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Instrument Dependency of Kubelka-Munk Theory in Computer Color Matching

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ABSTRACT

Different industries are usually faced with computer color matching as an important problem. The most famous formula, which is commonly used for recipe prediction is based on the Kubelka-Munk (K-M) theory. Considering that spectrophotometer's geometry and its situation influence the measured spectral values, the performance of this method can be affected by the instrument. In the present study, three spectrophotometer geometries including 45/0, d/8 with specular component included mode and d/8 with specular component excluded mode were compared in the case of recipe prediction of textile samples using K-M theory. Comparing the applied measuring situations, the color matching results obtained from d/8 geometry in SCE mode were far better than the others, while 45/0 geometry gives inferior performance which may be caused by the textured surface of textile fabrics. Prog. Color Colorants Coat. 5(2012), 85-90. © Institute for Color Science and Technology.

1. Introduction

An important industrial problem is the color match prediction. It is a complex process to predict the proportions of the colorants required to produce a color match for an object to show the same color as a standard [1-2]. Among several theories used for color recipe prediction, the most famous one is the Kubelka-Munk (K-M) theory [1-5]. The simple mathematical form of Kubelka-Munk theory is expressed as Eq. (1).

$$\left(K/S\right)_\lambda = \frac{(1-R_\lambda)^2}{2R_\lambda} \qquad (1)$$

where, R is the reflectance factor at the surface for a sample of infinite thickness and K and S are the absorption and scattering coefficients of the sample, respectively.

Based on single-constant K-M theory, there is a linear relationship between the ratios of absorption and scattering coefficients (K/S) of each colorant and the colorant concentration. This ratio, K/S, is known as the colorant's "unit 'K' over 'S'" [3]. The final equation for the single-constant for n colorants is expressed as

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equation 2.

$$\left(K/S\right)_{\lambda,mixture} = c_1\left(K/S\right)_{\lambda,1} + c_2\left(K/S\right)_{\lambda,2} + c_3\left(K/S\right)_{\lambda,3} + ... + c_n\left(K/S\right)_{\lambda,n} \quad (2)$$

Considering that K/S values are computed from the measured reflectance values, it is expected that the measuring instrument could affect the results. Spectrophotometers which measure the spectral data, have been usually built based on two geometries, including d/8 and 45/0 [5-6]. Based on the CIE definitions, the first number refers to the illumination geometry and the second indicates the observation geometry [5]. The term "d" (diffuse) means that the illuminating or viewing is not directional, but is somewhat diffuse, usually using an integrating sphere [5-6]. The 8° viewing variance from the normal allows some of the instrument to measure reflectance in either specular-included mode which measures the total reflectance (including diffuse reflectance and specular reflectance) or specular-excluded mode to measure the diffuse reflectance only. In 45/0 geometry, the sample is illuminated with a collimated beam of light at 45° to the surface normal, and the reflected light is collected from a narrow range of angles centered on the observation angle, which is 0° relative to the surface normal.

The viewing angle and the illuminating condition, considerably influence the perceived color [7-8]. There are some recommendations for applying each of these two geometries for different applications [6-7]. Comparison of these two geometries has been reported previously for different applications in the color industry [6-10]. Also, there are researches which have either compared the accuracy of different spectrophotometers based on a reference spectrophotometer or two measuring geometries in different applications [11-13].

In the present study, the performance of K-M theory in textile color matching is investigated for different spectrophotometer geometries (d/8 and 45/0) and conditions (SCI and SCE). Research related to this issue are quite rare. One of the most related researches has been done in 1988, investigated the effect of spectrophotometer geometry on computer color formulation for matching standard samples with varying gloss [9]. It has been reported that bidirectional geometry may be superior to integrating-sphere geometry for this kind of sample.

