Reprinted from:
Journal of Imaging Science and Technology® 59(3): 030401-1–030401-8, 2015.

Yarn Color Measurement and Reproduction by a Multispectral Imaging System

Isabella W. S. Tang and John H. Xin
Institute of Textiles & Clothing, The Hong Kong Polytechnic University, Hong Kong
E-mail: 12901155r@connect.polyu.hk

Abstract. *Conventionally, measuring and thus reproducing yarn color is mainly done in an indirect way, involving the preparation of yarns in card or even fabric forms, which consumes both time and labor. A direct yarn color measurement and reproduction method based on a multispectral imaging system would be one solution to avoid this problem. In this research, 100% raw cotton yarn hanks dyed using several reactive colorants, being different sample sets, were measured by both a spectrophotometer in yarn card form and a multispectral imaging system innovatively in yarn form itself, for back-prediction and fore-prediction matching comparisons. Experimental results showed that the multispectral imaging system can perform closed-loop color reproduction satisfactorily by yarn form color measurements, with color difference means all within industrial tolerance. This new method is capable of shortening the yarn specimen handling time and, more importantly, giving more accurate yarn color measurements without the influence of neighboring colors, so as to give improved coloration accuracy.*

[DOI: 10.2352/J.ImagingSci.Technol.2015.59.3.030401]

INTRODUCTION

The initial phase of textile coloration is mainly based on the experience of the colorists who predict the usage amount of different colorants for producing the target color and sometimes with reference to previous dyeing records to give a similar color, while several correction dyeings may be needed to amend the results. To achieve this, accurate visual color assessment is of prime importance, where human eyes are the detector at 90° to the specimen placed at 45° to a specific illuminant in the light cabinet.[1] However, it was found that such kinds of assessment method can be easily affected by a series of factors such as the change of viewing conditions in terms of lighting, background color, etc., and observer metamerism, in such a way that it is no longer reliable to give the correct dyeing recipe by a human.[2–5] With technological advancement, instrumental color measurement using a spectrophotometer has been adopted to perform color measurement and then reproduction. It is used to establish a calibration database through measurements, measuring the target color, analyzing the color content, and formulating the dying recipes of the colorant concentrations by the built-in color-matching software.[6] However, it is only convenient for measuring and then reproducing color on textile fabric, not on yarn. Owing to the mechanism and operation of a spectrophotometer, color measurement results are given by averaging the points within the aperture area and thus the method is applicable to textile fabric covering the measurement area but not yarn. To overcome this limitation, yarns need to be wound onto a card first by either a human hand or a winding machine with great uniformity in terms of inter-yarn spacing and tension. Otherwise, non-uniformity arising from overlapping shadows and the yarn card background color would be regarded as the yarn color itself, degrading the accuracy of the color measurement and imposing problems in color reproduction and communication.[7]

With multispectral imaging systems, yarn color measurement is made possible by a color-region segmentation technique which is able to detect and extract the yarn color from the captured image mainly using two approaches: clustering algorithms, e.g., fuzzy c-means clustering algorithm,[8] and image segmentation methods, e.g., edge-based,[9] graph-based,[10] histogram-based[11] and region-based methods.[12] This helps to minimize the yarn specimen handling time, needing no human hand or winding machine to make them in yarn card wound form beforehand. Having no such specimen non-uniformity, the yarn calibration sets can be done with the measurements of yarn in its twisted form to establish a more accurate calibration database and then going on to the color reproduction procedures step by step. This study revealed that the merits of obtaining the yarn color spectral information using a spectrophotometer can also be achieved using a multispectral imaging system as well as giving spatial information while, more usefully, overcoming the limitations of sample size, shape, and configuration so as to eliminate the existence of specimen non-uniformity. This new closed-loop color measurement and reproduction process is aimed at providing an improvement in coloration accuracy with satisfactory repeatability.

Regarding recipe formulation, Kubelka–Munk theory[13,14] plays an important role in establishing a relationship between the reflectance and the K/S value. The core equations are listed as follows, where R_∞ is the reflectance of an opaque layer, K is the absorption coefficient attributed to dyes, and S is the scattering coefficient from the substrate:[15]

$$R_\infty = 1 + \left(\frac{K}{S}\right) - \left[\left(\frac{K}{S}\right)^2 + 2\left(\frac{K}{S}\right)\right]^{1/2} \quad (1)$$

$$K/S = (1 - R_\infty)^2/(2R_\infty). \quad (2)$$

Received Mar. 16, 2015; accepted for publication May 20, 2015; published online June 16, 2015. Associate Editor: Marius Pedersen.
1062-3701/2015/59(3)/030401/8/$25.00

