Effective Correction Modeling Between Colorimetric Datasets

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Abstract

This paper describes an effective method for solving a common problem in colorimetry: transforming the colorimetric data sets between two colour measuring instruments, standard colorimetric observers, or illuminants. The method is based on the polynomial modeling. It is found that the model gave quite satisfactory transformation and could be almost exactly reversed even through it does not have an analytical expression for the inversion.

Introduction

Instrumental correction has been widely used in industry for correlating colour measurement results between two different instruments. The theoretical corrections for different types of systematic errors based on spectral reflectance were first investigated by Robertson [1], and then by Berns and Petersen [2]. More recently, Morovic et al [3], Li et al [4] and Nilsson [5] were also carried out the study. The method developed here is based on transformation between two sets of colorimetric values, XYZ or CIELAB.

In some applications, it requires the transformation between the CIE 1931 (2^o) and 1964 (10^o) standard colorimetric observers. For example, the colour order systems such as NCS and Munsell were defined in terms of 2^o observer. The measurement data based on 10^o data are required to be transformed to 2^o data in order to find the corresponding NCS [6] or Munsell [7] colour coordinates.

Chromatic adaptation transforms (CATs) are used for transforming from a set of tristimulus values under the test illuminant to another set under the reference illuminant. The two sets of colorimetric data are known as ‘corresponding colours’, which have the same colour appearance under two different illuminants. The CAT02 is the CAT included in the current CIE colour appearance model, CIECAM02 [8]. Each CAT assumes a perfect colour constancy for the sample considered, i.e. no change of appearance under the two illuminants considered. Of course, it is untrue in real world situation. Hence, it sometimes needs to predict the corresponding colours between a measurement data set from one illuminant to the other say for colour management purpose.

In this paper, a polynomial model was proposed for the applications described above to transform between two sets of colorimetric data. The performance of the model was tested by various data sets. Furthermore, because of no analytical solution for the polynomial model, the same polynomial model was developed to reversely predict the results. Its performance in terms of reversibility is also reported.

The Polynomial model

In this section, a generic polynomial model is derived. The model concerns the transformation between two data sets of tristimulus values, denoted by Ω_A and Ω_B. The polynomial model which transforms $p \in \Omega_A$ to $q \in \Omega_B$ has the following main steps:

Step 1: Transform $p \in \Omega_A$ to vector v_k. Here k is the order of the polynomial.

Let $p^T = (c_1, c_2, c_3)$ (here, superscript T is the transpose of a vector or matrix), then

$$v_0(c) = p\,,\ v_1(p) = \begin{pmatrix} 1 \\ p \end{pmatrix},\ v_k(p) = (u_k)\,, \qquad (1)$$

where u_k is a column vector and each element of it has the form of $(c_1)^{j_1}(c_2)^{j_2}(c_3)^{j_3}$ with $j_1 + j_2 + j_3 \le k$, and all j_1, j_2, j_3 being nonnegative integers. The number of elements of vector v_k (denoted by Noe) depends on the order k and are listed in Table 1 below for k=0, 1, 2, 3 and 4.

Table 1**: The number of elements (Noe) of vector v_k with k from 0 to 4**

k	0	1	2	3	4
Noe	**3**	**4**	**10**	**20**	**35**

Step 2: Determine the mapping matrix $W^{(ATB)}$ (here superscript ATB indicates transformation from Ω_A to Ω_B)

Let S and Q denote the matrices consisting of all tristimulus values in Ω_A and Ω_B respectively, and let V be the matrix consisting of all v_k transformed from S (or Ω_A) using Step 1. The matrix $W^{(ATB)}$ is obtained by solving the following minimization problem:

$$\text{Minimize: } \| Q - WV \|$$

Here $\| M \|$ denotes the sum of squares of all elements of the matrix M.

Thus, after matrix $W^{(ATB)}$ is obtained, the transformed trsistimulus values denoted by q ($\in \Omega_B$) from $p \in \Omega_A$ is computed using the following two steps:

1. Compute v_k from $p \in \Omega_A$
2. $q = W^{(ATB)} v_k$

The above model maps $p \in \Omega_A$ to $q \in \Omega_B$. In a similar way, the matrix $W^{(BTA)}$ can be derived and used for transforming from $q \in \Omega_B$ to $p \in \Omega_A$, as the inverse model. The order k of the polynomial affects the performance of the model. It was found that the forth order gave the best performance. Hence all results reported in this paper were obtained using the 4th order polynomial.

