doi: 10.1111/j.1478-4408.2008.00172.x

Coloration Technology

Society of Dyers and Colourists

Colour management of a low-cost four-colour ink-jet printing system on textiles

Yuqian Zhang, Vien Cheung, Stephen Westland* and Katherine J Beverley

School of Design, University of Leeds, Leeds & LS2 9JT, UK
Email: S.Westland@leeds.ac.uk

Received: 24 July 2008; Accepted: 13 November 2008

A low-cost four-colour (RBYK) dye-based ink-jet printing system for textiles was introduced in this study, in which red and blue inks were employed instead of the magenta and cyan inks used in half-tone printing. The basis of a colour-management system for this device was developed by determining the mapping between XYZ tristimulus values of output colours and the digital RBYK values using polynomial transforms. A second-order equation was found to give the best performance with an average characterisation error of under 7 CIELAB units.

Introduction

It has been suggested that direct digital printing of textiles will one day take over from screen-printing [1,2]. Digital colour printing of textiles using ink-jet (or similar) technology is established in production environments and has been particularly effective for short-run prints for the so-called mass-customisation market [3]. However, the printing machines are large and relatively expensive [4]. A project at the University of Leeds has been concerned with the use of inexpensive consumer-level ink-jet technology for textile printing; such a low-cost system could be used in a small design studio or in a craft environment. This paper is concerned with the colour management of such a low-cost system for textile printing and explores whether the colour-management techniques that have been used extensively to characterise paper-printing systems (or other imaging devices) can be employed effectively for small-scale textile printing.

Development of electronic technology and the proliferation of low-cost colour imaging devices allows more and more users to transfer images between devices (for example, from a computer screen to a printer). Colour management enables this communication between devices minimal loss of colour fidelity. This requires that devices be calibrated and characterised and a device profile constructed for each device [5–7]; the profile enables the mapping between the device-independent colorimetric tristimulus data representing the output (CIE XYZ) and the device-dependent coordinates (typically RGB or CMYK). Consumer devices are supplied with default profiles for the typically used colorants and these, in conjunction with the computer's operating system, allow for basic colour management. However, more accurate colour management requires that a specific profile be developed that takes into account, amongst other things, the user settings on the device. Methods for defining the mapping include: look-up tables (LUTs), physical models, artificial neural networks (ANNs) and polynomial transforms. In the following sections, the basic concepts behind these mathematical approaches to printer characterisation are briefly described.

The LUT method requires that a large number of coloured samples are printed and their CIE colorimetric values measured. A multidimensional interpolation technique is then used to create a process for determining the conversion from desired colour outputs (XYZ) to the digital signal (RGB). The LUT is sometimes prepared by a printing house based on the results of their own products. One of the disadvantages of this method is the work required to print and measure the large number of samples [8–10]. It has been suggested that, for the characterisation of printers, the number of samples required is at least 200 [11].

In contrast with the LUT method, a relatively small amount of example data may be required to determine the model parameters of a physical model. The Neugebauer equations are an example of a model specifically designed for half-tone printing systems; it predicts reflectance by summing the reflectance of colour components weighted by their areas [12–14]. A method to determine the areas of the components was introduced by Demichel [14]. Although the effect of light scattering in the substrate is not considered in the Neugebauer equations, there are more advanced models that do take into account factors such as light scattering and dot gain [11]. The Kubelka–Munk model is also widely used to predict the colour of printed inks by characterising each ink or colorant using absorption and scattering coefficients [15–17]. One of the problems of using physical models is that they need to be inverted to find digital print values that will result in a desired colour; often achieved by iteration [18]. The number of samples required for an effective numerical model is certainly fewer that that required for LUTs and was found to be less than 100 even for a six-ink printer [19].

ANNs were inspired by studies of human neural processing. In colour management systems, an ANN can find the mapping between vectors of input colour signals and the output colour stimulus or vice versa [20,21]. The multilayer perceptron (MLP) is a type of feedforward ANN that is utilised extensively in the colour management system in conjunction with the back-propagation learning algorithm [9,15,22]. However, some faster ANN algorithms, such as conjugate gradient, quasi-Newton and Levenberg–Marquardt (LM), which use standard numerical optimisation techniques, have been evaluated for print quality control [8]. The algorithm of LM is a kind of approximate Newton's method, which uses the second-order derivatives of the cost function to obtain better convergence behaviour [8,23]. The number of samples required for an effective neural–network characterisation model is relatively high and the extra work required may not justify their use over conventional polynomial methods [24].

