Colorimetric characterization of scanner by measures of perceptual color error

Hui-Liang Shen
Zhejiang University
Department of Information and Electronic Engineering
Hangzhou 310027, China
E-mail: shenhl@zju.edu.cn

Tong-Sheng Mou
Zhejiang University
State Key Laboratory of Modern Optical Instrumentation
Hangzhou 310027, China

John H. Xin
The Hong Kong Polytechnic University
Institute of Textiles and Clothing
Hong Kong, China

Abstract. *Two methods for colorimetric characterization of color scanner are proposed based on the measures of perceptual color difference error. The first method is used to minimize the total color differences between the actual and predicted color samples. The second one, which is a generalization of the existing cubic-root preprocessing technique, derives the mapping between the p'th root of scanner responses and Commission Internationale de l'Eclairage $L^*a^*b^*$ (CIELAB) values. The experiment results indicate that the color accuracies of the proposed methods, especially the second one, are better than those of the traditional CIE XYZ (CIEXYZ)-space-based characterization methods.* [DOI: 10.1117/1.2199872]

1 Introduction

Most scanners are not colorimetric devices in that their spectral sensitivities cannot be expressed as a linear combination of the Commission Internationale de l'Eclairage (CIE) color matching functions. The goal of scanner characterization is to transform the device-dependent scanner responses (*RGB* values for typical three-channel scanners) to device-independent colorimetric values [such as CIE *XYZ* (CIEXYZ) and CIE $L^*a^*b^*$ (CIELAB)] or spectral reflectance values. In the literature, colorimetric characterization methods include polynomial regression,[1–3] neural networks,[4,5] and look-up tables.[3,6] As the look-up table method usually requires a large number of color samples, it is not preferred in scanner characterization.[7] In addition, as a neural network does not offer obvious advantages,[8] polynomial regression is actually the most appropriate method in scanner characterization. The major limitation of the colorimetric characterization is its constraint to specific combinations of illumination and observer functions. The spectral characterization is to recover high-dimensional spectral reflectance from low-dimensional scanner responses.[9,10] A recent study found that, under the same illuminant condition, the color accuracy of the colorimetric characterization is better than that of the spectral one.[11]

Note that, in the majority of previous studies, the polynomial regression is applied to transform the *RGB* values to the CIEXYZ values.[1–3,8] Usually, the polynomial regression is solved using either a least-squares (LS) method[1–3] or a total least-squares (TLS) method.[12,13] However, due to the nonlinear transform between CIEXYZ and CIELAB space, the optimal solution in CIEXYZ space does not mean the minimization of color difference in CIELAB space. To deal with this problem, we propose two methods to characterize a scanner with the measures of perceptual color difference error. The first method calculates the transform between *RGB* and CIEXYZ values by the minimization of total color difference (TCDM), while the second method transforms the *p*'th root of *RGB* to CIELAB values using least squares (LAB-LS). The second method is a generalization of the existing polynomial regression techniques, which adopt the cubic root of *RGB* values as a preprocessing step.[3,14–16] Section 2 presents these four characterization methods (LS, TLS, TCDM, and LAB-LS). Section 3 is dedicated to the evaluation and discussion of these methods, followed by the conclusion in Sec. 4.

2 Scanner Characterizations

In this section, we first address the problem formulation of colorimetric characterization, and then present the solutions of this problem using the four methods just mentioned.

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2.1 Problem Formulation

Vector space notation has been widely used in color imaging research and application. In this notation, the visual spectrum, 400 to 700 nm, is equally sampled in N wavelengths, and the spectral reflectance of an object can then be represented by a vector $\mathbf{r}$ with N elements. For a traditional three-channel color scanner, the scanner response $\mathbf{v}$ can be formulated as

$$\mathbf{v} = \mathbf{M}_s \mathbf{L}_s \mathbf{r}, \tag{1}$$

where $\mathbf{v}$ is a 3×1 vector, $\mathbf{M}_s$ is the $3 \times N$ matrix of scanner spectral responsivity, $\mathbf{L}_s$ is an $N \times N$ diagonal matrix with samples of the scanner-illuminants spectrum along the diagonal. Equation (1) assumes that the scanner responses are proportional to the intensity of the light entering the detector. The behavior of a common scanner may be subject to a nonlinear optoelectronic conversion function[9,11] $F(\cdot)$:

$$\boldsymbol{\rho} = F(\mathbf{v}) = F(\mathbf{M}_s \mathbf{L}_s \mathbf{r}), \tag{2}$$

where $\boldsymbol{\rho}$ is the 3×1 vector of the actual nonlinear responses of the scanner.

Similarly, the CIE tristimulus values, denoted by a 3×1 vector $\mathbf{b}$, is defined as

$$\mathbf{b} = \mathbf{M}_c \mathbf{L}_c \mathbf{r}, \tag{3}$$

where $\mathbf{M}_c$ is the $3 \times N$ matrix representing color matching functions, and $\mathbf{L}_c$ is an $N \times N$ diagonal representing CIE standard illuminant.