Data Sets

The colour patches in the Munsell and NCS colour books were measured using two commercial spectrophotometers in terms of spectral reflectance functions. Instrument A (denoted by IA) measured reflectance functions with a 45/0 geometry, and instrument B (denoted by IB) with a d/8 geometry. Thus, four sets of spectral reflectance functions were denoted as IA-MUN, IA-NCS, IB-MUN, and IB-NCS respectively. There are 1749 and 1560 samples for the NCS and Munsell colours, respectively. The four sets of data were interchanged for the use as training or testing data sets.

The training data set was chosen from the NCS samples which were chosen from one in every ten samples in the full set. Thus, the training data set only includes 175 samples. The whole Munsell and NCS data sets are used as the testing data sets.

Application 1: Instrument Corrections

In this section, polynomial model was developed to correlate between two instruments, IA and IB with 45/0 and d/8 geometry respectively.

For calculating tristimulus values, the CIE standard illuminant D65 and CIE 1964 standard colorimetric observer are used. CIE DE2000 colour difference (ΔE^*_{00}) is used for evaluating the difference between the two instrument measurements. Three statistical values are computed for measuring the difference between the instruments IA and IB, and the performance of the correction method. They are: mean (Ave), standard deviation (Std), and maximum (Max) colour differences, and reflect the average, the spread and the worst colour differences between the two sets of data considered.

Tables 2, 3 and 4 summarise the results for the NCS training set, NCS testing set and Munsell testing set, respectively. For each test, the results were reported in terms of 'no correction', 'polynomial' and 'reversibility'. The results are clearly showed that there is a large improvement (or effective correction) from the 'no correction' to the model performance. Note that all the samples measured here had low gloss, otherwise a lot larger discrepancy between the two instruments are expected [5]. The reversibility test also showed that the forward and reverse polynomial models are almost exactly reverse, with a mean of 0.0004 and a maximum of 0.0033 ΔE^*_{00} units.

It is expected that the model performed better for the NCS testing data than the Munsell data, because a subset of NCS was used as the training set.

	Ave	Std	Max
No Correction	0.32	0.09	0.63
Polynomial	0.03	0.03	0.23
Reversibility	0.0003	0.0002	0.0014

Table 2: Performance in ΔE^*_{00} units of Instrument Correction for Training Data Set

	Ave	Std	Max
No Correction	0.33	0.08	0.64
Polynomial	0.04	0.03	0.35
Reversibility	0.0003	0.0002	0.0022

Table 3: Performance in ΔE^*_{00} units of Instrument Correction for NCS Testing Data Set

	Ave	Std	Max
No Correction	0.31	0.08	0.55
Polynomial	0.05	0.04	0.40
Reversibility	0.0004	0.0003	0.0033

Table 4: Performance in ΔE^*_{00} units of Instrument Correction for Munsell Testing Data Set

Application 2: Observer Corrections

In this application, the polynomial model was developed to transform between the tristimulus values having same spectral reflectance functions and the same spectral power distribution of illumination but having different (1931 and 1964) standard colorimetric observers. In addition, the CAT02 [6] was used for the correction as well. Note that CAT02 was derived for predicting corresponding colours under two different illuminants defined by the tristimulus values. The two sets of tristimulus values were computed under the combinations of D65/2 and D65/10 conditions respectively.

The testing results are given in Tables 5-9 for the NCS training samples from IA, NCS testing data from IA, NCS testing data from IB, Munsell testing data from IA and Munsell testing data from IB respectively. It can be seen from those tables that all results are consistent regardless which data set is used. An average difference about 2.0 ΔE^*_{00} units, and the worse case could be up to 6 ΔE^*_{00} units for the original data. While the CAT02 transform gave very little improvement. On the other hand, the average difference is about 0.3 ΔE^*_{00} units with the maximum ΔE^*_{00} about 2.4 units for the polynomial correction. This strongly indicates that the performance of the proposed polynomial model is accurate. Furthermore, the reversibility error is negligible (0.03 ΔE^*_{00} units).

	Ave	Std	Max
No Correction	2.00	1.14	5.37
CAT02 Correction	1.92	1.15	5.08
Polynomial	0.24	0.21	1.54
Reversibility	0.024	0.02	0.12

Table 5: Performance in ΔE^*_{00} units of Observer Corrections for the Training data set

	Ave	Std	Max
No Correction	2.00	1.13	6.40
CAT02 Correction	1.87	1.17	6.19
Polynomial	0.27	0.26	2.31
Reversibility	0.024	0.023	0.233

Table 6: Performance in ΔE^*_{00} units of Observer Corrections for the testing data: (NCS,IA)

	Ave	Std	Max
No Correction	1.98	1.13	6.49
CAT02 Correction	1.88	1.17	6.29
Polynomial	0.27	0.27	2.37
Reversibility	0.025	0.024	0.243