2. Experimental

The effect of spectrophotometer's geometry and its condition on the performance of Kubelka-Munk theory for color recipe prediction in textile industry was investigated. To this end, 242 dyed polyester fabrics prepared in the previous research [14] were used. The fabric samples were dyed with a combination of one, two or three colorants selected from a set of five colorants.

The spectral reflectance values were measured in three different ways. First, the spectral data were measured with a GretagMacbeth Color Eye 7000A spectrophotometer which is an instrument with diffuse/8° geometry in specular component included (SCI) mode. Then, the spectral data were measured using the same instrument, but in the specular component excluded (SCE) mode. Finally, the spectral data were obtained using a HunterLab MiniScanEZ with 45/0 geometry. Other parameters of the three measuring systems were the same. Repeatability of Color Eye 7000 A Spectrophotometer using a ceramic white standard tile is: <0.01 RMS ΔE CIELAB. Inter instrument Agreement of Color Eye 7000 A Spectrophotometer Using 13 calibrated BCRA tile is < 0.08 Average ΔE CIELAB.

For the HunterLab instrument, the white tile repeatability is less than 0.03 ΔE CIELAB. For the green standard tile the ΔX, ΔY and ΔZ are <0.5 which pass the instrument's reproducibility condition.

The measurements were carried out on the fabrics which were folded 4-ply. For both instruments the size of sampling port and other laboratory conditions were the same. For all measurements, the spectral reflectance values were measured in the range of 400nm and 700nm with 10nm intervals without any ASTM weighting functions. It has been reported that the use of the ASTM weighting functions in the case of non-fluorescent reflectance spectra may not greatly affect the results [15].

The color coordinates of the samples were computed under CIE 1964 standard observer (10°) and illuminant D_{65}.

In the present investigation, the total K/S and subsequently the reflectance factor (R) of each of the 242 samples were computed based on equation 2, while the colorants' "unit K/S" was obtained using each of the three mentioned spectral measuring situations.

The performance of K-M theory in color matching was evaluated for each measuring condition. For this purpose, the spectral and colorimetric errors of each sample were computed between the measured data by the spectrophotometer and the computed ones applying equation 2.

Root Mean Square Error (RMSE) of spectral reflectance and Goodness-of- Fit Coefficient (GFC) [16] were applied for spectral error evaluation. The GFC metric is calculated by the following equation, where R and $\hat{R}$ are the actual and measured spectral reflectances, respectively.

$$GFC = \frac{\left|\sum_{\lambda} R_{\lambda} \hat{R}_{\lambda}\right|}{\sqrt{\left|\sum_{\lambda} R_{\lambda}^{2}\right|}\sqrt{\left|\sum_{\lambda} \hat{R}_{\lambda}^{2}\right|}} \qquad (3)$$

The GFC values run from 0 to 1, so that the mathematical reconstruction of the function R would be better as the GFC values approach unity.

The color difference was computed using the CIEDE2000 (1:1:1) [17] and CMC (2:1:1) [18] color difference formulae.

3. Results and discussion

Figure 1 shows the color coordinates of the dyed samples obtained from the three spectral measurements. The red circles indicate the samples with a color difference higher than 10 CIEDE2000 (1:1:1) unit. It can be seen that the distribution and location of the samples with a larger color difference are almost similar in the three measuring conditions. However, it shows a lower number for d/8(SCE) measures.