The multispectral imaging system used in this paper is the Imaging Color Measurement System ICM, which was invented by our research team. Based on multispectral imaging technology, it first calibrates the illumination and optical system and then measures the colors of all pixels in a color image captured by its charge-coupled device (CCD) camera. With the aid of a color-region segmentation technique,[16–18] accurate results of spectral reflectance can be generated. Concerning technical specifications, its repeatability in terms of average colorimetric error is 0.03 CMC(2:1), and its uniformity in terms of maximum and average colorimetric errors is 0.1 and 0.01 CMC(2:1), respectively. It takes less than 25 s measurement time to produce less than 1 nm spectral wavelength accuracy, and its optical configuration is 45/0° under D65/10 measurement conditions.[19]

EXPERIMENTAL

In this experiment, we used 100% raw cotton yarn with a count of 80 Ne made into yarn hanks, each with a weight of 2 g, by using a wrap reel machine. To dye the cotton yarns, four Levafix® CA reactive dyes supplied by Dystar were employed: Red CA-N, Amber CA-N, Blue CA, and Navy CA, with the auxiliaries of Glauber's salt and soda ash at 60°C temperature for 60 min, keeping the liquor ratio of 60:1 as suggested in the colorant menu. Each kind of dyestuff was made into 0.5% and 0.05% solutions for facilitating the use of specific concentrations as stated in the subsequent calibration, back-prediction, and fore-prediction dyeing recipes.

According to instrumental textile coloration procedures, the calibration set should be prepared consisting of each of the four colorants at different concentrations as well as a blank sample with no colorant. For red, amber, blue, and navy, respectively, yarn hanks were dyed at six concentration intervals: 0.1%, 0.5%, 1.0%, 2.0%, 3.0%, and 5.0% by weight of the yarn substrate based on the recipes shown in Table I. Besides ensuring the manual dyeing accuracy, the calibration dyeing was done twice, and therefore there were two calibration sets, being 50 (25 × 2) yarn hank specimens in total; the corresponding color differences between them were also studied. All these were measured by both a Gretag-Macbeth 7000A spectrophotometer and the multispectral imaging system ICM. The majority of each specimen was wound onto a yarn card with the highest possible uniformity manually, and yarn sections were cut, twisted, and mounted on the specific yarn holder for respective color measurements. After that, the calibration database could be established.

Table II shows the two repeatability tests done on the two calibration sets, named set1 and set2, first to validate the instrumental measuring accuracy by carrying out self-repeatability checks, namely to measure the same point of the yarn card or yarn twist at three different time intervals with one hour in between (i.e., 1st, 2nd, and 3rd hour), and second to verify the manual dyeing accuracy by checking the inter-repeatability, namely to compare the two different portions in either yarn card or yarn twist form of the same yarn specimen (i.e., set1 versus set1' and set2 versus set2') or of different corresponding yarn specimens (i.e., set1 versus set2). For both types of repeatability test, three comparisons were averaged, giving a color difference ΔE, and these all were further averaged to obtain the mean ΔE value and the standard deviation of ΔE to assess the results. According to the statistical information, for the self-repeatability, both the spectrophotometer and multispectral imaging system can perform with satisfactory accuracy, having a data dispersion of only 0.02 CMC(2:1) units and only a small color difference mean of 0.10 and 0.09 CMC(2:1) units, respectively, ensuring good device measuring accuracy. And for the inter-repeatability, again the two devices gave similar results, showing data dispersion of 0.05 and 0.06 CMC(2:1) units, respectively, with the corresponding mean of 0.25 and 0.23 CMC(2:1) units. Although these contained slightly higher color differences than the self-test, the results are still reasonably acceptable as these incorporated color differences due to both multiple machine measurement and dyeing levelness within and between yarn hanks, proving good manual dyeing accuracy.

Table I. Recipes for the calibration set dyeing.

