The Characterisation of Colour Printing Devices via Physical, Numerical and LUT Models

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Abstract

The aim of this study was, to derive well-performed four-color printer device characterisation models (DCMs), which were afterwards used to pack up entries of the look up table (LUT) to perform the actual complex colour-image transformations. Based on both non-linear and non-ideal behaviours of primary colorants, two types of printing device characterisation model approaches were proposed in this work. One is a physical type of bicubic-spline interpolation algorithm (referred to as Ext-SA-Bicubic) which is a modified version of sub-additivity algorithm (SAA). The SAA model, originally proposed by Yule, modelled superimposed inks behaviour of converging to a point. Another is a numerical type of the 2^{nd}-order polynomial regression equations, incorporated with singular-value decomposition (SVD) approach (referred to as 2^{nd}-SVD). Each of two printer DC algorithms integrated a grey-component replacement (GCR) approach into a 3^{rd}-order masking type of three-colour printer model to produce four-colour output. Preliminarily, both "with" and "without" a setup state of output linearization (OL), a function provided by a RIP (Raster image processing) software used to both calibrate the printer in question and produce an optimized tone curve for each primary colorant of CMYK, was applied in the printer characterisation process. Moreover, two different forms of "Equivalent Neutral Density" (END) and "Principal Density" (PD) were separately applied in the three-colour model (i.e. 3^{rd}-order masking equations) for both the numerical and the physical types of DC algorithms mentioned above. Hence, in terms of both END and PD, separately applied using both of "Without" and "With" Output Linearization (OL) in input-output relationship, totally, eight printer DCMs were derived. Each model was also carried out both the forward and the reverse transform processes. An Epson Stylus Pro4000 colour printer plus a RIP of EFI XF v2.6.1 was mainly tested in this study and used as the destination device, and incorporated with a well-characterised EIZO-CG210 LCD (used as source device) with ΔE_{94} of 1.05 using PLCC Characterisation model to perform a cross-media colour transform from monitor to printer. Performances of DCMs in question were firstly investigated using training/test data sets. Also a set of forced-choice paired-comparison psychological experiments was conducted. It was used to cross verify the prediction performances of those cross-media LUT models packed up using their corresponding mathematical DCMs in question.

*Overall, the results showed that all the models, with an output-linearization (OL) setup state, gave quite satisfactory prediction performances, but the 2^{nd}-SVD always performed much better than the Ext-SA-Bicubic under every of the same characterisation mechanism . Also all models with OL setup state in the characterisation process were significantly much better than those models using the same algorithms but without OL setup state. However four Ext-SA-Bicubic models (with and without OL) using END/PD approach performed slightly unsatisfactory in shadow areas of tested colour images. It was found that it is because of irregular distribution of training samples, used to model the sub-additivity behaviour, in colorimetric density domain/space; and especially too short distance in neighbourhood (or nearly piling up) of samples which were near shado*w region. *Therefore, it resulted in inaccurately predicted CMYK values for shadow areas of tested colour images, by using the bicubic-spline interpolation approach, and caused the colour shift and poor-smoothness.*

Key words: *CIEDE2000, cross-media colour reproduction, Device characterisation, 2^{nd}-SVD polynomial regression model,ECI2002, IT8.7/3, Tetrahedral interpolation, 3^{rd}-order masking-type model, Gamut mapping algorithm, Sub-additivity equations, Equivalent neutral density, Look-up tables, Principal density, singular-value decomposition, Bicubi-spline interpolation, Gray balance curves.*

Introduction

Practically, mathematically numerical or physical methods are initially implemented to characterise imaging devices of interest via training/test target sets. Sequentially entries of the look up table (LUT) used for each of imaging devices, in the interest of computational efficiency and simplicity, are generated using the correspondingly mathematical model well-derived. These LUTs produced were, then, used to perform the actual colour-image transformations.

