Color Correction in Color Imaging

Shuxue Quan
Sony Electronics Inc., San Jose, California

Noboru Ohta
Munsell Color Science Laboratory, Rochester Institute of Technology
Rochester, New York

Abstract

This paper discussed the color correction method with white point conversion in real digital camera signal processing. The color correction in both the RGB and XYZ color spaces are compared and it is found that the color correction performance in RGB space is better due to the sharper curves of camera RGB sensitivities than the color matching functions. It was also found that the performance is greatly affected by the shape of the illuminant.

Introduction

Illumination affects the recorded or observed colors of objects. Objects in pictures taken under tungsten light will tend to be reddish and they tend to appear pale under fluorescent light. These color shifts due to the illuminant changes in the image needed be corrected to the expected color under some reference illuminant. The human visual system has the ability to discount the color shift due to illuminant change, which is referred to as color constancy, yet color constancy is incomplete.[1]

One of the most important tasks for digital camera is illuminant estimation, that is, to infer the illuminant information from upon the scene it captures or diminish the affect of the illumination to obtain data which more precisely reflects the physical content of the scene. The gray world assumption is the simplest approach to estimate illuminant. In this paper, the task is not illuminant estimation, but the correction of color shifts once the illuminant is known through measurement or estimation. The color shifts due to the illuminant changes can be represented as a difference between the tristimulus values under different illuminants (Figure 1). If the surface reflectance spectra can be estimated from the tristimulus values under reference illuminant, it is possible to acquire the tristimulus values under any test illuminant. Some work was done in this area,[2] but its accuracy is limited to the number of channels.

In real camera signal processing, since it is impossible to calculate and store an illumination related matrix for all the illuminations that might occur when using the camera, generally one transformation matrix is embedded for a pair of reference taking and target illuminants. For any other illuminant, a color correction matrix to adjust the camera signal into the target signal under reference illuminant is calculated *in situ*. This paper discusses how to choose this correction matrix due to the illuminant change. Since cameras transform RGB signals to XYZ values, the conversion matrix may happen in the RGB space or XYZ space, which gives different performance.

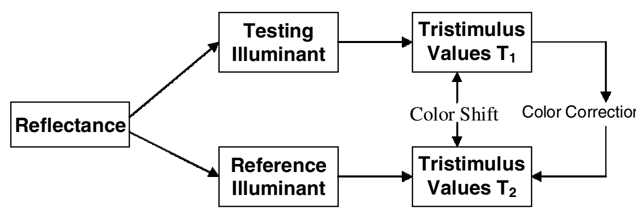


Figure 1. Correction of color shifts due to illuminant changes.

Color Correction Methods

White Point Mapping (WPM)

This method assumes that the proportional color shift due to the illuminant changes occurs in each color, and uses the relationship of testing white and reference white to determine the quantity of color correction. The correction matrix is defined as

$$D = \begin{pmatrix} \frac{X^w_{reference}}{X^w_{testing}} & & \\ & \frac{Y^w_{reference}}{Y^w_{testing}} & \\ & & \frac{Z^w_{reference}}{Z^w_{testing}} \end{pmatrix} \tag{1}$$

such that

$$T_2 = D \times T_1 \tag{2}$$

where

$$T^w_{reference} = [X^w_{reference}, Y^w_{reference}, Z^w_{reference}]$$

and

$$T^{w}_{testing} = [X^{w}_{testing}, Y^{w}_{testing}, Z^{w}_{testing}]$$

are the tristimulus values of the white point under the reference and testing illuminants respectively, T_2 and T_1 are tristimulus values of object under reference and testing illuminants.

Principal Components Method

Vrhel and Trussell introduced this correction method initially,[2] based on the well known assumption on natural reflectance spectra, that is, naturally occurred reflectance spectra can be adequately approximated by the linear combination of a small number of eigenvectors generated from a typical ensemble of spectra[3]:

$$R = \bar{R} + \sum_{i=1}^{m} a_i \mathbf{b}_i = \bar{R} + \mathbf{B}a \tag{3}$$

where matrix $\mathbf{B}$ contains the eigenvectors, a are the coefficients, $\bar{R}$ is the mean spectrum of the ensemble. The tristimulus values under testing illuminant is calculated as

$$T_1 = A^T L_T \mathbf{B}a + A^T L_T \bar{R} = A^T L_T \mathbf{B}a + \bar{T}_1 \tag{4}$$

where $\bar{T}_1 = A^T L_T \bar{R}$. From Equation (4) the coefficients can be calculated by

$$a = (A^T L_T \mathbf{B})^{-1}(T_1 - \bar{T}_1) \tag{5}$$

Therefore the tristimulus values under reference illuminant corrected by principal components method is