Polynomial transforms are widely used for the characterisation of cameras and monitors and can also be effective in printer characterisation [11,20,25]. With this method, as in the case of the ANN, the system is assumed to be a black box and coefficients are derived from a set of training samples [21]. Yule first suggested simple first-order equations to provide a linear transform of colorimetric density values to colour outputs [11]. However, the use of a linear transform is based on assumptions of additivity and proportionality; thus, higher-order polynomials were recommended by Clapper (and later by Yule) in order to improve the accuracy of the prediction [11]. As all but linear polynomials are not invertible, iteration is required to perform the inverse process. Polynomials can be implemented as matrix algebra and the coefficient matrix can be easily determined by a programming language such as MATLAB [26,27]. For example, the linear transform between the tristimulus XYZ values and the CMY output of the CMY three-colour printer can be simply expressed thus:

$$\mathbf{X} = \mathbf{AT} \tag{1}$$

in which, $\mathbf{X}$ is the $3 \times n$ matrix of XYZ values, $\mathbf{T}$ is the $3 \times n$ matrix of CMY values and $\mathbf{A}$ is the 3×3 matrix containing coefficients in polynomials. Often the CMY values are inverted (by subtracting their values, normalised in the range 0–1, from 1) as increasing the CMY values generally results in decreasing XYZ values [14,15]. The value of n in Eqn 1 represents the number of measured samples used in the training set. The coefficient matrix $\mathbf{c}$ can be solved by multiplying both sides of Eqn 1 by the inverse of the matrix $\mathbf{T}$. If $n = 3$, then $\mathbf{T}$ is the square matrix, the inverse of which can be denoted as $\mathbf{T}^{-1}$. Thus

$$\mathbf{A} = \mathbf{XT}^{-1} \tag{2}$$

However, if $\mathbf{T}$ is a non-square matrix, numerical methods must be applied to compute the pseudo-inverse matrix which is denoted by $\mathbf{T}^{+}$ [15]. Thus

$$\mathbf{A} = \mathbf{XT}^{+} \tag{3}$$

Once the values of the coefficient matrix $\mathbf{A}$ are obtained, the XYZ values of printed colours can be easily predicted from values of printer CMY outputs using the above equations and vice versa. Higher-order transforms can be treated in the same way but require increasing numbers of coefficients. Note, however, that if higher-order polynomials are used, then some form of iteration may be required as in the case of some of the other models. This technology has been used in the present work.

This study is concerned with a dye-based ink-jet printing system on textiles that uses conventional direct dyes on cotton. Several commercial so-called digital printing systems exist that allow textile printing [28–32]. However, such systems are large and expensive. A smaller low-cost system may be useful for application in small commercial design houses or for crafts purposes. The system in this study is based on a low-cost HP5940 ink-jet system. In an earlier part of the study not reported here, three direct dyes were selected based on several criteria including wash fastness and light fastness. These dyes were Solophenyl Red 4GE, Blue 4GL and Yellow GLE that together form a subtractive primary system. A black was also created using a mixture of the three primaries. This paper is concerned with the colour management of this low-cost four-colour printing system. Polynomial transforms have been used to define the mapping between the digital RBYK values (defined in the image-application software) and the CIE XYZ values of output colours.

Experimental

Materials

Cotton

Scoured and bleached woven cotton (191.5 g/m^2), provided by Whaleys Bradford Ltd, was used in the experiment.

Dyes

Three commercial direct dyes, Solophenyl Red 4GE (CI Direct Red 277), Solophenyl Blue 4GL (CI Direct Blue 78) and Solophenyl Yellow GLE (CI Direct Yellow 177) were used, as supplied by Huntsman Textile Effects.

Fixing agent

The polymeric cationic fixing agent, Matexil FC-ER, supplied by Uniqema Ltd, was employed to pretreat the cotton to improve the dye fastness.

