Colour separation of *n*-colour printing process using inverse printer models

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Abstract

Although the n-colour printing process increases the colour gamut, it presents a challenge in generating colour separations. This paper evaluates different methods of implementing the inverse printer model to obtain the colour separation for n-colour printing processes. The constrained optimisation and the look-up table based inversion methods were evaluated. The colorant space was divided into sectors of 4-inks and the inverse printer models were applied to each sector.

The results were found to be adequate with the mean CIEDE2000 values between the original colours and the model predicted colours below 1.5 for most of the models. The lookup table based inversion was computationally faster than the constrained optimisation approach. The 9-level lookup table model gave accurate prediction without costing the processing time. It can be used to replace spot coloured inks with the 7-colour printing process in packaging printing to achieve significant cost savings.

Introduction

The use of an *n*-colour printing process is growing in the printing industry especially in packaging printing. This project was mainly focussed on the benefit of replacing solid spot colours by use of an *n*-colour printing process. There are some markets, for example pharmaceutical and healthcare packaging, where the majority of the printing consists of solid spot colours using special inks. With the *n*-colour printing process, a fixed set of six or seven inks can be used to reproduce most of the artworks and the spot colours can be printed using combinations of these fixed process colours instead of special inks.

Several methods have been proposed that use the *n*-colour printing process [1-8]. In *n*-colour printing, a given colour can usually be matched using more than one combination of inks. This problem has been addressed by dividing the inks into 3-ink subgroups or 4-ink subgroups [1], [3]. As the colour gamuts of subgroups overlap however, it is difficult to find a unique colorant combination.

Researchers have developed and evaluated spectral models using multiple printing inks to make a reasonable spectral match [7, 8]. These models were based on criteria such as minimising metamerism and increasing colour constancy. Spectral models represent significant advancements in the multi-colour separation field, but they are complex and the inversion of the models is computationally expensive.

The inverse printer model derives colorant amounts from colorimetric values for a given viewing condition. If the forward relationship from colorant values to colour values is defined by a physical printer model then the inversion is possible using search-based optimisation methods. Due to the inherent nonlinearity of the printing process inversion is difficult. Previous studies have made the printer characterisation using spectral models [6-13]. A new colour separation method was proposed [14] by specifying the relative area coverages of the printer's Neugebauer primaries.

For a 3-colour process, the inversion is trivial since there is a unique combination of colorants to achieve any given colour. For a 4-colour process, where a black ink is used in addition to chromatic inks, there are many combinations of colorants resulting in the same colour. For an *n*-colour process with more than 4 inks this one-to-many mapping issue becomes more complex. By dividing the colorant space of the *n*-colour process into sectors of 4 inks, the inversion model is applied to the 4-colour process of each sector.

This paper investigates different methods of implementing the inverse printer model to obtain colour separation for the *n*-colour printing processes. For achieving good accuracy of an inversion model, it is important to use a precise forward model. The YNSN model is widely used for printer characterisation by researchers and it has been shown to perform best in terms of forward characterisation of the *n*-colour printing processes [15]. Hence this model was used as a basis for the inverse model. The constrained nonlinear optimisation method and the look-up table based inversion methods were implemented for a 4-colour printing process and then extended to the *n*-colour printing process with an example of a 7-colour printing process.

Experiment

Printing systems consisting of 7 process inks were used: Cyan, Magenta, Yellow, Black, Orange, Green and Violet. The colorant space was divided into sectors of 4-inks each as follows: CMYK, OMYK, CGYK and CMVK (Fig.1).

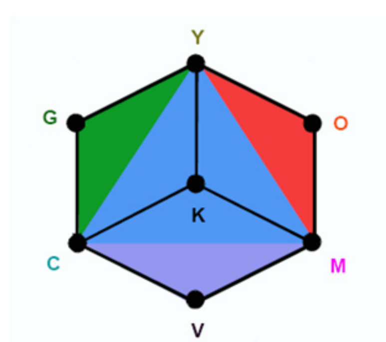

***Figure 1**. Four sectors of CMYKOGV colorant space*

Every sector contains an achromatic channel (K). In addition to CMYK, three sectors are defined based on the secondary colour as a dominant colour of the sector. For example, OMYK is the orange-sector with orange as a dominant colour, magenta and yellow as a primary colours and black as an achromatic colour. The same sectors can also be derived by use of black (K) as a common ink and replacing each of the chromatic colours (C, M and Y) by its complementary colours (O, G and V respectively).

This method can be generalised for any n-colour printing process. For example, in the case of an 8-colour printing there will be five sub-sets of 4-inks each containing black as a common ink and three chromatic inks in each sub-set.