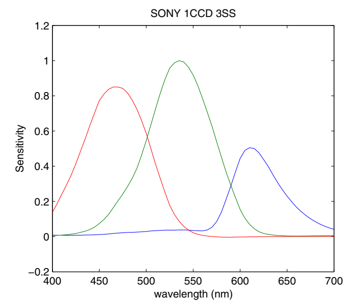
$$\begin{aligned} T_2 &= A^T L_R \mathbf{B}a + A^T L_R \bar{R} \\ &= A^T L_R \mathbf{B}(A^T L_T \mathbf{B})^{-1}(T_1 - \bar{T}_1) + \bar{T}_2 \end{aligned} \tag{6}$$

Since the processing capability within a camera unit is limited, and the signal transformation need be processed quickly, this study will discuss only white-point-conversion-type correction method.

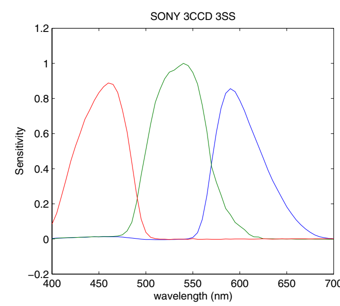
In this study, at first, the variation of the optimal 3×3 conversion matrix due to illumination changes will be investigated. The CIE D65 illuminant will be given as reference, any other illuminants, like CIE A, F2 and F6 will be specified as testing illuminants. Average color difference and maximal color difference will be calculated for a standard data set also when the illuminant changes. The standard data set used here are Vrhel-Trussell reflectance data set with 354 samples, alternative data set can be Macbeth ColorChecker with 24 samples.

Two sets of RGB spectral sensitivities will be tested: the Sony 1CCD3SS and 3CCD3SS spectral sensitivity functions, as shown in Figure 2.

In this paper, the notation "A→B" means the colorimetric information under illuminant A is converted to that under illuminant B. In general, the theoretical 3×3 matrix that transforms the raw RGB signals to standard signal in standard color space, e.g. CIE XYZ in the processing pipeline of digital camera signal will change when taking and viewing illuminants change from D65 to other illuminants. Simply, the matrix derived from D65→D65 can be applied when the taking and viewing illuminants are the same. The performance is shown in Table 1. In this table, since the conversion matrix is only truly optimal for D65→D65, it is only approximately optimal for other illuminant pairs, therefore the color difference performance for these illuminant pairs is not as good as for D65→D65. It can be seen that for Sony 3CCD 3SS single matrix is suitable for all cases, but for Sony 1CCD 3SS, the color difference is very large for F2→F2 and F6→F6.



(a)



(b)

Figure 2. Sony spectral sensitivity function sets: (a) 1CCD 3SS; (b) 3CCD 3SS.

Table 1. Using optimal matrix from illuminant pairs D65-D65 as conversion matrix for A-A, F2-F2 and F6-F6 to calculate color difference.

1CCD 3SS			Optimal Conversion Matrix		
	ΔE^*_{94}	Max ΔE^*_{94}	*RGB→XYZ from D65-D65*		
D65-D65	1.63	5.98	1.8119	0.4364	-0.0266
A-A	2.85	8.03	0.7768	1.1087	-0.2887
F2-F2	6.52	17.69	0.0588	-0.1362	1.5351
F6-F6	7.11	19.27			
3CCD 3SS			**Optimal Conversion Matrix**		
	ΔE^*_{94}	Max ΔE^*_{94}	*RGB→XYZ from D65-D65*		
D65-D65	0.81	3.57	1.4646	0.2121	0.2566
A-A	1.06	5.19	0.7155	0.9917	-0.0332
F2-F2	3.01	6.51	-0.0108	0.0386	1.8947
F6-F6	3.10	6.75			