Recent years in graphic arts industry, in order to utilize colour effectively, often a colour printer is employed to simulate reproductions of a press that is used to produce high-quality printed matters for clients. However there are many alternative printer devices available to be chosen from different manufactures due to open-systems and cross-media colour reproduction environments.

Therefore, the focus of this study was to derive well-performed colour printer device characterization models, and then a set of well-approximated LUT were packed up accordingly and applied in the process of cross-media colour transform.

Device Characterisation

Mathematically two type of printer characterisation algorithms were proposed in this paper, including a bicubic-spline interpolation and a 2^{nd}-order polynomial regression.

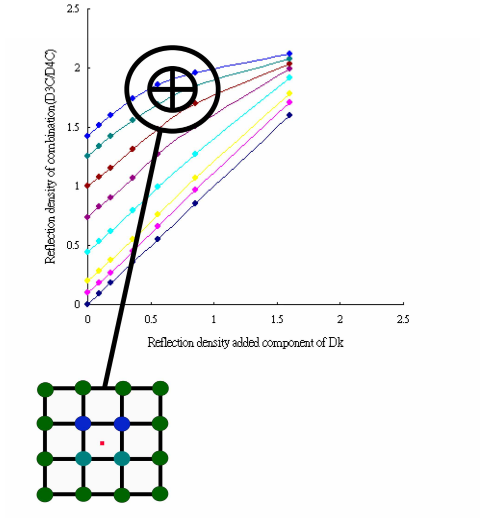


Figure 1. *Sub-additivity behaviour of superimposed inks and 16 training colour points surrounding the closest corresponding colour point in the source image*

Both mathematical device characterisation (DC) algorithms were derived for both processes of the forward and the reverse transform. Each of both printer DC algorithms mentioned above integrated a grey-component replacement (GCR) technique into a 3^{rd}-order masking type[1] of three-colour printer model, to produce four-colour output. The forward process mapped the CMYK data to their device independent values (i.e. CIEXYZ, CIELAB, or CIELCH) while the reverse transformed device independent values into CMYK. An Epson STYLUS Pro 4000 seven-colour Inkjet plus a RIP of EFI XF v2.6.1 was used in this research. But only the four-colour model was tested. The RIP software used also provided the choice of Output-Linearization (OL) Function which could be used to calibrate the printer in question. It was supposed that, with the state of OL setup, the relationship between each primary-colorant's FDA (Fractional Dot Area) and colorimetric principle density produced by the printer considered would be optimized to give the overall good detail/contrast rendition of reproductions. To investigate the effect of output-linearization function, two sets of ECI2002 test target with 1485 colour patches were produced separately using "With" and "Without" setup state of *output-linearization*, when using the RIP in the preliminary characterisation process. The ECI2002 is a superset of the ISO standard IT8.7/3 test target proposed by European Colour Initiative in 2002. The spectral reflectances were then measured using a GretagMacbeth TM Eye-one IO (spectrophotometer) across the visible spectrum (380-730nm) at 10-nanometer intervals. The colorimetric data including CIE XYZ, CIE LAB, and CIE LCH were, then, calculated in terms of CIE illuminant D_{50} and the CIE 1931 standard observers.

Bicubic-Spline Interpolation Algorithm

One of the focus of this study was, in particular, mainly on the physical type of a modified version of sub-additivity (SA) algorithm, originally proposed by Yule (1967) [1]. The modified version of sub-additivity algorithm modelled superimposed inks behaviour of additivity failure as shown in Fig. 1, and applied bicubic-spline interpolation algorithm[2,3] (referred to as Ext-SA-Bicubic later). The bicubic-spline interpolation approach, also illustrated in Fig. 1, estimated the colour at a pixel of interest in the destination image by an average of 16 training colours (or pixels), which are obtained from the sub-additivity behaviour modelling diagram (i.e. Fig. 1), and also surrounding the closest corresponding colour point/pixel in the source images. The sub-additivity behaviour modelling diagram was constructed from a group of 48 nearly neutral colour patched, extracted from the ECI2002 test target, and used to derive the bicubic-spline interpolation model. The CMYK Fractional Dot Areas (FDAs) of these 48 colour patches considered are shown in Table 1.