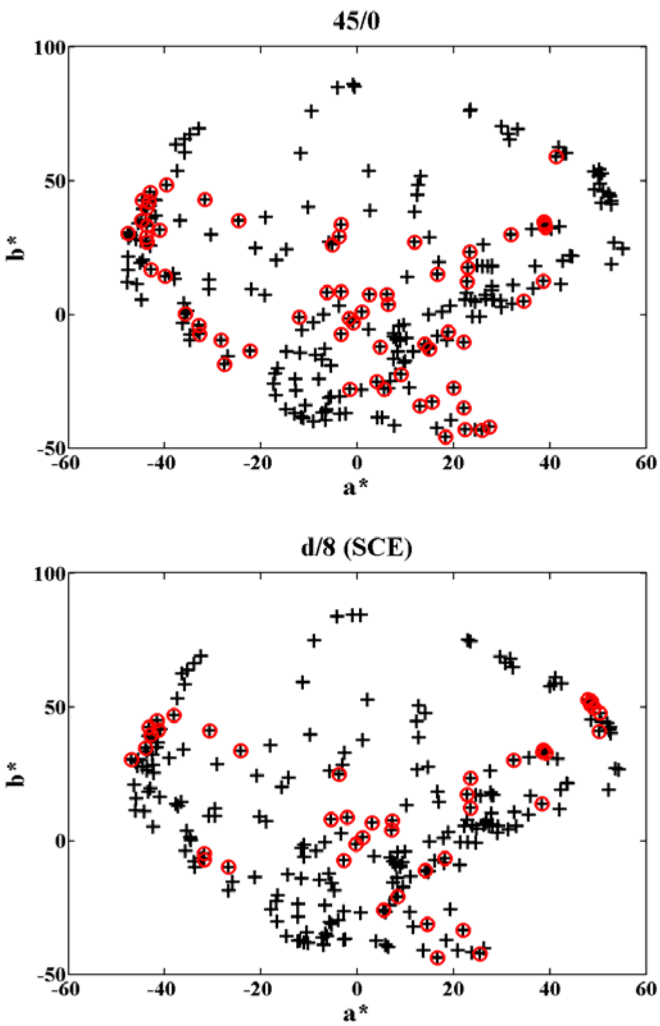

Figure 1: The color coordinates of the dyed samples with the three measuring instruments.

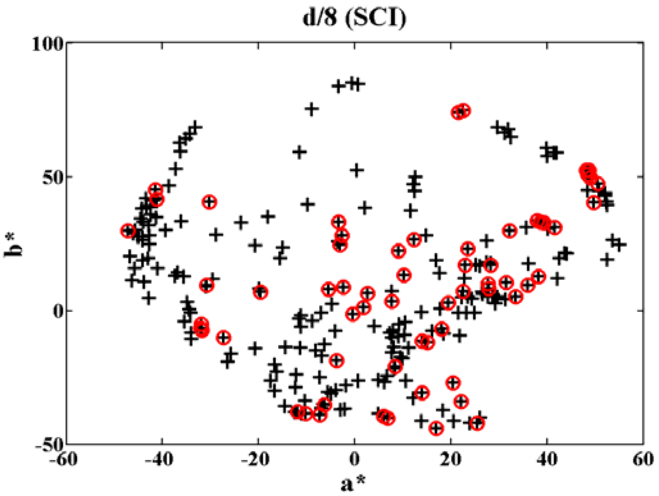

Figure 1: Continued.

Table 1: The mean of spectral and colorimetric difference between measured spectral values for each spectrophotometers.

	GFC	RMSE	ΔE (DE00)	ΔE (CMC)
45/0 & d/8 (SCI)	0.9919	0.0253	2.88	2.49
45/0 & d/8 (SCE)	0.9786	0.0364	1.96	1.70
d/8 (SCI) & d/8 (SCE)	0.9816	0.0333	1.44	1.23

Table 2: The mean of spectral and colorimetric difference between calculated spectral values from Kubelka-Munk theory for each spectrophotometers.

	GFC	RMSE	ΔE (DE00)	ΔE (CMC)
45/0 & d/8 (SCI)	0.9607	0.0547	7.54	8.09
45/0 & d/8 (SCE)	0.9807	0.0378	4.21	4.87
d/8 (SCI) & d/8 (SCE)	0.9700	0.0439	5.19	5.69

Table 1 shows the average of spectral and colorimetric differences between each two measuring situation. Correspondingly Table 2 gives similar values obtained for calculated spectral data based on K-M theory. As illustrated, the measured values of diffuse geometry in both included and excluded modes are close to each other based on measured spectral data; however, the calculated values via Kubelka-Munk theory shows almost the closest results for diffuse geometry in excluded mode with 45/0 one.