Correction with Different Taking and Viewing Illuminants

RGB Correction Matrix before Transformation

The ratio of raw signals in RGB space from the testing illuminant and CIE D65 is calculated as the diagonal elements of the color correction matrix M_d, and do the color correction:

$$M_d = \begin{pmatrix} R_{w_{D65}}/R_{w_{Other}} & & \\ & G_{w_{D65}}/G_{w_{Other}} & \\ & & B_{w_{D65}}/B_{w_{Other}} \end{pmatrix} \quad (7)$$

$$M_{\text{optimal Other}\rightarrow D65} = M_{\text{optimal D65}\rightarrow D65} M^{RGB}_{correction} \quad (8)$$

The process can be illustrated as

$$\begin{pmatrix} R^{white}_{Other} \\ G^{white}_{Other} \\ B^{white}_{Other} \end{pmatrix} \xrightarrow[\text{von-Kries-Type Color Correction}]{M_d} \begin{pmatrix} R^{white}_{D65} \\ G^{white}_{D65} \\ B^{white}_{D65} \end{pmatrix} \xrightarrow[\text{Optimized Transformation From D65}\rightarrow\text{D65}]{M_{3x3}} \begin{pmatrix} X^{white}_{D65} \\ Y^{white}_{D65} \\ Z^{white}_{D65} \end{pmatrix}$$

Corresponding calculation results of correction matrix and color difference are list in Tables 2 and 3. This time, it is found that, the optimal matrix from D65➔D65 together with the color correction matrix M_d obtained from the ratio of the RGB raw signals of the testing illuminant and CIE D65 can be a good choice to obtain the reasonable conversion. It is also true that the color difference performance for A➔D65 is better than that for F2➔D65 and F6➔D65 consistently for three sets of camera spectral sensitivities. The Sony 3CCD 3SS set performs the better than the Sony 1CCD 3SS.

Table 2. RGB Correction Matrix Before Transformation Matrix (3CCD 3SS).

➔D65	Diagonal Elements in the Correction Matrix			ΔE^*_{94}	Max ΔE^*_{94}
D65				0.81	3.57
A	0.688	1.246	3.101	1.77	7.78
F2	6.090	8.527	12.355	3.09	10.77
F6	6.191	8.515	13.888	3.47	12.26

Table 3. RGB Correction Matrix Before Transformation Matrix (1CCD 3SS).

➔D65	Diagonal Elements in the Correction Matrix			ΔE^*_{94}	Max ΔE^*_{94}
D65				1.63	5.98
A	0.641	4.25	4.25	4.25	14.46
F2	8.070	4.54	4.54	4.54	17.46
F6	8.420	4.95	4.95	4.95	19.75

XYZ Correction Matrix after Transformation

If the color correction matrix is modeled as the ratio of the XYZ values of the illuminant color for testing illuminant and reference illuminant (D65), and it is placed after the optimized color transformation, the signal transformation is shown below.

$$\begin{pmatrix} R^{white}_{Other} \\ G^{white}_{Other} \\ B^{white}_{Other} \end{pmatrix} \xrightarrow[\text{Optimized Transformation From D65}\rightarrow\text{D65}]{M_{3x3}} \begin{pmatrix} X^{white}_{Other} \\ Y^{white}_{Other} \\ Z^{white}_{Other} \end{pmatrix} \xrightarrow[\text{von-Kries-Type Color Correction}]{M_d} \begin{pmatrix} X^{white}_{D65} \\ Y^{white}_{D65} \\ Z^{white}_{D65} \end{pmatrix}$$

$$M_{\text{optimal Other}\rightarrow D65} = M^{XYZ}_{correction} M_{\text{optimal D65}\rightarrow D65} \quad (9)$$

The color correction performance, which is listed in Table 4, is reasonable, but is not as good as what obtained in RGB space. There are two reasons. First, the optimal transformation fit illuminant D65➔D65 the best; it has been shown in Table 5 that although the matrix is applicable to other illuminant pairs, but it is not optimal to do so. Second, the von-Kries-type of transformation is more accurate for sharper sensors.[4] All spectral sensitivity functions discussed here are comparatively sharper sensors than CIE XYZ color matching functions, color correction is more useful in RGB space and gives better color difference performance.

Table 4. XYZ Correction Matrix After Transformation Matrix.