This approach is similar to another method [3], in which the seven inks were split into six sub-sets of 4-inks. The proposed method uses only four sets. With six sectors of 4-inks, there are more overlaps adding complexity. In the case of four sectors of 4-inks, the adjacent sectors of orange, green and violet have only two inks in common.

Printing processes

The following printing processes were used: lithographic offset, flexography and thermal sublimation. The default screening method provided by the raster image processor (RIP) vendor was used for all printing processes; the halftone algorithm was not modified and used amplitude modulation (AM) screening with 150 lines per inch screen frequency.

Screen angles need to be carefully assigned to all inks in n-colour printing. Complementary colours were assigned the same screen angle and the following screen angles were used: Cyan and Orange = 15°, Magenta and Green = 75°, Yellow and Violet = 90° and Black = 45°.

The printing processes were calibrated to adjust their behaviour to known desired conditions. For example, in case of the lithographic offset printing process and the thermal sublimation process, tone values for Cyan, Magenta and Yellow were adjusted to achieve the tone value increase (TVI) targets of “curve A” specified by ISO 12647-2 [16]. Tone values for Black, Orange, Green and Violet were adjusted to achieve the tone value increase (TVI) targets of “curve B” specified by ISO 12647-2 [16]. Similarly for the flexographic printing process the ISO 12647-6 [17] aim values were used.

Test charts

For each 4-ink sector, the ECI2002 test chart [18] was generated and printed using the different printing processes. These charts were used for evaluating the inverse printer models and each contains 1485 colour patches. By combining all ink sectors, there are total 5940 colour patches representing the overall 7-colour printing process. Each test chart contains the same colorant values (dot areas). For example, in the OMYK chart, all values of cyan (C) ink in the CMYK chart are replaced by orange (O) ink. Fig.2 shows test charts for all sectors.

The colour patches in each test chart were measured using an X-Rite i1 Pro 2 spectrophotometer with D50 illuminant, 2° observer angle, 45°/0° measurement geometry and white backing material [19]. There was no UV content in the light source. Measurements for all ink sectors were collected to form a data set for each printing process. The training set consists of 16 Neugebauer primaries obtained from the ECI2002 test chart for each ink-sector to calibrate the YNSN model.

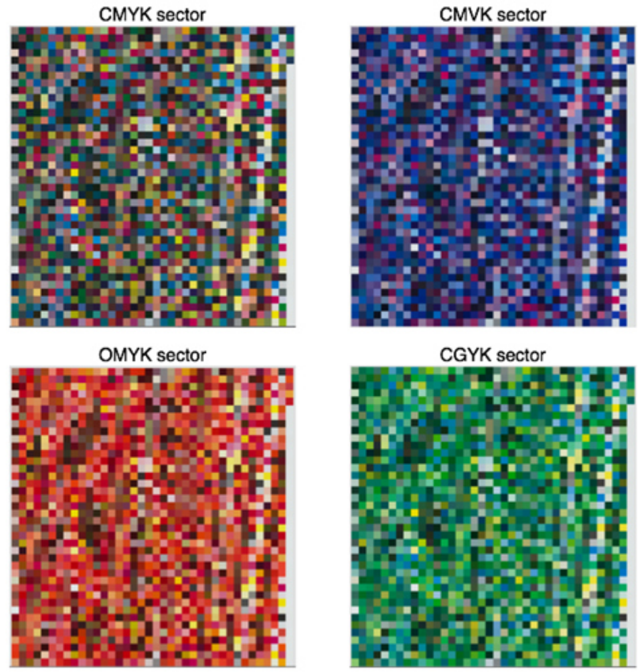

Figure 2. *Test chart for each sector of the 7-colour printing process*

Although, n-colour printing normally implies a printing system with any number of colorants greater than 4, we chose 7-colour printing with three additional inks that are complementary to C, M and Y. These additional inks are red (R) or orange (O), green (G) and blue (B) or violet (V). The method described below can be generalised to any n-colour printing process by use of sub-sets of 4-inks each containing a common black ink and three chromatic inks.

Forward characterisation

The YNSN model was applied for forward characterisation of each ink sector. In a 4-colorant printing system, there are 16 different colours formed by the solid colours and their overprints, which are the primaries in the Neugebauer model. This model assumes that the halftone reproduction can be considered as an additive process in which the reflectance of a print is the sum of the reflectances of each of the primaries weighted by its relative area. The YNSN model introduces the Yule-Nielsen value (n) to the wide-band Neugebauer model to account for internal light scattering in the substrate.

$$R(\lambda)^{(1/n)} = \sum_{i=1}^{N} w_i R_i\,(\lambda)^{(1/n)} \quad (1)$$

where $R(\lambda)$ is the predicted spectral reflectance as a function of wavelength of a given patch printed using N number of Neugebauer primaries, $R_i(\lambda)$ is the spectral distribution of the patch with only the i-th Neugebauer primary, the weight w_i is the fraction of the i-th Neugebauer primary in the given patch, and n is the Yule-Nielsen factor.

