T$ in an image is derived by solving the linear system from the relation between the sRGB and XYZ color space under the D65 illuminant. This relation maps $(Ri,Gi,Bi)^T$ in the sRGB space into $(Xi,Yi,Zi)^T$ in the XYZ space. In addition, substituting formula (6) into formula (1), we can obtain the equations presenting the relation between the sRGB coordinates and its spectral reflectance, shown in formula (7).

$$\begin{aligned} X_i &= f_X(R_i,G_i,B_i) = k\int_{vis} B_4(h) P_{D65}(\lambda)\bar{x}(\lambda)d\lambda \\ Y_i &= f_Y(R_i,G_i,B_i) = k\int_{vis} B_4(h) P_{D65}(\lambda)\bar{y}(\lambda)d\lambda, \\ Z_i &= f_Z(R_i,G_i,B_i) = k\int_{vis} B_4(h) P_{D65}(\lambda)\bar{z}(\lambda)d\lambda \end{aligned} \quad (7)$$

where (f_X,f_Y,f_Z) presents the conversion of a color point from sRGB to XYZ space, $h=(\lambda-380)/(780-380)$, that is, the interval of λ is considered from 380nm to 780nm, and $P_{D65}(\lambda)$ is the spectral power distribution of the D65 daylight illuminant.

Since the discrete representation of the D65 spectrum and the three color matching functions from the CIE standard data, formula (7) can be rewritten as follows.

$$\begin{aligned} X_i &= f_X(R_i,G_i,B_i) = k\sum_{j=0}^{80} B_{4,j} P_{D65,j}\overline{x_j} \\ Y_i &= f_Y(R_i,G_i,B_i) = k\sum_{j=0}^{80} B_{4,j} P_{D65,j}\overline{y_j}, \\ Z_i &= f_Z(R_i,G_i,B_i) = k\sum_{j=0}^{80} B_{4,j} P_{D65,j}\overline{z_j} \end{aligned} \quad (8)$$

where k is the normalization constant that

$$k = \frac{100}{\sum_{j=0}^{80} P_{D65,j}\overline{y_j}},$$

j = 0, 1, 2, … , 80, that is, the visual spectrum from 380nm to 780nm is equally spacing as 80 interval s of 5nm, there are 81 data points to present the original continuous functions, and $B_{4,j}=B_4(j/80)$.

Furthermore, the two control coefficients c_0 and c_4 in $B_4(h)$ in formula (6) are assigned to be 0, the degree of freedom of $B_4(h)$ is reduced to be three, which only c_1, c_2, and c_3 are the parameters needed to be determined. In fact, they can be easily obtained by solving the three equations of formula (8) directly.

Thus, the spectral reflectance of an image pixel with sRGB color $(Ri,Gi,Bi)^T$ can be derived from the following formula (9).

$$\begin{aligned} X_i &= f_X(R_i,G_i,B_i) = k\sum_{j=0}^{80} B^*_{4,j} P_{D65,j}\overline{x_j} \\ Y_i &= f_Y(R_i,G_i,B_i) = k\sum_{j=0}^{80} B^*_{4,j} P_{D65,j}\overline{y_j}, \\ Z_i &= f_Z(R_i,G_i,B_i) = k\sum_{j=0}^{80} B^*_{4,j} P_{D65,j}\overline{z_j} \end{aligned} \quad (9)$$

where

$$B^*_{4,j} = 4c_1h(1-h)^3 + 6c_2h^2(1-h)^2 + 4c_2h^3(1-h)$$

for

$$h = \frac{j}{80}, j = 0,1,2,...,80.$$

The solutions, c_1, c_2, and c_3, of the linear system represented by formula (9) determine the shape of the spectral reflectance of color $(Ri,Gi,Bi)^T$ in an artificial manner based on the principle of metamerism. The spectral reflectance of the reference colors used in this study, that is, green, cyan, magenta, yellow, and white, are shown in Figure. 1.

The simulation of an image virtually captured with the daylight illuminant of a specified color temperature can be directly acquired from changing the spectral power distribution $P_{D65}(.)$ in formula (7) as another spectrum with the reflectance obtained.

Some experimental results including both estimation and simulation of color temperature are shown in the next section.