	3CCD 3SS		1CCD 3SS	
	ΔE^*_{94}	Max ΔE^*_{94}	ΔE^*_{94}	Max ΔE^*_{94}
D65	0.81	3.57	1.63	5.98
A	4.50	13.56	5.86	15.25
F2	3.66	8.28	7.78	17.21
F6	3.79	9.12	8.44	18.74

Illuminant Dependency of Color Correction

Most of the color correction results above show that the correction matrix works better for CIE A illuminant than for the fluorescent illuminants (F2 and F6). Possible reasons may be that: (1) CIE A Spectrum has better smoothness; (2) CIE A has high correlation with CIE D65; (3) CIE fluorescent illuminants F2 and F6 have emission lines. In this part, the illuminant dependency of color correction matrix will be tested. Color correction approach in camera RGB space will be applied to the following tests.

Test 1:

Randomly insert several emission lines onto the CIE A spectrum; boost the red end of fluorescent illuminants such that the trend of their spectra is similar to original A spectrum. The SPDs are plotted in Figure 3. After the color correction matrix is employed, the color difference performance is calculated. The result in Table 5 and 6 shows that the color differences for the three modified illuminants are better than their original correspondence. Evaluation on both spectral sensitivity sets is consistent. It seems that emission lines in this case is not the reason to cause the low color correction performance.

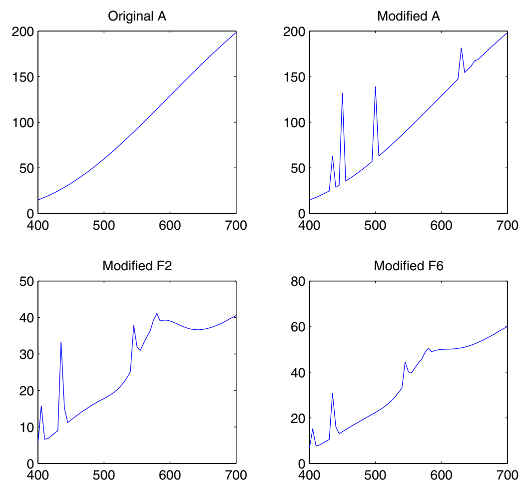


Figure 3. Modified illuminant set #1.

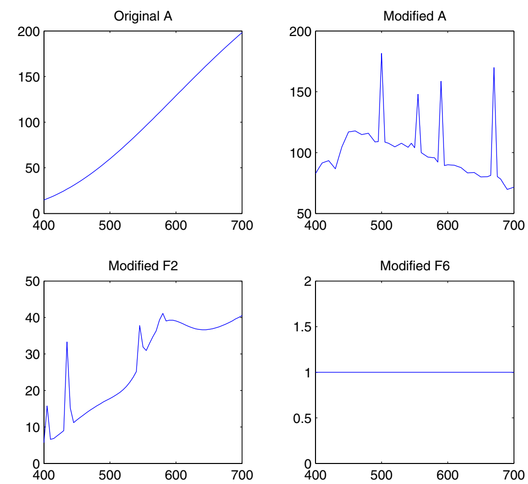


Figure 4. Modified illuminant set #2.

Table 5. Test #1 of Illuminant Dependency of Correction Matrix (3CCD 3SS).

	Diagonal Elements in the Correction Matrix			ΔE^*_{94}	Max ΔE^*_{94}
D65→D65				0.81	3.57
A→D65	0.688	1.246	3.101	1.77	7.78
A'→D65	0.681	1.204	2.412	1.47	6.27
F2'→D65	2.369	3.932	7.737	1.86	8.35
F6'→D65	1.821	3.096	6.795	1.83	8.50

Table 6. Test #1 of Illuminant Dependency of Correction Matrix (1CCD 3SS).

	Diagonal Elements in the Correction Matrix			ΔE^*_{94}	Max ΔE^*_{94}
D65→D65				1.63	5.98
A→D65	0.641	1.252	2.525	4.25	14.46
A'→D65	0.631	1.208	2.054	3.81	11.94
F2'→D65	2.432	3.932	7.113	4.09	14.64
F6'→D65	1.815	3.106	6.003	4.20	14.77

Test 2:

Multiple emissions are inserted into the spectrum of CIE D65. The modified F6 in Test 1, and equi-energy illuminant are used as test illuminants here. The modified illuminants are shown in Figure 4. Only Sony 3CCD 3SS is tested here. Result in Table 7 shows that all three modified illuminants give good color correction performance.