In this project, the Yule-Nielsen value (n) is treated as a correction factor to optimise the fit of the model to empirical data. The forward YNSN model is applied iteratively with increasing values of n. The optimised Yule-Nielsen value is obtained when the mean colour difference between the predicted and the measured colours of the ECI2002 test chart is minimised. For each 4-inks sector, the Yule-Nielsen value is optimised and used when applying the forward printer model.

Gamut mapping

Before applying the inverse printer models, gamut mapping was performed. The coordinates lying outside the sector gamut were first mapped to the gamut surface by using a hue-preserving minimum ΔE clipping method [20].

Constrained nonlinear optimisation

For a typical 4-colour printing process, direct analytical inversion of the forward YNSN model is not possible. One solution is to use an iterative method of constrained nonlinear optimisation by minimising the objective function, such as a colour difference between the desired colour and the predicted colour. Previous studies include the linear regression iteration method for inversion of the YNSN model [12] and the conjugate gradient approach [10]. In another study different techniques of nonlinear optimisation for a 6-colour inkjet printer characterisation were assessed [8]. A general problem description is given as follows.

$$\min_x F(x) \quad (2)$$

$$F(x) = \|R_\lambda(x) - r_\lambda\|_2^2 \quad (3)$$

with the following constraints

$$x_i \in [0,1] \; for \; i = 1, \ldots, n. \quad (4)$$

where x is an ink combination for n inks, $R_\lambda(x)$ is the estimated spectral reflectance for the ink combination x derived from the YNSN model and r_λ is the desired or the target spectral reflectance. Nonlinear constrained optimisation was performed for each sector using two optimisation algorithms by minimising the spectral root mean squared (RMS) error between the predicted spectra and the measured spectra. The constraints for the effective area coverage were set as 0 to 1. Maximum number of iterations allowed was 1000. The termination tolerance on the objective function value was set to 10^{-6} to halt the iterative process. The Matlab optimisation toolbox was used to perform the optimisation algorithms. The following algorithms were tested.

Active set algorithm

This algorithm is based on the Karush-Kuhn-Tucker (KKT) equation. It cancels the gradient between the objective function and the active constraints at the solution point. The deviations in magnitude of the objective function and constraint gradients are balanced by using Lagrange multipliers.

Sequential quadratic programming (SQP)

Every iterative step in the SQP algorithm is taken in the region constrained by bounds. If any iteration fails, the algorithm tries to take a smaller step to find the solution. If the constraints are not satisfied, the algorithm combines the objective function and the constraint functions into a merit function and attempts to minimise this merit function [21, 22]. But this can slow the speed since it now involves more variables.

Lookup table (LUT) based inversion

A 3-dimensional lookup table (LUT) based method [23] was used to map the device-independent colour values to device-dependent colorant values as follows.

The forward YNSN model was used to generate a uniform lookup table in CMY values and corresponding CIELAB values. 5-level, 9-level and 17-level lookup tables were evaluated. For example, a 9-level uniform lookup table generates 6561 coordinates which act as a training set. A set of 1485 samples was used as the test set, and all samples were printed and measured. These CIELAB values were mapped to estimated CMY values by the lookup table. A linear interpolation method was used to derive the inverse model with the 5-level, 9-level and 17-level lookup table sizes.

Next, a unique transform from CMY to CMYK was obtained by applying grey component replacement (GCR). The estimated device values (CMYK) were mapped through the forward printer model to obtain the CIELAB values. The colour difference values between the final CIELAB values and the original target CIELAB values of all test samples were calculated. The above mentioned process of inversion was applied to the remaining ink sectors in a similar way.

Inverse model for 7-colour printing process

The aim is to achieve the colorimetric reproduction of the given solid spot colour using 7-colour printing process. Any given colour can be reproduced using a maximum of four inks belonging to the corresponding ink-sector.

The target colour is first checked against the colour gamut of each ink-sector to find the best sector for reproducing the target colour. If the target colour is inside a single sector-gamut, then this becomes the best sector. If the target colour is inside multiple sector-gamuts, for example the CMYK and OMYK sector gamuts, the inverse model is applied to each of those sectors. The sector which gives the least CIEDE2000 between the target colour and the model predicted colour is selected as the best sector. If the target colour is not inside any of the sector-gamuts, then the closest gamut boundary to the colour is determined. The ink-sector represented by this gamut boundary is the best sector.