Table 1. C, M, Y, K fractional dot areas of the 48 colour patches used to derive the bicubic-spline interpolation algorithm.

FDA_C	FDA_m	FDA_y	FDA_k
100	100	0	100, 80, 60, 40, 20, 0
0	100	100	100, 80, 60, 40, 20, 0
85	65	65	100, 80, 60, 40, 20, 0
65	45	45	100, 80, 60, 40, 20, 0
40	27	27	100, 80, 60, 40, 20, 0
20	12	12	100, 80, 60, 40, 20, 0
10	6	6	100, 80, 60, 40, 20, 0
0	0	0	100, 80, 60, 40, 20, 0

In the forward process of bicubic-spline interpolation approach, every resultant 4-color colorimetric density (i.e. $D_{r\text{-}4c}$, $D_{g\text{-}4c}$, or $D_{b\text{-}4c}$) was respectively predicted by adding the black component (i.e. $D_{r\text{-}k}$, $D_{g\text{-}k}$, or $D_{b\text{-}k}$ colorimetric densities) to the 3-color component (i.e. $D_{r\text{-}3c}$, $D_{g\text{-}3c}$, or $D_{b\text{-}3c}$ colorimetric densities), to model the sub-additivity behavior. For example, a two-dimensional interpolation function of $D_{r\text{-}k}$ and $D_{r\text{-}3c}$ was derived to carry out the prediction of $D_{r\text{-}4c}$, via the known tabulated LUT (look-up table) of black and 3-color densities, and the corresponding 4-color densities. The mathematical formula for the bicubic-spline interpolation function is listed as below.

$$P(u,v)=\sum_{i=0}^{3}\sum_{j=0}^{3} a_{ij}u^i v^j$$

The u and v are variables related to black and 3-color densities respectively; the predicted 4-color density is represented by P. The sixteen a_{ij} can be obtained from the known tabulated 4-color densities[4], obtained from those 48 colour patches as mentioned above. A similar process was used in the reverse printer model.

2^{nd}-order Polynomial Regression Algorithm

Also a numerical type of the 2^{nd}-order polynomial regression algorithm[5] (referred to as 2^{nd}-SVD later), which was applied the singular-value decomposition (SVD)[4] and derived from previously early work, was implemented here.

Fig. 2 illiterates the computational procedures, used to compute the forward process of printer/printing device characterisation. For 2^{nd}-SVD approach, the FDAs of CMY for every colour in question are first converted to the principal colorimetric densities ($D_{r\text{-}c}$, $D_{g\text{-}m}$, and $D_{b\text{-}y}$.) via LUT. Then the 3-color densities ($D_{r\text{-}3c}$, $D_{g\text{-}3c}$, $D_{b\text{-}3c}$) are obtained by the forward 3^{rd}-order masking models. On the other hand, the black component densities ($D_{r\text{-}k}$, $D_{g\text{-}k}$, or $D_{b\text{-}k}$) of K ink are obtained using the FDA of K ink via LUT. Finally the forward 2^{nd}-order printer models are used to predict the 4-color densities ($D_{r\text{-}4c}$, $D_{g\text{-}4c}$, or $D_{b\text{-}4c}$), and then transformed to the predicted XYZ by using the log-density function.