Other chemicals

Several chemicals were incorporated in the printing ink formulations in order to enhance the performances of the inks. These include the cosolvent isopropyl alcohol; the humectants ethylene glycol and diethylene glycol; the chelating agent ethylene diamine tetraacetic acid, sodium salt; the surfactant Dynol 604; and ammonia buffer solution. Dynol 604 was supplied by Air Product and all of the others were supplied by Sigma-Aldrich Co. Ltd.

Procedure

Pretreatment

The fixing agent, Matexil FC-ER, was printed on to the cotton using the ink-jet printer via the black-ink cartridge (see printing section for further details). The formulation of fixing ink is shown in Table 1.

Ink preparation

Three inks, red, blue and yellow, were prepared and used to fill the chambers in the HP three-colour CMY ink cartridge. The red, blue and yellow inks were put into the magenta, cyan and yellow chambers, respectively. The

Table 1 Formulation of fixing ink[a]

Matexil FC-ER (wt%)	EG (wt%)	DEG (wt%)	IPA (wt%)	Dynol 604	Distilled water (wt%)
15	3	3	5	0.05	73.95

a DEG, diethylene glycol; EG, glycol; IPA, isopropyl alcohol

main ingredients are shown in Table 2. The pH value of each ink was adjusted to *ca.* 8 using ammonia buffer solution. A black ink was formulated by mixing the red, blue and yellow inks according to the ratio of 6:7:7 (R:B:Y) and used to fill the separate black ink cartridge.

Table 2 Formulations of red, blue and yellow inks[a]

Inks	Dye (g)	EG (g)	DEG (g)	IPA (g)	EDTA (g)	Dynol 604 (g)	Distilled water (g)
CI Direct Red 277	4.00	6.00	3.00	2.00	0.10	0.05	84.85
CI Direct Blue 78	4.00	6.00	3.00	2.00	0.10	0.05	84.85
CI Direct Yellow 177	1.20	6.00	3.00	2.00	0.10	0.00	87.70

a DEG, diethylene glycol; EDTA, ethylene-diaminetetraacetate; EG, glycol; IPA, isopropyl alcohol

Printing

Printing was carried out using a HP Deskjet 5940 printer, a thermal drop-on-demand ink-jet printer. The cotton fabric was cut to 10 × 15 cm and mounted onto an A4 transparency film to guide the fabric through the printer. The colourless fixer was first used in the black-ink cartridge and applied to the cotton. Practically, this involved creating a digital image consisting of a black rectangle (of equal dimensions to the colour chart used later) and sending this to the printer with the appropriately filled black-ink cartridge in place. Next, a black-ink cartridge filled with the black ink was put in place and the CMY cartridge filled with the inks was attached for four-colour printing. An IT8.7/2-1993 chart containing 264 colour patches and 12 repeated greyscale colours and a ColorChecker DC chart containing 84 colour patches were both printed via Photoshop CS3 software. The digital files containing the colour charts were obtained by scanning hard copies of the charts in the laboratory. However, the details of this image acquisition process are not relevant because, in this study, we are not attempting to develop a closed-loop colour-management system. A closed-loop system may be valuable but would require characterisation of the scanner, the display device and the printer, and the closed-loop performance would be affected by the characterisation performance of all three devices. In this study we wish to focus only on the characterisation of the printer.

The automatic ‘colour management’ setting was disabled during the whole printing process. The colour distributions of patches in both IT8.7/2-1993 chart and ColorChecker DC chart are shown in the CIE a^*b^* diagram (Figure 1).

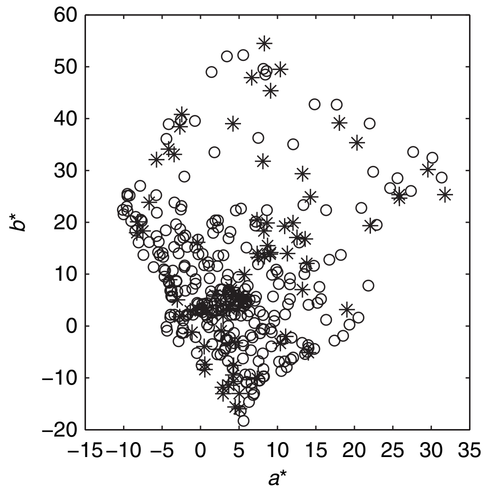

Figure 1 Colour distributions of patches for the IT8.7/2-1993 chart (circles) and in ColorChecker DC chart (stars) as measured when printed onto cotton

Steaming

Once printed, all samples were saturated and steamed in a Werner Mathis AG steamer at 100 °C for 15 min. Steaming can provide the moisture and heating so as to make Matexil FC-ER have an effect on dye molecules and improve the dye fixation onto cotton fabric.