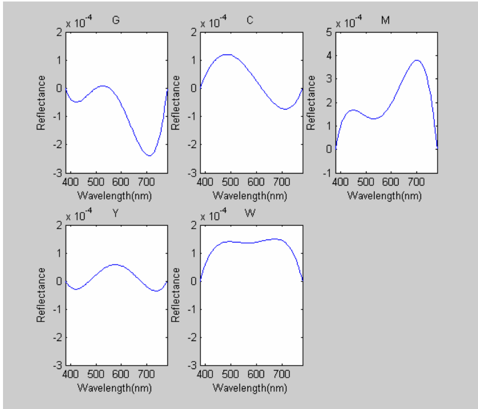


Figure 1. Spectral reflectance of the reference colors, green, cyan, magenta, yellow, and white.

Experimental Results

The images collected for our experiments contain two parts, one is the standard images for the color management of printing, and the other is some images captured from a digital camera. The camera used is Canon EOS 400D with the disable of the function of white balance. A color meter, Konica Minolta Color Meter IIIF, was also taken in the capture process to recode the truly color temperature.

Table 1 shows the performance of the estimation method we proposed for the standard images. The error is defined as follows.

$$Error = \frac{|CT_{true} - CT_{estimate}|}{CT_{true}} \times 100\%,$$

where CT_{true} and $CT_{estimate}$ are the truly color temperate and the color temperature estimated respectively. All the standard images are captured under the D65 illuminant restrictedly. All the errors are less than 5% excepting the last one in Table 1. There are two images with their errors of even 0.07% and 0.13%.

The results of the image we captured are shown in Table 2. Most errors of the captured images look well but those of lower color temperature. The last two images of 4910K and 4920K in Table 2 are with their estimation errors of 27.93% and 19.08% respectively.

Finally, Table 3-1 and Table 3-2 illustrate some simulations of two individual standard images to evaluate the usefulness of changing the virtual daylight illuminant from D65 to others. These results seem reasonable and fit our intuition.

Table 1. Performance of standard images

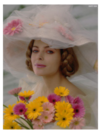
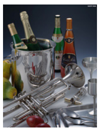
images	CT_{true} (° K)	$CT_{estimate}$ (° K)	Error (%)
	6500	6495.21	0.07
	6500	6177.77	4.96
	6500	6268.62	3.56
	6500	6599.91	1.54
	6500	6207.39	4.50
	6500	6618.02	1.82
	6500	6406.31	1.44
	6500	6508.64	0.13
	6500	5859.88	9.94

Table 2. Performance of captured images

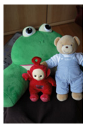
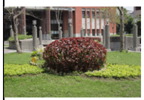
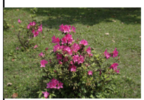
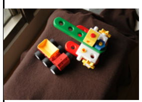
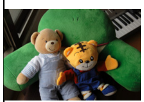
images	CT_{true} (° K)	$CT_{estimate}$ (° K)	Error (%)
	7200	7139.41	0.08
	7160	7427.66	3.74
	5350	5618.28	5.01
	6170	6505.79	5.44
	5240	5228.99	0.21
	4910	6281.54	27.93
	4920	5858.91	19.08

Table 3-1. Simulation of various color temperatures

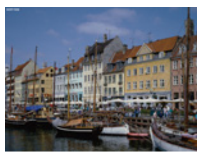
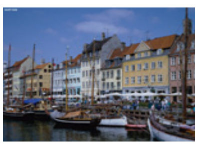
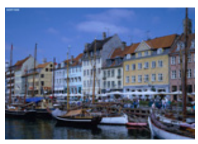
 6500K	 3000K
 5000K	 7000K
 9000K	 15000K

Table 3-2. Simulation of various color temperatures

 6500K	 3000K
 5000K	 7000K
 9000K	 15000K

Conclusions

In this paper, an estimation method of color temperature of the daylight illuminant was proposed for a natural complex image. According to the experimental results obtained, this estimation is very accurate for images with various daylight illuminants. In addition, a simulation method was also developed to virtually change the illuminant in an image captured. Some experimental results show that the performance of this simulation seems good enough.

However, further studies are needed for more experimental images especially for those with lower color temperature. It is also worthy of removing the constraint of a single illuminant of daylight for more practical applications in the future study. Additionally, the accurate evaluation of the simulation performance will serve as the confirmation of its usefulness.

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