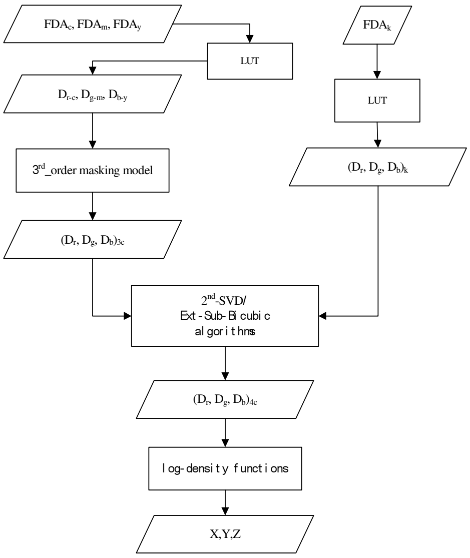


***Figure 2**. The computational procedure used in the forward models*

Preliminarily All the reverse models were derived to predict FDAs of the CMY inks of all the colour patches in ECI2002 test target using the measured XYZ values with known FDA of K ink. Afterwards, integrating a GCR algorithm, they could be applied in the actual complex image transform. Therefore, in the preliminary stage, except by keeping the same upper right part of the transforming FDA to black component densities ($D_{r\text{-}k}$, $D_{g\text{-}k}$, or $D_{b\text{-}k}$) of K ink via LUT, the computational procedures of the reverse models are those by reversing the forward ones shown in Fig. 2. In order to test the prediction performances of models derived in the reverse transformation, every test colour of the predicted XYZ values were calculated using its predicted FDAs of CMY and the known FDA of K via the corresponding derived forward models described in Fig. 2. These calculated XYZs were, then, compared with the measured XYZs.

Equivalent Neutral Density and Principal Density

Moreover two different forms of "Equivalent Neutral Density" (END) and "Principal Density" (PC)[1] were separately applied in the three-colour model of 3^{rd}-order masking equations as mentioned previously for both the numerical and the physical type of four-colour printer algorithms mentioned above. For the derivation of END version of models, it is essential to linearise gray-balance curves for the printer tested. However it was found that there was not enough gray tone of training samples in the ECI2002 target to derive the grey-balance LUT. Therefore the first step toward obtaining the gray-balance curves was to extract the colour patches located on the near lightness axis in CIELAB space, from ECI2002 test target. Totally 100 samples were selected. Gray balance curves, representing Gray-balancing LUT of CMY FDAs vs. lightness (i.e. L), were then generated by regression method via the derivation of 3rd-order polynomial equations using the 100-samples neutral or near-neutral training data. These curves were then used to extract END value (obtained from lightness via equation of ***log***(100/L)) for each of CMY colorants; or vice versa.

LUT and Cross-media Colour Transform

Consequently, in terms of both END and PD, separately applied using both "With" and "Without" linearization setup state in input-output relationship, totally eight printer DCMs were derived. Their corresponding prediction performances, evaluated in both of forward and reverse processes, tested using the ECI2002 training/test data sets, are tabulated in Table 2. Additionally, a well-characterised EIZO-CG210 LCD (with ΔE_{94} of 1.05) using PLCC linear model [7] was also used here as the source imaging media. Subsequently, every mathematical approach of derived printing DCMs (by implementing GCR technique) and LCD DCM, populated the lattice-sample points of LUTs of interest.

Later on, to cross verify performances of the printer DCMs, eight sets of image processing algorithms (IPAs) using LUT approach using tetrahedral interpolation[6] were developed. These 8 sets of IPAs implemented actual colour/image transforms across media from monitor to printer in this study. Also an S-type of gamut mapping method[8] was integrated into every of cross-media colour transform algorithms developed.

Totally, a set of 5 images, as shown in Fig. 3, were tested and rendered using each of image processing algorithms implemented as mentioned above. These 5 images included GATF, Sofa, Magic, Ski and Women. Both softcopy Images displayed on the LCD and hard-copy images produced using the LUT methods tested were representations of the originals and the reproductions respectively.

Psychological Experiments

Finally, a set of forced-choice paired comparison psychophysical experiments[9] was carried out, to make comparisons of colour appearance matching between the original images (displayed on the LCD) and the corresponding reproduction images (produced using LUT approaches of DCMs). It was, as mentioned above, used to cross verify the prediction performances of those printer LUT DCMs derived.