The purpose of colorimetric characterization of a scanner is to calculate CIEXYZ values $\mathbf{b}$ from scanner responses $\mathbf{v}$. Three-order cross-terms of elements in $\mathbf{v}$ will produce M ($M=20$ in this study) new terms a_n:

$$a_n \equiv a_{i,j,k} = v_1^i v_2^j v_3^k, \quad 0 \leqslant i+j+k \leqslant 3, \quad 1 \leqslant n \leqslant M, \tag{4}$$

and a_n is regarded as the n'th element of vector $\mathbf{a} = [a_1, a_2, \ldots, a_M]^T$. The colorimetric values $\mathbf{b}$ can then be obtained from scanner responses $\mathbf{v}$ by an unknown $M \times 3$ transform matrix $\mathbf{H}$:

$$\mathbf{a}^T \mathbf{H} = \mathbf{b}^T. \tag{5}$$

Suppose there are K ($\geqslant M$) color samples used in characterization, we can collect all the polynomial terms for these samples into a $K \times M$ matrix $\mathbf{A}$ and collect all the corresponding scanner responses into a $3 \times M$ matrix $\mathbf{B}$. Then, Eq. (5) can be written as

$$\mathbf{AH} = \mathbf{B}, \tag{6}$$

where $\mathbf{H} = [\mathbf{h}_1, \mathbf{h}_2, \mathbf{h}_3]$ and $\mathbf{B} = [\mathbf{b}_1, \mathbf{b}_2, \mathbf{b}_3]$.

2.2 LS and TLS Methods

The LS method assumes that the matrix $\mathbf{A}$ is free of error, and all errors are confined to the vector $\mathbf{b}_j$. The LS method tries to find a solution $\mathbf{h}_j$ that minimizes

$$J_{\mathrm{LS}} = \|\mathbf{b}_j - \hat{\mathbf{b}}_j\| \quad \text{subject to } \mathbf{A}\mathbf{h}_j = \hat{\mathbf{b}}_j. \tag{7}$$

Any $\mathbf{h}_j$ satisfying $\mathbf{A}\mathbf{h}_j = \hat{\mathbf{b}}_j$ is an LS solution, and $\Delta \mathbf{b}_j = \mathbf{b}_j - \hat{\mathbf{b}}_j$ is the corresponding LS correction.

The TLS method considers errors in both the vector $\mathbf{b}_j$ and the matrix $\mathbf{A}$. It tries to give the best estimates (in a statistical sense) when all variables are subject to independently and identically distributed errors with zero mean and common covariance matrix equaling to the identity matrix, up to a scaling factor. The TLS method finds a solution $\mathbf{h}_j$ that minimizes

$$J_{\mathrm{TLS}} = \|[\mathbf{A}; \mathbf{b}_j] - [\hat{\mathbf{A}}; \hat{\mathbf{b}}_j]\|_F \quad \text{subject to } \hat{\mathbf{A}}\mathbf{h}_j = \hat{\mathbf{b}}_j, \tag{8}$$

where $\|\cdot\|_F$ denotes the Frobenius norm.[17] Any $\mathbf{h}_j$ satisfying $\hat{\mathbf{A}}\mathbf{h}_j = \hat{\mathbf{b}}_j$ is a TLS solution, and $[\Delta\hat{\mathbf{A}}; \Delta\hat{\mathbf{b}}_j] = [\mathbf{A}; \mathbf{b}_j] - [\hat{\mathbf{A}}; \hat{\mathbf{b}}_j]$ is the corresponding TLS correction. The TLS problem can also be solved in multidimensions, as discussed in Ref. 13. Both of the 1-D and multidimensional TLS problems could be computed through the use of singular value decomposition.

In color printer calibration, it was reported that the TLS method outperformed the LS method as it considered[12] the errors in both the left-side matrix and the right-side vector in Eq. (8).

2.3 TCDM and LAB-LS Methods

Despite the different assumptions made, both the LS and TLS methods try to determine a suitable solution of the polynomial regression in CIEXYZ space. The color accuracy of the characterization methods, however, is evaluated using color difference error in CIELAB space. Because of the nonlinear cubic-root transform, the statistical distribution of color error in CIELAB space may be quite different from that in CIEXYZ space. Therefore, the optimal solution obtained in CIEXYZ space using LS or TLS methods is not optimal in the CIELAB space.