Table 7. Test #2 of Illuminant Dependency of Correction Matrix (3CCD 3SS).

	ΔE^*_{94}	Max ΔE^*_{94}
D65→D65	0.81	3.57
A→D65	1.77	7.78
A'→D65	0.81	3.53
F2'→D65	1.86	8.35
F6'→D65	0.81	3.79

Test 3:

More emission lines are inserted into the spectrum of CIE D65, still the previously modified fluorescent, and a hypothetical illuminant with several dominant emissions together on a weak background spectrum were tested. The spectra of illuminants were shown in Figure 5. From the test results in Table 8, the first two modified illuminants gave good color correction, the last illuminant gave bad correction. It seems that if the emission lines dominant in the spectrum of illuminant, the color correction performance becomes bad.

Table 8. Test #3 of Illuminant Dependency of Correction Matrix (3CCD 3SS).

	ΔE^*_{94}	Max ΔE^*_{94}
D65→D65	0.81	3.57
A→D65	1.77	7.78
A'→D65	0.84	3.55
F2'→D65	1.86	8.35
F6'→D65	4.20	10.80

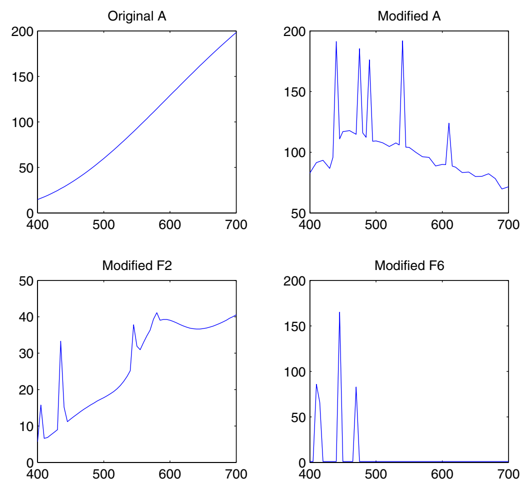


Figure 5. Modified illuminant set #3.

Discussions and Conclusions

The method to discount color shifts due to illuminant changes have been discussed in this paper. Color correction is a method to discount color shifts such that adjusted color approximates its appearance under a reference illuminant. White point mapping has been found to be an effective color correction method.

When the taking illuminant and target illuminant are different, the research assumes the target illuminant is D65, and the color signal under other illuminant is converted to that under D65. Two white point mapping methods were found to be effective. The best color correction matrix is the one obtained as the ratio of camera output signals of white from the reference illuminant and testing illuminant.

Since color correction matrix is von-Kries-type of transformation, this kind of transformation works better when the sensitivity curves are sharp, and is accurate in extreme case if the curves are delta functions, the RGB spectral sensitivity functions used in this paper are "sharper" than CIE XYZ color matching functions, therefore the obtained best correction matrix performs much better than others.

The color correction performance depends on the illuminant spectral power distribution. In order to know what causes this, modification of these illuminants were generated, the optimal conversion and correction matrices were calculated, and color difference values were then compared with their original performance. Some trivial tests found that if the emissions are dominant in the spectrum of illuminant, the color correction performance will not be good. The smoothness of illuminant spectrum was not a source causing color correction performance variation. But no concrete conclusion has been drawn yet. Some further research on illuminant dependency is necessary to find the cause.

Acknowledgement

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Biographies

Shuxue Quan received his B.S. and M.S. degree in Optical Engineering from Beijing Institute of Technology in 1994 and 1997 respectively. Since 1997 he had been a Ph.D. candidate in Imaging Science with Rochester Institute of Technology and received his Ph.D. degree in 2002. He is currently a senior engineer with Sony Electronics Inc. He is interested in the color imaging and image analysis area and his current work focuses on the optimal design of spectral sensitivity functions for color imaging systems. He is a member of IS&T and IEEE.

Noboru Ohta received his Ph.D. degree in Applied Physics from Tokyo University. For over thirty years he was a senior research scientist in the Fuji Photo Research Laboratories. He is currently Xerox Professor with Rochester Institute of Technology.