Calibration recipes	red/amber/blue/navy		Salt	Soda ash	D.I. water
	0.50%	0.05%	10%	10%	
red/amber/blue/navy_0.1		4	40	10	58
red/amber/blue/navy_0.5		20	40	10	58
red/amber/blue/navy_1.0	4		40	10	42
red/amber/blue/navy_2.0	8		40	10	42
red/amber/blue/navy_3.0	12		40	10	42
red/amber/blue/navy_5.0	20		40	10	42
Blank			40	10	70

Then set1 was chosen to establish the calibration database for both devices by their corresponding yarn specimen measurements. Figure 1 shows the K/S versus concentration curves, being an indicator of the effectiveness of calibration dyeing, where the color strength should be theoretically proportional to the colorant concentrations, and thus a straight line was expected giving a more accurate recipe prediction. It is common to find the phenomenon of dye saturation, so that at the higher concentrations, i.e., 3.0 or 5.0, the color strength growth tends to be slower and the line becomes flattened. Considering the calibration database for the spectrophotometer, the four K/S versus concentration curves of red, amber, blue, and navy were generally straight lines, and dye saturation was found in the red and blue colorants. And this is the same for the calibration database of the multispectral imaging system having navy dye saturation, while all the rest resulted in straight curves, proving that the calibration dyeing was well done and ensuring recipe prediction accuracy in the next stage. Figure 2 shows the CIE L*a*b* distributions of the calibration set1 specimens. For both spectrophotometer and multispectral imaging system results, the locations and the

Table II. Repeatability measurements for the calibration set1 & set2.

Self-repeatability	Coloureye-7000A						ICM imaging system					
D65/10° CMC(2:1)	1st versus 2nd	1st versus 3rd	2nd versus 3rd	ΔE	Mean ΔE	Std dev. ΔE	1st versus 2nd	1st versus 3rd	2nd versus 3rd	ΔE	Mean ΔE	Std dev. ΔE
red_3.0	0.07	0.05	0.09	0.07	0.10	0.02	0.09	0.13	0.05	0.09	0.09	0.02
red_5.0	0.11	0.16	0.08	0.12			0.12	0.06	0.14	0.11		
amber_3.0	0.08	0.15	0.07	0.10			0.05	0.07	0.09	0.07		
amber_5.0	0.10	0.14	0.10	0.11			0.06	0.10	0.11	0.09		
blue_3.0	0.04	0.12	0.09	0.08			0.13	0.11	0.07	0.10		
blue_5.0	0.06	0.13	0.15	0.11			0.11	0.16	0.11	0.13		
navy_3.0	0.05	0.11	0.10	0.09			0.10	0.06	0.07	0.08		
navy_5.0	0.12	0.08	0.12	0.11			0.07	0.09	0.10	0.09		
Inter-repeatability	Coloureye-7000A						ICM imaging system					
D65/10° CMC(2:1)	set1 versus set1′	set2 versus set2′	set1 versus set2	ΔE	Mean ΔE	Std dev. ΔE	set1 versus set1′	set2 versus set2′	set1 versus set2	ΔE	Mean ΔE	Std dev. ΔE
red_3.0	0.28	0.17	0.14	0.20	0.25	0.05	0.14	0.10	0.19	0.14	0.23	0.06
red_5.0	0.18	0.26	0.28	0.24			0.17	0.24	0.24	0.22		
amber_3.0	0.12	0.31	0.26	0.23			0.24	0.15	0.19	0.19		
amber_5.0	0.40	0.26	0.20	0.29			0.13	0.30	0.31	0.25		
blue_3.0	0.13	0.23	0.21	0.19			0.08	0.19	0.19	0.15		
blue_5.0	0.24	0.33	0.24	0.27			0.31	0.14	0.26	0.24		
navy_3.0	0.27	0.38	0.28	0.31			0.31	0.26	0.33	0.30		
navy_5.0	0.25	0.32	0.35	0.31			0.20	0.54	0.19	0.31		

sequences of the calibration points were similar to each other correspondingly for all the red, amber, and blue, but not for navy. These differences indicated a discrepancy in yarn color measurements between the two devices.

Back-prediction matching comparison based on pre-determined dyeing recipes

Repeating the same procedures for both the spectrophotometer and the multispectral imaging system, there were 20 pre-determined dyeing recipes consisting of different concentrations, i.e., 0.1%, 0.5%, 1.0%, 3.0%, and different combinations of the four colorants, i.e., red, amber, blue, and navy. As observed from the K/S versus concentration curves in the previous section, there was dye saturation for the concentration at 5.0%, so all recipes were purposely made under this cut-off line in order to avoid any dye-uptake obstacles affecting the resultant color and thus the comparison. Table III shows the recipes for the back-prediction set dyeing which was used to calculate the virtual reflectance of the pre-determined amount and the kind of each colorant based on the established calibration database as the standard for matching comparison. For the corresponding batch, the results were obtained by practically carrying out the dyeing according to these recipes to produce real yarn specimens and then measuring the color using each of the two devices in either yarn card or yarn twisted form.