Colour measurement

The XYZ tristimulus values of the patches on the prints of the two charts were measured using a Minolta CM-2600d portable spectrophotometer and calculated for illuminant D65 and the 10° standard observer. The digital CMYK values of each patch in each chart were obtained from Photoshop CS3, although recall that the C and M values are controlling the amounts of blue and red ink, respectively.

Reproducibility

The ColorChecker DC chart was printed five times and a representative 26 patches were measured on each print so that the reproducibility of the printing system could be assessed.

Characterisation

In this work, a characterisation method is developed to predict the XYZ values of the printed output from the digital CMYK values. This allows a convenient way to test the characterisation performance because the predicted XYZ values can easily be compared with the actual XYZ values of the prints and performance can be assessed using conventional metrics such as CIELAB $\triangle E$. However, we note that in a closed-loop system the inverse relationship is required. In a typical closed-loop system we would include a scanner, a display unit and a printer and compare the XYZ values of the physical samples with those of the printed representation of those physical samples (following scanning, processing and printing). A closed-loop system would require a method to predict the digital print values (CMYK) that are required to generate target XYZ values on the prints. However, as discussed earlier, a closed-loop colour-management system is not being developed in this study.

The 286 patches in the IT8.7/2-1993 chart were used as the training sets to determine the coefficients in the polynomial transforms. The first-order transform from CMYK values to XYZ tristimulus values is:

$$\begin{aligned} X &= a_1C + a_2M + a_3Y + a_4K + a_5 \\ Y &= a_6C + a_7M + a_8Y + a_9K + a_{10} \\ Z &= a_{11}C + a_{12}M + a_{13}Y + a_{14}K + a_{15} \end{aligned} \tag{4}$$

where XYZ are the tristimulus values, CMYK are the digital values (normalised in the range 0–1 and subtracted from 1) and a_i, i ε{1…15}, are the coefficients of the affine transform. These simultaneous equations can be represented in matrix form, thus:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} a_1 & a_2 & a_3 & a_4 & a_5 \\ a_6 & a_7 & a_8 & a_9 & a_{10} \\ a_{11} & a_{12} & a_{13} & a_{14} & a_{15} \end{bmatrix} \begin{bmatrix} C \\ M \\ Y \\ K \\ 1 \end{bmatrix} \tag{5}$$

which can be expressed as:

$$\mathbf{X} = \mathbf{AT} \tag{6}$$

For the 286 patches in the IT8.7/2-1993 chart, **X** is the 3×286 matrix of XYZ tristimulus values, **A** is the 3×5 matrix of coefficients and **T** is the 5×286 matrix of CMYK digital values. As **T** is a non-square matrix, the pseudo-inverse of **T**, denoted by $\mathbf{T}^+$, is computed using numerical methods. The matrix **A** can be obtained directly from Eqn 7:

$$\mathbf{A} = \mathbf{T}^+\mathbf{X} \tag{7}$$

The pseudo-inverse of a non-square matrix can be computed in MATLAB using the function *pinv*. Essentially, this function computes the coefficients of Eqn 4 such that, if XYZ values are computed from CMYK values using Eqn 4, then the sum of the squares of the errors between actual and predicted XYZ values will be minimised.

A non-linear second-order transform from CMYK to XYZ values was also tested which results in an equation similar to Eqn 6 but where **A** is a 3×15 matrix and **T** is a 15×286 matrix containing the terms C, M, Y, K, C^2, M^2, Y^2, K^2, CM, MY, YK, CY, MK, CK, 1.

Full third-order and fourth-order transforms were also tested. Finally, a linear transform of CMYK was also tested.

The training performance of each of the five transforms was evaluated by computing the root-mean-square (RMS) errors in XYZ values and also the median CIELAB colour differences for D65 and the 1964 standard observer for the training data set (the IT8.7/2-1993 chart). However, as the order of the transform increases, we would expect to see the error on the training set reduce; ultimately, we could construct a transform with a sufficient number of coefficients that the training data would be fitted with zero error. Therefore, the transforms were also tested by computing the errors for an independent test set (containing samples that were not used to derive the coefficients). In this study, 84 patches from the ColorChecker DC chart were used as the test set.