The TCDM method tries to obtain the solution by minimizing the following error term:

$$J_{\mathrm{TCDM}} = \sum_{k=1}^{K} \Delta E_{ab}^* \quad \text{subject to } \mathbf{AH} = \hat{\mathbf{B}}, \tag{9}$$

where ΔE_{ab}^* is the Euclidean distance between the measured and predicted CIELAB values for the k'th sample. Although other color difference formulas can be used in Eq. (9), we consider that ΔE_{ab}^* is the most general and therefore suitable here. Note that the vector $\mathbf{h}_j$ in matrix $\mathbf{H}$ no longer independent, but is optimally adjusted under the objective function of total color difference. A downhill simplex is used to solve the multidimensional minimization problem of Eq. (9), as it does not require the calculation of derivatives of the objective function.[18,19] As the objective function for minimization in device characterization is quite complicated ($M \times 3$ terms) and not continuous, a random starting point is not a good choice. The reasonable selection of starting point is the matrix $\mathbf{H}$ obtained by the LS method.

An alternative way is to perform polynomial regression in CIELAB space using LS. Let the transform T_{Lab} be the transform function mapping[20] CIEXYZ to CIELAB:

Table 1 Influence of the p value on color accuracy for the LAB-LS method when color target CDC was used.

	p value				
	1	3	6	9	12
Average ΔE^*_{94}	2.49	1.43	1.32	1.29	1.28

$$\mathbf{c} = T_{\mathrm{Lab}}(\mathbf{b}). \tag{10}$$

In the studies of scanner filter design, the 3×3 Jacobian matrix of the transform T_{Lab} was proposed to map the CIEXYZ errors into CIELAB errors linearly.[21,22] We note that, in colorimetric characterization, the Jacobian matrix may not be necessary as reflectance $\mathbf{r}$ is not involved in the calculation. Considering the cubic root in the transform T_{Lab}, it is useful to calculate the p' th root of the scanner responses as

$$\mathbf{u} = T_p(\mathbf{v}) = \mathbf{v}^{1/p}, \tag{11}$$

where $\mathbf{u}$ is a 3×1 vector, and p is an integer such as 3, 6, 9, etc. The purpose of the p' th root is to cancel out the cubic root in the transform T_{Lab}. Then, the high-order polynomial terms of $\mathbf{u}$ can be calculated, and the transform matrix $\mathbf{H}$ can be obtained under the LS meaning.

3 Experimental Evaluation and Discussion

Three color targets, namely, GretagMacBech ColorChecker DC (CDC), Kodak Q60 photographic standard (IT8), and Kodak Gray Scale Q-14 (Q14), were used in the experiment. These three targets were scanned in using the scanner Epson GT-10000+ at an appropriate resolution. During the scanning process, all the color adjustment functions of the scanner were disabled. The RGB values of gray patches on target Q14 and their corresponding average reflectance values were used to calculate the inverse optoelectronic conversion function[9] in Eq. (2). The targets CDC and IT8 were employed to evaluate the color accuracy of each characterization method. The spectral reflectance values of CDC and Q14 were measured using a GretagMacbeth Spectrophotometer 7000A, and those of IT8 were measured using a GretagMacbeth Spectrolino spectrophotometer.[9] The CIEXYZ and CIELAB values under D65 were then calculated from these reflectance data for scanner characterization. Note that there is instrumental disagreement between these two different spectrophotometers.[23] However, this problem does not matter in this study, since there is no need to apply the transform obtained from CDC on IT8 or vice versa.

In color characterization, two-thirds of samples (1st, 2nd, 4th, 5th, 7th, 8th, 10th, etc.) are used for training purpose and the remaining one-third of samples (3th, 6th, 9th, etc.) were used for testing purpose. In color accuracy evaluation, the color difference formula ΔE^*_{94} (Ref. 24) was adopted considering it is closer to visual perception when compared with ΔE^*_{ab}. Table 1 gives the influence of the p value on ΔE^*_{94} for the LAB-LS method when CDC was used. It can be found that $p=9$ is suitable for third-order polynomial regression, and is better than the existing cubic root ($p=3$) technique.

The color difference errors ΔE^*_{94} of the LS, TLS, TCDM, and LAB-LS methods are listed in Table 2. The reason that the TLS does not perform better than LS may be that the errors in matrix $\mathbf{A}$ do not satisfy the conditions required by the TLS method. As the colorimetric values $\mathbf{B}$ were measured by spectrophotometers with high accuracy, TLS is not very suitable in scanner characterization. It was expected that the TCDM method would be better than the

Table 2 Color accuracies for the LS, TLS, TCDM, and LAB-LS methods in terms of mean, standard deviation (Std.), and maximum (Max.) of ΔE^*_{94} using color targets CDC and IT8.