After using the respective calibration database of both the spectrophotometer and the multispectral imaging system for the virtual reflectance calculation, there were in total 40 (20 × 2) calculated colors, being the standards. And after completing the mentioned dyeing, 20 colored yarn hanks were produced and measured individually by the two devices, where there were again 40 (20 × 2) measured colors, being the batches, so that the matching comparisons could then be processed by finding the color difference ΔE between each pair. Statistical values of the mean ΔE and the standard deviation of ΔE were then computed to assess the data dispersion and overall data average. Both result sets for the two devices are shown in Table IV, with the predicted reflectances referring to the calculated standards and the actual reflectances being the measured batches.

For the spectrophotometer results, the color differences ranged from 0.83 to 2.48, obtaining a data dispersion of 0.49 CMC(2:1) units and data mean of 1.41 CMC(2:1) units, which was still acceptable against the textile industry's color tolerance of about $\Delta E = 1.5$, and these represented the current color reproduction status for dyeing the textile yarn materials in yarn card form. For the results of the multispectral imaging system, the range of ΔE was wider, being from 0.64 to 2.69, having a higher data dispersion of 0.57 CMC(2:1) units and overall average of 1.45 CMC(2:1) units, but still it was within the tolerance norm, indicating that the ICM can perform as well as the previous device for reproducing yarn colors in yarn twisted form. For those with ΔE above 2.0, correction dyeing may be needed to give a

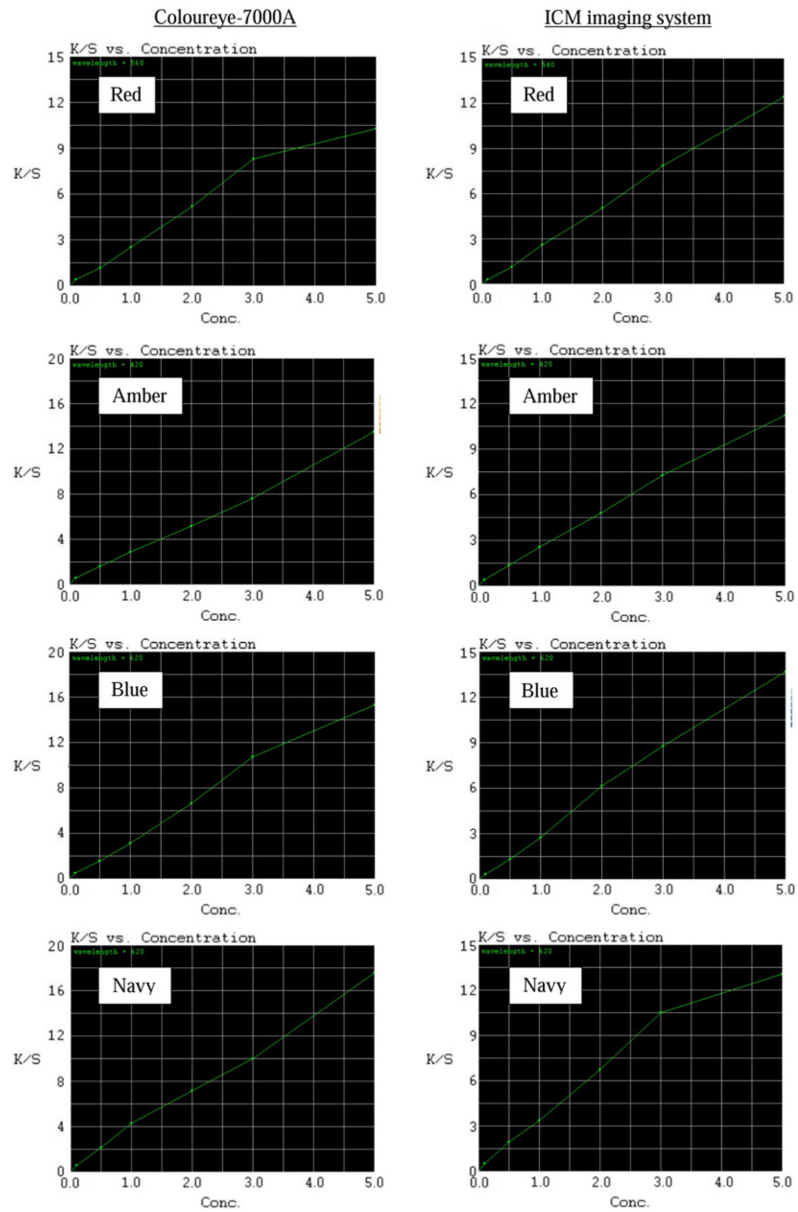

Figure 1. K/S versus concentration curves of the set1 calibration database of the two devices.

better match; there were three from the spectrophotometer set and four from the multispectral imaging system set being subjected to amendments of the colorant amounts.