Once the best sector was obtained, the colour separation was calculated by applying the inverse model. The colour difference CIEDE2000 between the model predictions and the measured colours of the test set were calculated.

Reproduction of spot colours using the *n*-colour separation

A set of 35 spot colours were converted using 7-colour separations and reproduced on the lithographic offset printing process to evaluate the colour separation. These colours are reallife brand colours and they are well-distributed across CIELAB colour space representing pastel, saturated, neutral, light and dark colours of different hues.

Since the 9-level LUT method performed well in balancing colour accuracy and computational cost (see results in the next section), this method was used to calculate the colour separation for each of the 35 spot colours. The colours printed with seven inks were measured and then compared against the colour measurements of the original spot colours. The CIEDE2000 values between the printed colours and the original spot colours were calculated.

Results

Forward printer characterization

The accuracy of the YNSN model for all ink sectors of the 7-colour lithographic offset printing process is given in Table 1. The mean CIEDE2000 values between the predicted colours and the measured colours for all sectors were between 1.34 and 2.85. The optimised *n*-values were between 1.54 and 1.74.

Table 1: Accuracy of the forward printer model for 7-colour offset printing process

Ink sector	Optimised *n*-value	Mean CIEDE2000
CMYK	1.66	1.75
OMYK	1.68	1.34
CGYK	1.54	2.85
CMVK	1.74	2.15

Inverse printer characterization

Mean values, 95th percentile and maximum values of the CIEDE2000 were used to evaluate the model accuracy. In addition, the speed of each optimisation algorithm in calculating the colour separations for the given test set was measured in terms of milliseconds (ms) per colour on a 2.50 GHz processor with 4 GB installed memory.

The overall performance for the 7-colour Offset printing process (CMYKOGV) was evaluated by combining the results of all ink sectors (Table 2). For each ink sector, there were 1485 colour patches of the test set. By combining all ink sectors, there were a total of 5940 target colour patches of the overall 7-colour printing process.

In terms of the mean colour difference values, the 17-level LUT method showed the highest accuracy of 0.88 CIEDE2000 followed by the SQP optimisation method with 0.95 CIEDE2000. However, they showed poor speed performance. The Active-set optimisation method had the worst accuracy with the mean and max CIEDE2000 values of 4.92 and 33.43 respectively.

As expected the lookup table based inversion was significantly faster than the constrained nonlinear optimisation method. Comparing the accuracy and the speed performance of three LUT sizes, it was clear that the 9-level LUT size gave reasonably accurate prediction without costing the time and computational expenses. The 17-level LUT size showed significantly slower performance than other two LUT sizes. The speed performance of each method is compared against the mean CIEDE2000 values in Fig.3.

Table 2: Results of the inverse printer models for the 7-colour Offset printing process

Inversion method	CIEDE2000			Speed (ms per colour)
	Mean	95th percentile	Max	
SQP	0.95	2.59	5.25	104.06
Active-set	4.92	17.70	33.43	54.37
5-level LUT	1.47	5.01	10.64	8.62
9-level LUT	1.02	3.56	9.90	9.01
17-level LUT	0.88	3.21	9.90	57.61

It can be seen that an increase in LUT size improves accuracy, but at the cost of speed. Processing time for the algorithm increases significantly with the increase in the LUT size beyond 9-levels.

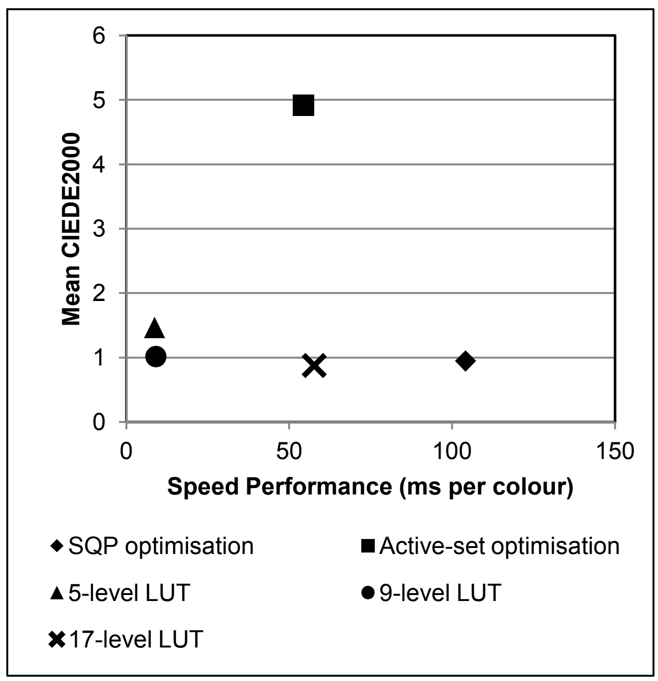

Figure 3.*Accuracy and speed of each model for 7-colour offset printing process*

Fig.4 illustrates the mean CIEDE2000 results of the inversion models for each of the 4-inks sectors for the 7-colour Offset printing processes. Table 3 shows the overall accuracy and speed of the 9-level LUT inverse model for all printing processes.