Results and Discussion

The reproducibility of the printing system was assessed by printing the ColorChecker DC chart five times each on a separate day. A set of 26 patches were selected and measured and, for each patch, the mean CIELAB colour difference was calculated from the average patch colour over the 5 days. The largest mean colour difference was 2.12 CIELAB units and the smallest was 0.29. Averaged over all patches, the mean colour difference for reproducibility was 1.19 CIELAB units.

For the printer characterisation, errors between the predicted and measured XYZ values are shown in Table 3 and illustrated in Figures 2–6, for both training

Table 3 RMS errors for XYZ

	Training set			Test set		
Transform	X error	Y error	Z error	X error	Y error	Z error
Linear	3.14	3.61	5.10	5.84	6.02	6.54
First order	2.15	2.11	3.58	6.11	6.27	6.25
Second order	1.37	1.13	2.00	5.60	6.00	5.28
Third order	0.82	0.77	1.26	5.69	6.05	5.12
Fourth order	1.37	1.32	1.85	5.47	5.97	5.28

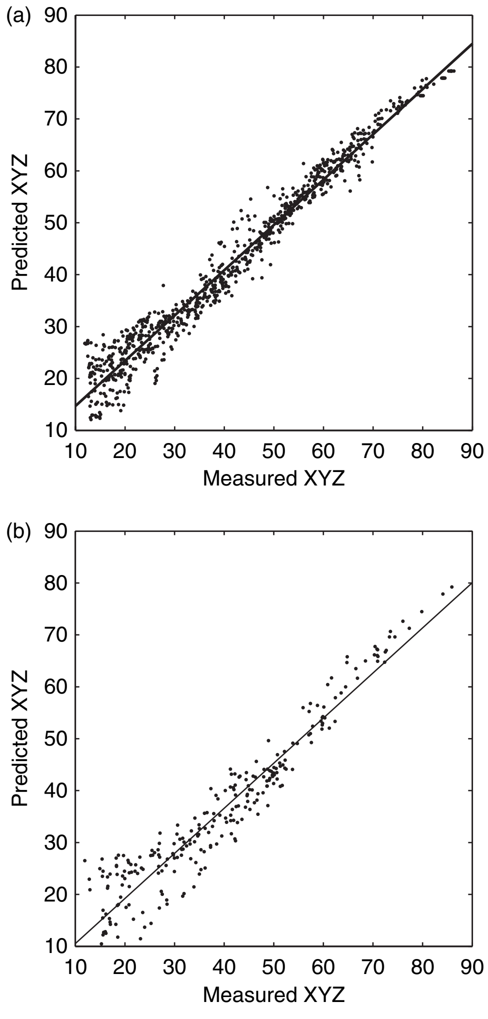

Figure 2 Predicted *vs* measured tristimulus XYZ values of the training (a; R^2 = 0.9662) and test (b; R^2 = 0.9082) sets using the linear transform