Fore-prediction matching comparison based on formulated dyeing recipes

Further studying the performance of yarn color reproduction and measurements made by the two devices, there were ten extra formulated dyeing recipes which were generated by measuring the ten Pantone color specifier papers: 14-1038 (new wheat), 15-1523 (shrimp), 15-1611 (bridal rose), 16-3931 (sweet lavender), 17-3917 (stonewash) 18-0629 (lizard), 18-0933 (rubber), 18-1619 (maroon), 18-3027 (purple orchid), and 18-5105 (sedona sage). They were selected randomly in different hues for formulating the required recipes using the four colorants to mix out these ten target colors. Practical yarn colorations were done according to the formulated recipes, and ten real dyed yarn hanks were produced to be the standards. At this stage, there were in total 30 dyeing recipes (20 pre-determined in the previous section and 10 formulated in this section) which were then repeated once again to dye another 30 yarn specimens accordingly to make color difference comparisons to see if the measurement results from the two devices are similarly consistent with each other.

Table V shows the recipes for the fore-prediction dyeing, which were obtained by inputting the target color information via the means of color papers into the calibration database of the spectrophotometer and using its built-in prediction software to determine the correspondingly

Table III. Recipes for the back-prediction dyeing.

20 pre-determined recipes	Red		Amber		Blue		Navy		Salt 10%	Soda ash 10%	D.I. Water
	0.50%	0.05%	0.50%	0.05%	0.50%	0.05%	0.50%	0.05%			
0.1red_0.1amber_0.1blue		4		4		4			40	10	58
0.1red_0.1amber_0.1navy		4		4				4	40	10	58
0.1red_0.1amber_0.5blue		4		4		20			40	10	42
0.1red_0.1amber_0.5navy		4		4				20	40	10	42
0.1red_0.5amber_0.1blue		4		20		4			40	10	42
0.1red_0.5amber_0.1navy		4		20				4	40	10	42
0.5red_0.1amber_0.1blue		20		4		4			40	10	42
0.5red_0.1amber_0.1navy		20		4				4	40	10	42
0.5red_0.5amber_1.0blue		20		20	4				40	10	26
0.5red_0.5amber_1.0navy		20		20			4		40	10	26
0.5red_1.0amber_0.5blue		20	4			20			40	10	26
0.5red_1.0amber_0.5navy		20	4					20	40	10	26
0.5red_1.0amber_3.0blue		20	4		12				40	10	34
0.5red_3.0amber_1.0navy		20	12				4		40	10	34
1.0red_0.5amber_0.5blue	4			20		20			40	10	26
1.0red_0.5amber_0.5navy	4			20				20	40	10	26
1.0red_0.5amber_3.0navy	4			20			12		40	10	34
1.0red_3.0amber_0.5blue	4		12			20			40	10	34
3.0red_0.5amber_1.0navy	12			20			4		40	10	34
3.0red_1.0amber_0.5blue	12		4			20			40	10	34

Table IV. Color difference results of the back-prediction matching comparisons.

Predicted versus actual reflectance D65/10° CMC(2:1)	Coloureye-7000A			ICM imaging system		
	ΔE	Mean ΔE	Std dev. ΔE	ΔE	Mean ΔE	Std dev. ΔE
0.1red_0.1amber_0.1blue	1.03	1.41	0.49	1.19	1.45	0.57
0.1red_0.1amber_0.1navy	1.17			0.98		
0.1red_0.1amber_0.5blue	0.84			1.85		
0.1red_0.1amber_0.5navy	0.97			1.02		
0.1red_0.5amber_0.1blue	1.74			2.01		
0.1red_0.5amber_0.1navy	1.31			2.35		
0.5red_0.1amber_0.1blue	1.64			0.64		
0.5red_0.1amber_0.1navy	1.14			0.64		
0.5red_0.5amber_1.0blue	1.94			1.25		
0.5red_0.5amber_1.0navy	2.48			2.69		
0.5red_1.0amber_0.5blue	1.67			1.65		
0.5red_1.0amber_0.5navy	1.22			0.97		
0.5red_1.0amber_3.0blue	1.13			2.10		
0.5red_3.0amber_1.0navy	0.83			1.29		
1.0red_0.5amber_0.5blue	0.85			1.68		
1.0red_0.5amber_0.5navy	1.14			1.86		
1.0red_0.5amber_3.0navy	2.10			0.94		
1.0red_3.0amber_0.5blue	1.03			1.48		
3.0red_0.5amber_1.0navy	2.18			1.47		
3.0red_1.0amber_0.5blue	1.36			0.85		

Table V. Recipes for the fore-prediction dyeing.