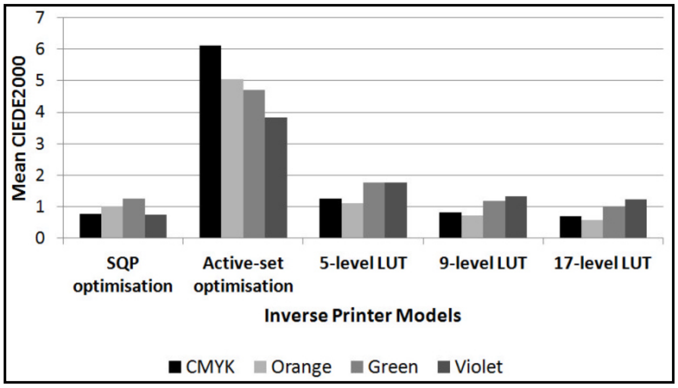

***Figure 4**.Mean CIEDE2000 values between the measured and the model predicted colours for each sector of 7-colour offset printing process.*

The overall accuracy for all printing processes was found to be very good with typical mean CIEDE2000 values below 1.5 at the average speed of approximately 9 ms per colour.

Table 3: Overall accuracy and speed of the 9-level LUT inverse model for different printing processes

Printing Process	CIEDE2000			Speed (ms per colour)
	Mean	95th percentile	Max	
Offset	1.02	3.56	9.90	9.01
Flexography	0.70	2.41	11.00	8.88
Thermal Sublimation	0.85	3.09	10.57	9.03

Reproduction of spot colours

Table 4 shows the mean, 95th percentile and maximum values of the CIEDE2000 between the 35 target spot colours and the printed colours. The inverse model showed good results with the mean CIEDE2000 of 1.60 with the average speed of 12.6ms per colour.

Table 4: Accuracy of the reproduction of spot colours

Inversion method	CIEDE2000			Speed (ms per colour)
	Mean	95th percentile	Max	
9-level LUT	1.60	3.20	3.61	12.6

These colour difference values represent the accuracy of the final printed colours covering the model prediction accuracy, error due to the process variables including the printing conditions, measurement uncertainty etc. The frequency of the CIEDE2000 values is shown in Fig.5. Most of the colours were achieved within 3 CIEDE2000.

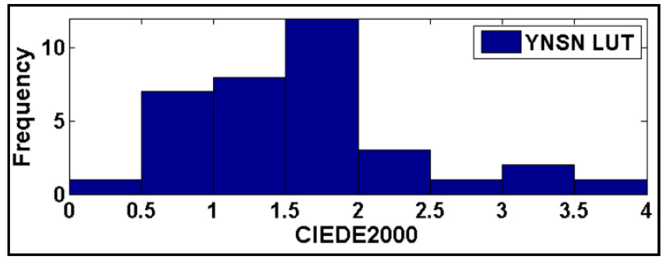

***Figure 5**.Histogram of the CIEDE2000 values between the target colours and the printed colours using 7-colour offset printing process*

Conclusion

Different inversion models were evaluated to derive the colour separation of the 7-colour printing processes. The challenge was to find a balance between the accuracy of the model and the computational cost. The 9-level lookup table based model showed the best overall performance.

Three printing processes were used, lithographic offset, flexographic and thermal sublimation printing process, consisting of 7 process inks. The YNSN model was used as a forward characterisation model since it showed the best performance. For each 4-inks sector, the Yule-Nielsen value was optimised by printing and measuring the training set of 16 Neugebauer primaries. The results show that the YNSN model can be successfully used as a forward printer model to populate the lookup table and to perform the inversion for all three printing processes.

A combined inverse model based on a 9-level LUT can be implemented to replace spot colour inks and achieve the target colours with the 7-colour printing process. This could save significant material, time and costs in packaging printing where the printing jobs mainly consist of the solid spot colours.

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Acknowledgements

This work is supported by London College of Communication, UK. We would like to thank Multi Packaging Solutions for providing the print facilities.