	ΔE^*_{94} Training			ΔE^*_{94} Testing			ΔE^*_{94} Total		
	Mean	Std.	Max.	Mean	Std.	Max.	Mean	Std.	Max.
CDC									
LS	1.72	1.82	12.90	1.63	1.52	6.38	1.69	1.72	12.90
TLS	2.73	6.23	51.66	2.16	2.75	15.93	2.54	5.32	51.66
TCDM	1.54	1.54	8.51	1.54	1.52	8.31	1.54	1.53	8.51
LAB-LS	1.33	1.14	6.65	1.22	0.80	3.15	1.29	1.04	6.65
IT8									
LS	1.24	1.08	6.73	1.44	1.24	7.79	1.31	1.13	7.79
TLS	1.41	1.25	6.73	1.58	1.36	7.70	1.46	1.29	7.70
TCDM	1.19	0.94	5.59	1.42	1.11	6.47	1.27	1.00	6.47
LAB-LS	0.85	0.49	2.63	1.13	0.66	3.67	0.95	0.56	3.67

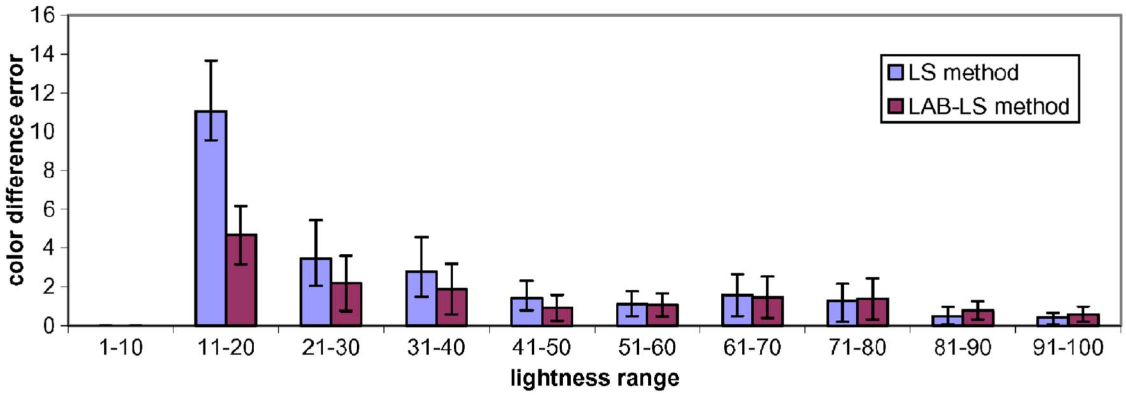

Fig. 1 Distribution of ΔE^*_{94} with respect to the lightness range of the LS and LAB-LS methods for the CDC target. The Y error bars show ±1 standard deviation.

LS method, as the former minimizes the total color difference. However, the improvement is slight. The reason is that the TCDM method may fail to find the global optimal solution due to the large size of the transform matrix $\mathbf{H}$. In comparison, the LAB-LS method appears to be substantially better than the other methods. The additional advantage of the LAB-LS method is that it can be solved in a closed form and does not require iterative searching like the TCDM method.

Figure 1 illustrates the distribution of color difference with respect to lightness range for all the samples on CDC. It can be found that the improvement of the LAB-LS method is quite obvious for the lightness in range of 10 to 50. The reason is that the LAB-LS method is carried out in the CIELAB space, with lightness CIE L^* being more uniform than luminance CIE Y.

4 Conclusions

Considering the limitation of the LS and TLS methods traditionally used in colorimetric characterization of imaging devices, we proposed two methods, namely TCDM and LAB-LS. Both of these methods consider the perceptual color difference error in CIELAB space, not in CIEXYZ space. The experimental evaluation indicated that the LAB-LS method performs the best, while the TCDM method is better than the LS and TLS methods.

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Hui-Liang Shen received his BEng and PhD degrees in electronic engineering from Zhejiang University, China, in 1996 and 2002, respectively. He was a researcher with the Institute of Textiles and Clothing, the Hong Kong Polytechnic University, from 2001 to 2005.

In 2005 he joined the Department of Information and Electronic Engineering, Zhejiang University, where he is currently an associate professor. His research interests are color imaging, computer vision, and image processing.

Tong-Sheng Mou received his MEng degree from the Department of Optical Engineering, Zhejiang University in 1986. He is currently an associate professor with the State Key Laboratory of Modern Optical Instrumentation, Zhejiang University. His research interests include photometry, colorimetry, and spectrum radiation measurement.

John H. Xin graduated with a PhD degree from the University of Leeds, United Kingdom, in 1989 and joined the multinational textile company Coats Viyella, United Kingdom, as a technologist in the color section of the Research and Development Department. He became a project coordinator for the development of a new-generation computer color management and color quality control system with the University of Derby, United Kingdom, in 1994. He has been with the Institute of Textiles and Clothing, Hong Kong Polytechnic University, since 1996 and is currently a professor. His research interests are color management, digital color communication and reproduction, and the psychological aspect of color. He is a Charted Colorist, awarded by the Society of Dyers and Colorists, United Kingdom.