10 formulated recipes	Red		Amber		Blue		Navy		Salt 10%	Soda ash 10%	D.I. Water
	0.50%	0.05%	0.50%	0.05%	0.50%	0.05%	0.50%	0.05%			
14-1038 (new wheat)		2.3	2.6					1.7	40	10	63
15-1523 (shrimp)		18.2		19.3				1.1	40	10	51
15-1611 (bridal rose)		17.4		6.0				2.1	40	10	50
16-3931 (sweet lavender)		9.6		1.1		15.7			40	10	60
17-3917 (stonewash)		11.6		4.7	3.2				40	10	58
18-0629 (lizard)		11.0	10.9		3.2				40	10	48
18-0933 (rubber)		17.5	14.4					13.0	40	10	25
18-1619 (maroon)	8.8		3.9		2.3				40	10	66
18-3027 (purple orchid)	8.9					0.8		6.7	40	10	63
18-5105 (sedona sage)		19.0	2.9		4.2				40	10	48

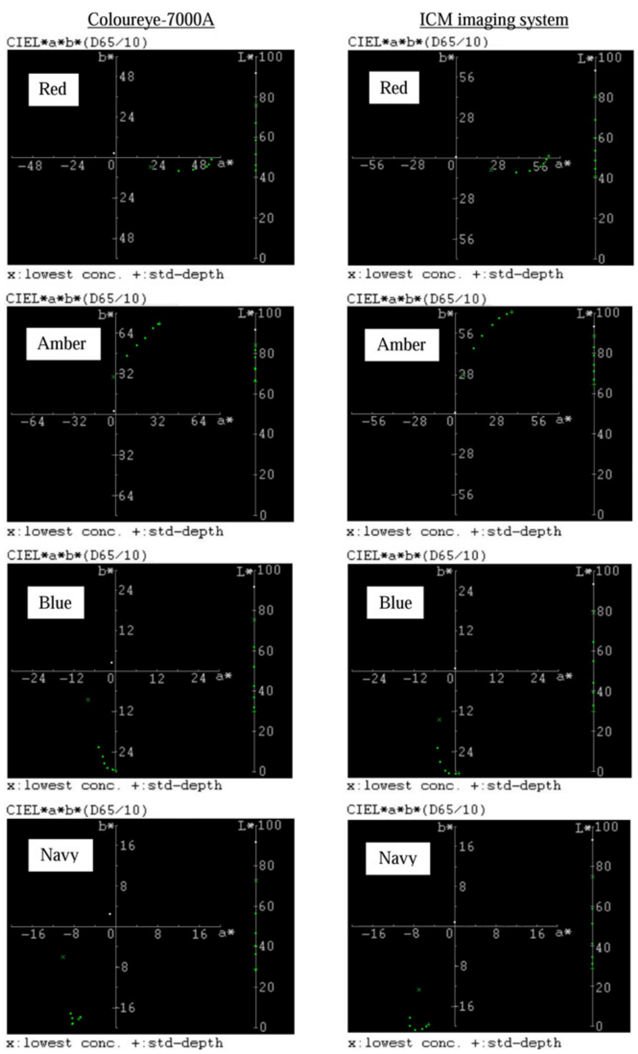

Figure 2. CIE L*a*b* distributions of the set1 calibration database of the two devices.

needed colorants and their concentrations. These were corrected to one decimal place so as to make the dye solution usage as accurate as possible under the constraint of manual dyeing pipettes. As the main purpose of this section is to test if the color difference existing between each 1st dyed and 2nd dyed yarn hanks based on the same 30 recipes can be objectively detected by the two devices, there were two measurements made for each batch, producing the 1st and 2nd results. These were then averaged to give a final color difference ΔE to eliminate any possible manual dyeing unevenness in different yarn hank sections affecting the comparisons (see Table VI).