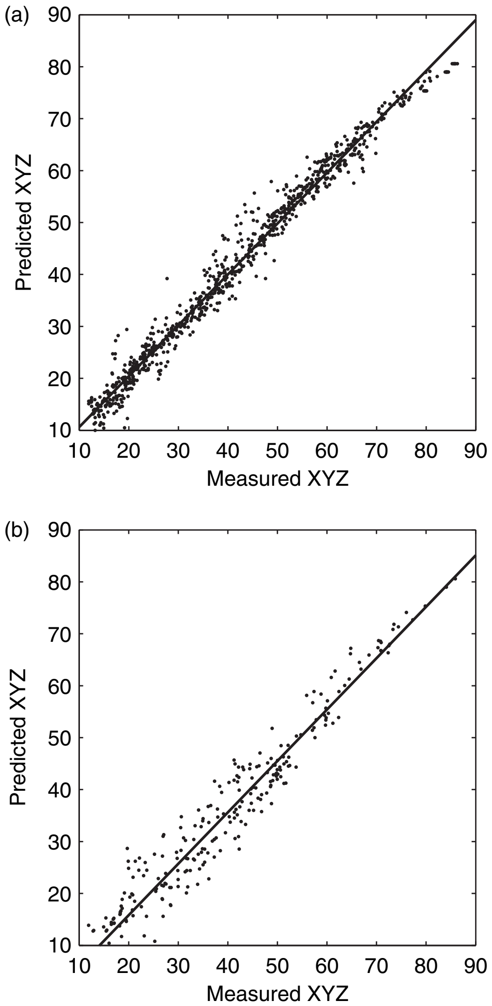

Figure 3 Predicted *vs* measured tristimulus XYZ values of the training (a; R^2 = 0.9801) and test (b; R^2 = 0.9346) sets using first-order (affine) transform

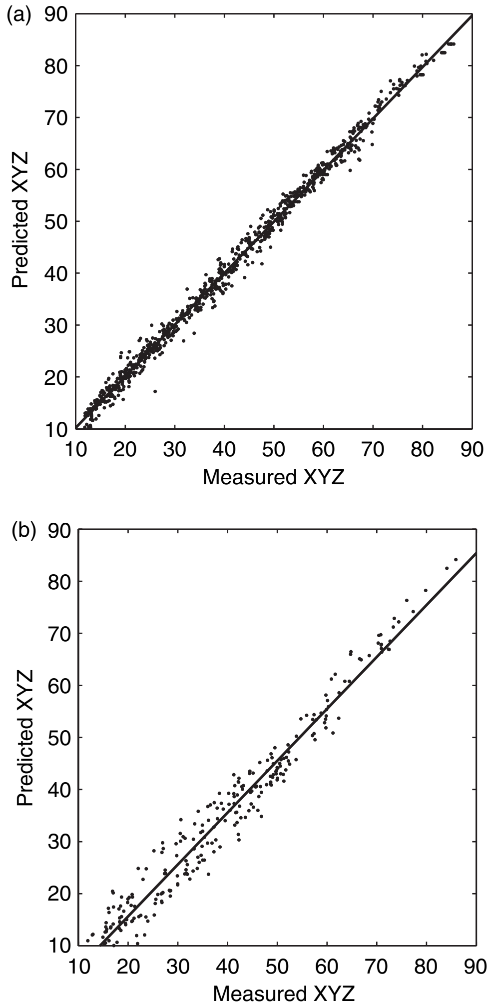

Figure 4 Predicted *vs* measured tristimulus XYZ values of the training (a; R^2 = 0.9935) and test (b; R^2 = 0.9584) sets using second-order transform

and test data sets. The measured XYZ values are the actual measurements using reflectance spectrophotometry of the printed cotton samples that result from the digital CMYK values; the predicted XYZ values are the values of XYZ predicted by the polynomial transforms to result on the cotton prints from the digital CMYK values.

It can be seen from Table 3 that the errors for both training and test sets gradually decrease with the complexity of the model and the second-, third- and fourth-order transforms perform better than the linear and first-order transforms.

Average colour differences ΔE^*_{ab} for the training and the test sets are given in Table 4. It demonstrates that errors of the training set gradually decrease with the order of the transform. However, the minimum testing error occurs for the second-order polynomial transform. This suggests that the third-order transforms over fit the training data and increase the testing error [24,33].

By comparison, a similar study conducted with a paper printer (Kodak Color Proofer 9000A using dye-sublimation technology) showed that a third-order polynomial model gave mean CIELAB errors of *ca*. 4 units [34]. Given that even paper-based printing characterisation leads to errors of *ca*. 4 CIELAB units, the performance of 6–7 CIELAB units obtained in this study (where a much more complex printing system on cotton is employed) can be put into context.

Conclusions

A low-cost RBYK dye-based ink-jet printing system on textiles was introduced in this study. The reproducibility of the printing system was shown to be *ca*. 1 CIELAB unit. Various linear and polynomial equations were used to predict CIE XYZ values from digital print values. The best performance was obtained using a second-order polynomial equation and the mean error on an independent test set was just under 7 CIELAB units.