Table 7: Performance in ΔE^*_{00} units of Observer Corrections for the testing data: (NCS,IB)

	Ave	Std	Max
No Correction	1.96	1.14	6.36
CAT02 Correction	1.85	1.17	6.11
Polynomial	0.33	0.27	2.03
Reversibility	0.026	0.026	0.243

Table 8: Performance in ΔE^*_{00} units of Observer Corrections for the testing data: (Munsell,IA)

	Ave	Std	Max
No Correction	1.9619	1.1426	6.4398
CAT02 Correction	1.8581	1.1737	6.1811
Polynomial	0.3330	0.2738	2.0804
Reversibility	0.0266	0.0279	0.2780

Table 9: Performance in ΔE^*_{00} units of Observer Corrections for the testing data: (Munsell, IB)

Application 3: Illuminant Corrections

In this application, the model was trained and tested using the same training and testing data sets used in the last section, but the tristimulus values were calculated under D65/10 and A/10 conditions. All results are listed in Tables 10-14.

It can be seen that for the original data sets between the D65 and A illuminants, the mean difference is as large as 21 ΔE^*_{00} units with the worst case of 36 ΔE^*_{00} units. This implies that there is a very large difference due to different illuminants. For the CAT02 corrections, the mean difference is significantly reduced to about 2.8 ΔE^*_{00} units with the worst case about 8.0 units. While for the polynomial model, the average is about 0.7 colour difference units and the worst case is about 4 ΔE^*_{00} units. However, the reversibility error between the forward and reverse models is about 200% worse compared with those between the instrument and between the observer corrections. On the other hand, for a mean difference of 0.2 ΔE^*_{00} units, it can still be considered as satisfactory.

Conclusions

In this paper, a model based on polynomial was proposed to convert between two sets of data in terms of tristimulus values. Three colorimetric applications were illustrated by transforming data sets between different instruments, between different observers and between different illuminants. The findings are:

1. The polynomial model can successfully achieve the transformations between all three applications.
2. The disagreement (0.05 ΔE^*_{00} units) after the instrument correction is 6 times smaller than the original disagreement (0.3 ΔE^*_{00} units).
3. The disagreement (0.33 ΔE^*_{00} units) after the observer correction is 6 times smaller than the original disagreement (2.0 ΔE^*_{00} units).
4. The disagreement (0.7 ΔE^*_{00} units) after the illuminant correction is 30 times smaller than the original disagreement (20 ΔE^*_{00} units).
5. The model can be trained using less than 200 samples, a tenth of the full data set.
6. The polynomial model has very good reversibility through it has no analytical formula for the inversion.
7. The polynomial model proposed can also be used to predict the tristimulus values between two different illuminants. The useful application can be to transform the data of the other illuminants to that of the D50 illuminant, which is the standard condition for ICC colour management. To apply CATs such as CAT02 is undesired in this case, because all CATs assume the samples considered are colour constant.

	Ave	Std	Max
No Correction	20.39	5.67	33.45
CAT02 Correction	2.75	1.64	7.03
Polynomial	0.51	0.48	2.24
Reversibility	0.22	0.22	1.13

Table 10: Performance in ΔE^*_{00} units of Illuminant Corrections for the testing data

	Ave	Std	Max
No Correction	20.64	5.66	36.02
CAT02 Correction	2.61	1.63	7.94
Polynomial	0.59	0.58	4.10
Reversibility	0.22	0.21	1.13

Table 11: Performance in ΔE^*_{00} units of Illuminant Corrections for the testing data: (NCS, IA)

	Ave	Std	Max
No Correction	20.56	5.68	36.06
CAT02 Correction	2.63	1.65	8.04
Polynomial	0.60	0.58	4.25
Reversibility	0.22	0.21	1.13

Table 12: Performance in ΔE^*_{00} units of Illuminant Corrections for the testing data: (NCS, IB)

	Ave	Std	Max
No Correction	21.36	5.37	35.87
CAT02 Correction	2.72	1.62	7.06
Polynomial	0.74	0.59	3.45
Reversibility	0.24	0.22	1.07

Table 13: Performance in ΔE^*_{00} units of Illuminant Corrections for the testing data: (Munsell, IA)

	Ave	Std	Max
No Correction	21.28	5.38	35.90
CAT02 Correction	2.74	1.63	7.12
Polynomial	0.75	0.59	3.56
Reversibility	0.24	0.22	1.11

Table 14: Performance in ΔE^*_{00} units of Illuminant Corrections for the testing data: (Munsell, IB)

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