For both the spectrophotometer and multispectral imaging system results, the final color difference ΔE ranged from 0.23 to 0.87 and from 0.23 to 0.82, respectively, which were all below visual perceptibility, i.e., $\Delta E = 1.0$, showing that manual dyeing accuracy was satisfactory. From the statistical values of the mean ΔE and the standard deviation of ΔE, the two devices gave a similar performance, with only a small color difference mean, 0.56, or 0.57 CMC(2:1) units, and barely negligible data dispersion of the same 0.15 CMC(2:1) units. This means that, though the measurement principles and the mechanical geometries of the two devices are different, which may not give the same results for the color lightness, chroma, and hue for a yarn specimen, keeping measurement parameters constant using the same device, the actual color difference between each pair can then be detected, being compatibly correlated. Figure 3 shows the coefficient of determination r^2 between the two devices' measured color differences for the 30-pair standard and batch yarn hank specimens, and it reveals their data correlation. It was computed that $r^2 = 0.7966$, and the points were aligned along the trend line without any obvious outliers, and thus it can be proved that the two result sets are consistent, with good agreement.

CONCLUSION

The spectrophotometer plays an important role in the current practice of textile coloration as it is nearly the sole instrument which can give the color measurement and

Table VI. Color difference results of the fore-prediction matching comparisons.

Standard versus batch reflectance D65/10° CMC(2:1)	Coloureye-7000A 1st	2nd	ΔE	Mean ΔE	Std dev. ΔE	ICM imaging system 1st	2nd	ΔE	Mean ΔE	Std dev. ΔE
0.1red_0.1amber_0.1blue	0.56	0.39	0.48	0.56	0.15	0.56	0.65	0.61	0.57	0.15
0.1red_0.1amber_0.1navy	0.46	0.55	0.51			0.55	0.59	0.57		
0.1red_0.1amber_0.5blue	0.75	0.85	0.80			0.85	0.79	0.82		
0.1red_0.1amber_0.5navy	0.38	0.46	0.42			0.43	0.39	0.41		
0.1red_0.5amber_0.1blue	0.82	0.92	0.87			0.82	0.82	0.82		
0.1red_0.5amber_0.1navy	0.55	0.52	0.54			0.39	0.55	0.47		
0.5red_0.1amber_0.1blue	0.41	0.45	0.43			0.42	0.40	0.41		
0.5red_0.1amber_0.1navy	0.41	0.39	0.40			0.51	0.55	0.53		
0.5red_0.5amber_1.0blue	0.54	0.45	0.50			0.36	0.46	0.41		
0.5red_0.5amber_1.0navy	0.57	0.56	0.57			0.65	0.61	0.63		
0.5red_1.0amber_0.5blue	0.31	0.36	0.34			0.33	0.29	0.31		
0.5red_1.0amber_0.5navy	0.56	0.57	0.57			0.57	0.58	0.58		
0.5red_1.0amber_3.0blue	0.67	0.54	0.61			0.52	0.58	0.55		
0.5red_3.0amber_1.0navy	0.5	0.42	0.48			0.40	0.57	0.49		
1.0red_0.5amber_0.5blue	0.19	0.26	0.23			0.18	0.27	0.23		
1.0red_0.5amber_0.5navy	0.63	0.59	0.61			0.48	0.53	0.51		
1.0red_0.5amber_3.0navy	0.61	0.67	0.64			0.65	0.65	0.65		
1.0red_3.0amber_0.5blue	0.60	0.62	0.61			0.59	0.61	0.60		
3.0red_0.5amber_1.0navy	0.7	0.67	0.69			0.82	0.71	0.77		
3.0red_1.0amber_0.5blue	0.52	0.66	0.59			0.65	0.51	0.58		
14-1038 (new wheat)	0.69	0.71	0.70			0.72	0.58	0.65		
15-1523 (shrimp)	0.68	0.62	0.65			0.79	0.71	0.75		
15-1611 (bridal rose)	0.44	0.37	0.41			0.56	0.46	0.51		
16-3931 (sweet lavender)	0.64	0.70	0.67			0.70	0.82	0.76		
17-3917 (stonewash)	0.63	0.65	0.64			0.76	0.70	0.73		
18-0629 (lizard)	0.60	0.78	0.69			0.70	0.67	0.69		
18-0933 (rubber)	0.81	0.59	0.70			0.61	0.61	0.61		
18-1619 (maroon)	0.43	0.44	0.44			0.39	0.38	0.39		
18-3027 (purple orchid)	0.77	0.85	0.81			0.66	0.73	0.70		
18-5105 (sedona sage)	0.41	0.35	0.38			0.36	0.31	0.34		