The statistical values of RMSE and GFC obtained from color matching with K-M theory for each spectrophotometer are shown in Table 3 and 4, respectively. It can be seen that based on both criteria, 45/0 gives the largest error in color recipe prediction. Applying d/8 geometry can improve the results, and it is so interesting that d/8(SCE) mode yields the best result.

Table 3: The statistical values of RMSE for each spectral measuring condition.

	Mean	std	Min	Max
45/0	0.0734	0.0775	0.0011	0.3705
d/8 (SCI)	0.0681	0.0734	0.0016	0.4056
d/8 (SCE)	0.0648	0.0443	0.0015	0.3215

Table 4: The statistical values of GFC for each spectral measuring condition.

	Mean	std	Min	Max
45/0	0.9625	0.0903	0.4008	1.0000
d/8 (SCI)	0.9685	0.0787	0.4371	1.0000
d/8 (SCE)	0.9732	0.0420	0.6610	1.0000

Table 5: The statistical values of color difference (CIEDE2000 (1:1:1)) for each spectral measuring condition.

	Mean	std	Min	Max	No >10
45/0	10.4565	11.7615	0.1722	60.7120	63
d/8 (SCI)	9.6049	9.0350	0.1027	50.2037	62
d/8 (SCE)	7.4439	6.2471	0.1974	38.7476	43

Table 6: The statistical values of color difference (CMC (2:1:1)) for each spectral measuring condition.

	Mean	std	Min	Max	No >10
45/0	10.8994	14.8742	0.1333	73.2337	58
d/8 (SCI)	10.5657	13.5225	0.0804	79.6928	55
d/8 (SCE)	7.4959	7.5571	0.1491	47.7659	41

Table 5 and 6 give the colorimetric error for recipe prediction for each measuring system. Apparently, color difference values show also similar results for spectral errors. The d/8 (SCE) measuring condition gives the best results as is illustrated in Tables 5 and 6. Considering the basis of K-M theory, which has no view to gloss, it can be justified that gloss-excluded mode gives better results. However, comparing 45/0 and d/8(SCE), which both are glossed-excluded, showed that such a conclusion is not entirely correct, and the other parameters are also important. In addition, the tested samples were polyester fabrics without almost any gloss and contained a fine texture. Therefore, it seems that the d/8(SCE) mode has better agreement with single constant Kubelka-Munk theory for predicting the spectral reflectance of textured samples. It may be due to the fact that for textured samples, the specular reflectance is diffused and mixed with diffuse reflectance. Thus, 45/0 instrument is not suitable for this purpose and the diffuse illuminating condition is recommended. In addition, in d/8(SCI) mode the reflected light in specular angle is highly considered because of the detector angle, which may not be preferable for texture samples with completely diffuse reflection, so d/8(SCE) mode would be the best.

Consequently, it shows that diffuse illuminating condition with gloss-excluded mode has more consistency with K-M theory.

4. Conclusions

Color match prediction is always a problem in color industries. The most famous theory, which is usually applied for computer color matching is the Kubelka-Munk. The performance of this theory can be affected by the spectral measuring instrument. Besides, the geometry and the condition of spectrophotometer influence the measured data. In this research, the effect of the spectrophotometer on the performance of Kubelka-Munk theory in color recipe prediction of textile samples was investigated for three measuring situations including 45/0, d/8(SCI) and d/8(SCE). The results show that diffuse geometry can be totally a better choice than 45/0, and d/8(SCE) gives the superior results based on spectral and colorimetric criteria. Considering that, this research was carried out for polyester samples, more investigations applying different kinds of fabrics would be done to be able to suggest these results for textile industry. This would be the goal of the future studies.

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