Given that the system studied in this work is a textile-printing system, the characterisation performance may be considered satisfactory. However, other characterisation methods such as LUTs may be investigated and may yield superior performance. It should be noted that, in this study, a method was developed to predict CIE XYZ values from digital print values; this was carried out so as to allow a convenient method to assess the performance of the system. However, in practical use (for example, a closed-loop colour-management system), a user would more likely wish to predict the digital print values required to print a desired colorimetric target. Therefore, an iterative system would have to be employed with the

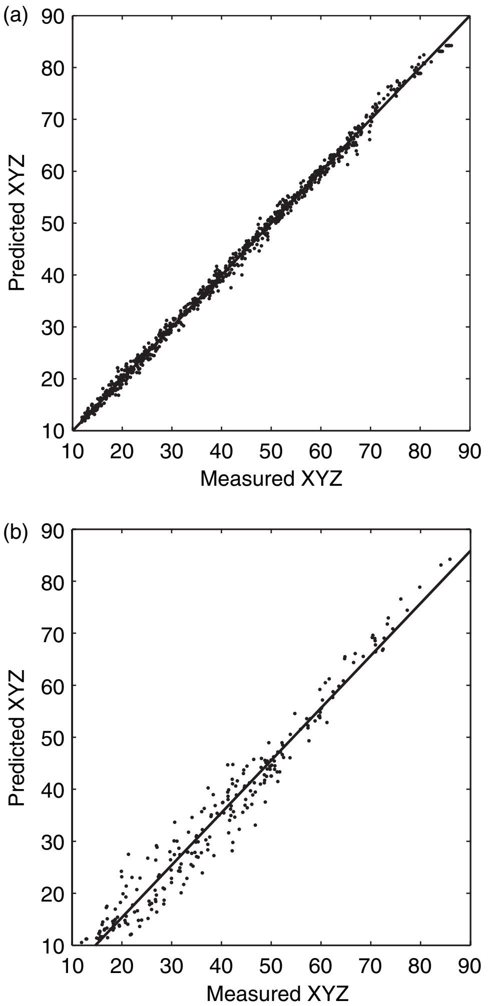

Figure 5 Predicted *vs* measured tristimulus XYZ values of the training (a; R^2 = 0.9947) and test (b; R^2 = 0.9622) sets using third-order transform

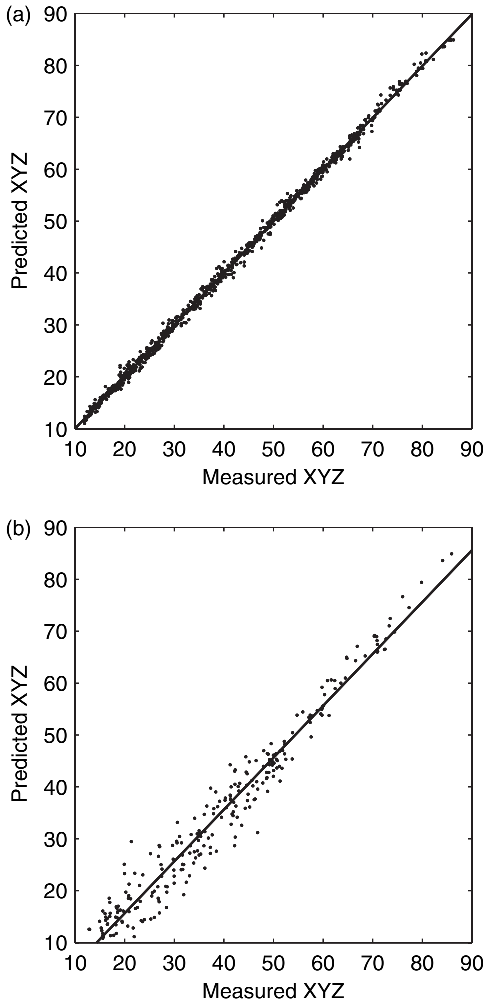

Figure 6 Predicted *vs* measured tristimulus XYZ values of the training (a; R^2 = 0.9981) and test (b; R^2 = 0.9586) sets using fourth-order transform

Table 4 ΔE^*_{ab} of training and test set using different transforms

	ΔE^*_{ab}	
Transform	Training set	Test set
Linear	5.69	9.00
First order	4.91	9.60
Second order	2.40	6.91
Third order	1.47	7.10
Fourth order	1.18	7.52

RBYK → XYZ model or it would be necessary to develop the inverse model XYZ → RBYK.