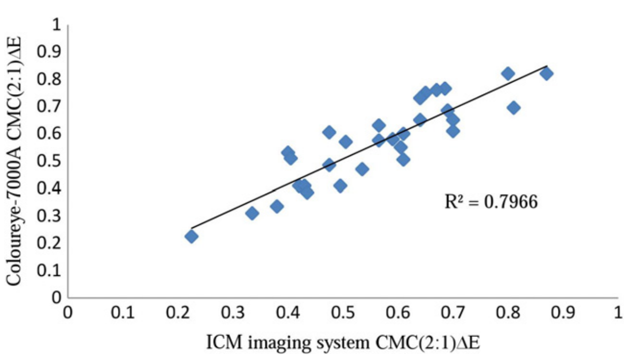

Figure 3. Coefficient of determination r^2 between Coloureye-7000A and ICM results.

color reproduction function through a calibration database establishment and built-in recipe prediction software. It performs conveniently for textile fabric but not yarn, as it is necessary to first wind the yarn specimen onto the yarn card uniformly, which increases the handling time and cost as well as measurement inaccuracy due to the neighboring color influence. As demonstrated in this paper, a multispectral imaging system can perform similarly as the current device, but it requires only a few yarn sections twisted and mounted onto the yarn holder for yarn color measurement, obtaining both the spectral and spatial information for carrying out color reproduction procedures step by step. Therefore, it can effectively enhance the specimen handling efficiency and the color measurement, and thus reproduction accuracy, as it can extract the yarn color from the captured image, so it makes the database establishment and recipe prediction with higher fidelity, contributing to an improvement in yarn color reproduction and communication.

REFERENCES

1 T. Valia, "Colour matching and assessment by visual methods," Colourage **34**, 45–48 (1987).

2 B. Rigg, "Factors affecting instrumental measurement and visual assessment of colour differences," J. Soc. Dyers & Colourists **97**, 504–507 (1981).

3 E. Coates, B. Rigg, and J. R. Provost, "Measurement and assessment of colour differences for industrial use. 4. Accuracy of visual assessments," J. Soc. Dyers & Colourists **88**, 363–366 (1972).

4 R. Mcdonald, "A review of the relationship between visual and instrumental assessment of colour different. 1," J. Oil & Colour Chemists Ass. **65**, 43–53 (1982).

5 R. Mcdonald, "A review of the relationship between visual and instrumental assessment of colour different. 2," J. Oil & Colour Chemists Ass. **65**, 93–106 (1982).

6 S. Commanda, "Application of colour measurement technology to textile dyeing," Amer. Chemical Soc. 37–40 (1972).

7 R. Schaich, "Possibilities and limitations for the use of instruments for colour measurement in the textile-industry," Textilveregłung **15**, 23–29 (1980).

8 R. Pan, W. Gao, J. Liu, and H. Wang, "Automatic detection of the layout of colour yarns for yarn-dyed fabric via a FCM algorithm," Text. Res. J. **80**, 1222–1231 (2010).

9 W. Ma and B. Manjunath, "EdgeFlow: A technique for boundary detection and image segmentation," IEEE Trans. Image Process. **9**, 1375–1388 (2000).

10 P. Felzenszwalb and D. Huttenlocher, "Efficient graph-based image segmentation," Int. J. Comput. Vis. **59**, 167–181 (2004).

11 H. Cheng, X. Jiang, and J. Wang, "Colour image segmentation based on homogram thresholding and region merging," Pattern Recognit. **35**, 373–393 (2002).

12 Y. Chang and X. Li, "Adaptive image region-growing," IEEE Trans. Image Process. **3**, 868–872 (1994).

13 P. Kubelka, "Ein Beitrag zur Optik der Farbanstriche," Z. Tech. Phys. **12**, 593 (1931).

14 P. Kubelka, "New contributions to the optics of intensely light-scattering materials part I," J. Opt. Soc. Am. **38**, 448 (1947).

15 A. K. Georg, "Theory of Kubelka and Munk," *Industrial Color Physics*, edited by T. R. William (Springer, New York, USA, 2010), pp. 326–337.

16 L. Luo, S. J. Shao, H. L. Shen, and J. H. Xin, "An unsupervised method for dominant colour region segmentation in yarn-dyed fabrics," Col. Technol. **129**, 389–397 (2013).

17 L. Luo, S. J. Shao, H. L. Shen, and J. H. Xin, "An efficient method for solid-colour and multicolour region segmentation in real yarn-dyed fabric images," Col. Technol. **131**, 120–130 (2014).

18 L. Luo, S. J. Shao, H. L. Shen, and J. H. Xin, "A novel method for weft and warp yarn segmentation in multicolour yarn-dyed fabric images," Col. Technol. **131**, 165–171 (2015).

19 J. H. Xin, S. J. Shao, and H. L. Shen, US Patent No. US 2013/0293702 A1. Washington, DC: US Patent and Trademark Office (2013).