***Figure 3.** Images used in the process of scanner-to-monitor colour transformation.*

A panel of 10 observers, repeated twice in a period of time, viewed a paired of reproductions randomly presented, and judged which of the two gave a better match (i.e. colour fidelity) to an original image in question. They then rated the colour-fidelity quality of each hardcopy image, against its corresponding original softcopy, on a category scale with seven category scales of ordinal values from 1 (" exact match") through 4 ("acceptable match") to 7 ("awful match"). Both every original softcopy and its two corresponding reproduced hardcopies were displayed side-by-side on gray background fields with approximate 50 of L*. A viewing cabinet with a light source of D50 simulator was used to display two hardcopies. The colour temperature of the monitor was set to be D50 condition. The luminance levels of white points for both the LCD's and the viewing cabinet were set to140 cd/m^2. The paired comparison results, for "Total" (five image combined) are summarised in Table 3 which is attached with a plotted figure, in terms of z scores,

Results and Discussions

From the comparisons between Tables 2 and 3, it shows that the SVD_Lin_END model, applying the 2nd-order polynomial regression algorithm, in terms of END form and using the setup of OL function provided by RIP software, outperformed the others. Overall, all models derived performed reasonably in the characterisation of printer/printing device tested.

The results also clearly indicate that, with the setup state of output-linearization in RIP software in the preliminary process of printer characterisation, the 2nd-order polynomial regression algorithm always performed much better than the one without, for either version of END and PD. But this wasn't the case for bicubic-spline interpolation algorithm (i.e. Ext-SA-Bicubic). There existed insignificant performance differences among all 4 models implemented using the Ext-SA-Bicubic algorithm no matter "With" or "without" output-linearization set-up state on RIP software. Moreover, with linearization setup, the 2nd-order model with the END version, gave slightly better prediction results than the one using the PD version. Also from the complex-images evaluation, reflected from observers, it suggests that, by using gray balancing approach (i.e. in terms of END form), the 2nd-order model produced much better neutral/near-neutral colour renditions of images, compared to those produced using the PD (principle density) approach.

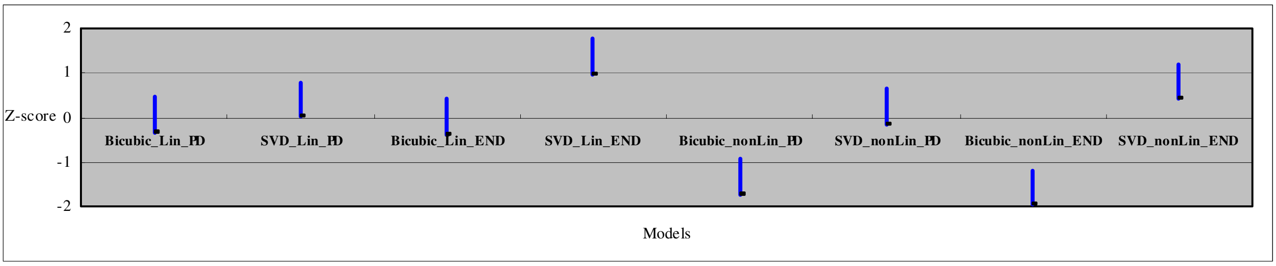
Additionally images produced using the bicubic-spline interpolation algorithm, (no matter with/without OL state and using PD/END form), had more or less unsatisfactorily noticeable poor-smoothness colours in shadow areas. From the further evaluation the colour patches, which were used to model sub-additivity behaviour of colorants, it was found that

Table 2. Prediction performances, in terms of mean ΔE_{94}, of twelve derived Models for transform processes of both the forward (denoted as F) and the reverse (denoted as R).