We note that the colours produced from the printed cotton were a little desaturated compared with the original hard copies of the colour charts. If we were developing a closed-loop colour-management system, this would be a concern. It may be possible to obtain stronger, more saturated, colours by using different inks (for example, a good pigment-based black), fixing agents and/or printer settings. Nevertheless, the work carried out demonstrates the principle that techniques that have been developed for characterising printing systems for paper can be usefully applied to low-cost systems that print on textiles.

References

1. T L Dawson and C J Hawkyard, *Rev. Prog. Color.*, **30** (2000) 7.
2. T L Dawson and H Ellis, *J.S.D.C.*, **110** (1994) 331.
3. T L Dawson, *J.S.D.C.*, **116** (2000) 52.
4. T L Dawson, *Color. Technol.*, **117** (2001) 185.
5. M D Fairchild, *Color Appearance Models* (Chichester: Wiley, 2005).
6. J R Campbell, *Total colour management in textiles*, Ed J H Xin (Cambridge: Woodhead Publishing, 2006).
7. R W G Hunt, *The Reproduction of Colour* (Chichester: John Wiley & Sons, 2004) 160–190.
8. E Köse, T Şahinbaşkan and İ Güler, *Expert Systems with Applications*, **36** (2009) 745–754.
9. J S Ker, C C Hsu, Y H Kuo and B D Liu, *Fuzzy Sets and Systems*, **91** (1997) 53.
10. S Usui, Y Arai and S Nakauchi, *Inf Sci.*, **123** (2000) 115.
11. T Johnson, *Displays*, **16** (1996) 193.
12. M Xia, E Saber, G Sharama and A M Tekalp, *IEEE. Trans. Image Process.*, **8** (1999) 700.
13. D R Wyble and R S Berns, *Color Res. Appl.*, **25** (2000) 4.
14. G Sharma and H J Trussell, *IEEE Trans. Image Process.*, **6** (1997) 901.
15. S Westland and C Ripamonti, *Computational colour science using MATLAB* (Chichester: Wiley, 2004).
16. P Emmel and R D Hersch, *J. Imaging Sci. Technol.*, **44** (2000) 351.

17. T Ogasahara, *J. Imaging Sci. Technol.*, **48** (2004) 130.
18. M Mahy and P Delabastita, *Color Res. Appl.*, **21** (1996) 404.
19. L A Taplin and R S Berns, *Proc. IS&T/SID 9th Color Imaging Conf.*, Scottsdale, USA (2001) 209.
20. L W MacDonald, *Displays*, **16** (1996) 203.
21. C-H Lee, E-J Lee, S-C Ahn and Y-Ho Ha, *J. Imaging Sci. Technol.*, **45** (2001) 427.
22. S Usui, Y Arai and S Nakauchi, *Inf. Sci.*, **123** (2000) 115.
23. D Marquard, *J. Soc. Ind. Appl. Math.*, **11** (1963) 431.
24. V Cheung, S Westland, D Connah and C Ripamonti, *Color. Technol.*, **120** (2004) 19.
25. T Johnson, *Displays*, **16** (1996) 183.
26. J H Mathews and K D Fink, *Numerical Methods Using MATLAB* (Upper Saddle River: Pearson Prentice Hall, 2004).
27. R Pratap, *Getting started with MATLAB 7: a quick introduction for scientists and engineers* (Oxford: Oxford University Press, 2006).
28. B Glover, in *Textile ink jet printing: a review of ink jet printing of textiles, including ITMA 2003*, Eds T L Dawson and B Glover (Bradford: SDC, 2004) 13–29.
29. R Magee, J C McCay and S W Cox, *US2007260352* (2007).
30. U Sayed and S K Khobian, *Colourage*, **50** (2003) 35.
31. H Ujiie, D Wood, B George and M Govindaraj, *Proc. IS&T Int. Conf. Digital Printing Technologies*, New Orleans, USA (2003) 643.
32. W C Tincher, Q-A Hu and X Li, *AATCC Proc. Int. Conf. Exhib.*, Atlanta, USA (1997) 263.
33. G Hong, M R Luo and P A Rhodes, *Color Res. Appl.*, **26** (2001) 76.
34. S Sueepresan, *Evaluation of colour appearance models and daylight illuminant simulators to provide predictable cross-media colour reproduction*, PhD Thesis, University of Derby, UK (2003).