CIE$_{94}$ Colour Difference of Models									
Without Linearization Set-up (PD)					**Without Linearization Set-up (END)**				
Models	**2nd-SVD**		**Bicubic**		**Models**	**2nd-SVD**		**Bicubic**	
	F	**R**	**F**	**R**		**F**	**R**	**F**	**R**
Max	9.471	7.642	10.026	6.241	**Max**	8.941	7.170	9.553	6.536
Average	1.379	1.115	1.218	0.996	**Average**	1.349	1.177	1.200	1.070
STD	0.848	0.749	1.010	0.725	**STD**	0.829	0.765	1.016	0.738
>6 Counts	9	5	9	1	**>6 Counts**	8	4	9	1
With Linearization Set-up (PD)					**With Linearization Set-up (END)**				
Models	**2nd-SVD**		**Bicubic**		**Models**	**2nd-SVD**		**Bicubic**	
	F	**R**	**F**	**R**		**F**	**R**	**F**	**R**
Max	7.390	6.312	8.801	8.262	**Max**	7.374	6.334	8.816	8.320
Average	0.970	0.798	1.360	0.590	**Average**	**<u>0.928</u>**	0.898	1.321	0.731
STD	0.628	0.677	1.332	0.827	**STD**	0.605	0.688	1.345	0.836
> 6 Counts	2	1	11	1	**>6 Counts**	2	1	12	1

Note: 1) The underlined+bold figure indicates the best performing model; 2) STD stands for Standard Deviation.

Table 3. Models' performance (combined from 5 test images) evaluated using paired comparison results.



$$95\%CL = \pm \frac{1.96 * 0.707 * \sqrt{8_{(models)}}}{\sqrt{10_{(observers)} * 2_{(times)} * 5_{(images)}}} = \pm 0.392$$

Models	Bicubic Lin_PD	2nd-SVD Lin_PD	Bicubic Lin_END	2nd-SVD Lin_END	Bicubic nonLin_PD	2nd-SVD nonLin_PD	Bicubic nonLin_END	2nd-SVD nonLin_END
Z-score	0.07	0.41	0.03	**<u>1.36</u>**	-1.33	0.24	-1.58	0.80
Rank	5	3	6	1	7	4	8	2

Note: 95% CL represents 95% confidence limit (2σ) those training samples were irregularly distributed in colorimetric density domain/space, and especially samples near shadow region had too short distance in neighbourhood (or nearly piled up). This caused inaccurately predict CMYK values of the test samples which are near shadow areas, by using the bicubic-spline interpolation approach; and resulted in the artefacts of colour shift and poor-smoothness. It implies that it is needed to make further improvements or modifications on the selection/creation of sub-group data set from ECI2002 test/training target to optimally implement the bicubic-spline interpolation algorithm, for printing devices.

Conclusions

This paper proposed two types of printing characterisation algorithms, including the 2nd-order polynomial regression and the bicubic-spline interpolation, based on both non-linear and non-ideal behaviours of primary colorants. Totally eight DCMs were derived, and afterwards packed up entries of the look up table (LUT) to perform the actual colour image transformations. To achieve satisfactory rendition quality of hardcopies using colour printers, it was suggested that the preliminary stage of printer characterisation process should involve the setup state of output-linearization function provided by RIP software. With either version of PD and END, the 2nd-order polynomial regression algorithm by applying SVD could be well characterised printing devices of interest under OL setup, and applied in the application of cross-media colour reproduction. It was also found that, with the application of gray-balancing approach (i.e. using END version), the 2nd-order polynomial regression algorithm gave better colour renditions in neutral/near-neutral areas of images than those using PD form. The results also suggested that, although the bicubic-spline interpolation algorithm could reasonably characterise printer devices in question, it is still needed to make some proper modifications to further improve prediction performances. Candidates of the training data, used to model the sub-additivity behaviour, should be carefully selected or created using the training/test target, especially for those colour samples in dark regions. The training samples, forming lattices to implement bicubic-spline interpolation, should have a smooth transition or distribution form highlight to shadow regions in the colour space/domain of interest.

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Biography

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