Model Based Color Separation for CMYKcm Printing

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Abstract

Recently, with the advent of printers with more than four colorants, the development of characterization and calibration techniques for these printers has been an important area of research in color printing. In addition to the "hi-fi" printers having colorants such as green, orange, red, blue and violet to increase the gamut of traditional $CMYK$ (cyan, magenta, yellow, black) printers, $CMYKcm$ printers which have light dye load colorants light cyan (c) and light magenta (m) have also become popular. In this paper, we investigate the $CMYKcm$ printers. We propose an spectral model based approach for the problem of color printer separation in $CMYKcm$ printing. We employ a parametric spectral model for color printers based on Yule-Nielsen modified spectral Neugebauer equations to characterize a $CMYKcm$ printer. We find the Yule-Nielsen parameter from a least squares regression over a training set of spectral measurements. We then apply the spectral model for the $CMYKcm$ printer and to compute the color separation function from $CMYK$ to $CMYKcm$.

1. Introduction

Modern color management systems require that color printers be characterized in some device independent color space such as CIE (Commission Internationale de L'Éclairage) $L^*a^*b^*$. To characterize a 6 colorant $CMYKcm$ printer in the CIE $L^*a^*b^*$ space, we must evaluate the printer transfer function which maps points in the printer input $CMYKcm$ colorant space to the points in the printer output CIE $L^*a^*b^*$ space for every point in the $CMYKcm$ space, i.e. every possible colorant combination. The inverse of this function constitutes the profile of the printer. The highly complex nonlinear interactions between the colorants and between the colorants and the paper substrate require that a very large number of sample color patches be printed and measured for accurate empirical characterization and hence accurate profiling of a color printers. For example, a very coarse sampling of 4 points per colorant axis necessitates the printing and measurement of 4096 (4^6) color test patches. This empirical approach does not take into account the correlation between the colorants which is very high for the case of $CMYKcm$ printers. Furthermore, this characterization should be repeated each time there is a change in the colorants, the paper substrate or the halftoning method.

The alternative approach is to model the printer colorimetrically, or spectrally, or to model the printing process physically. Using model based approaches, a color printer can be characterized using a small number of parameters. Therefore, these approaches require considerably fewer measurements than the empirical ones, especially for printers with more than 4 colorants.

In this paper, we employ a parametric spectral model for color printers based on Yule-Nielsen modified spectral Neugebauer equations to characterize a $CMYKcm$ printer and to develop a color separation function from $CMYK$ to $CMYKcm$. We first explain the spectral model we exploit and discuss model based color printer characterization and color separation. We then describe our method and lastly, we present our experimental results and conclusions.

2. Spectral Models for Color Printers

The most commonly used spectral model that mathematically analyzes the color printing process is the Neugebauer color mixing model. Neugebauer [1] found that there are 8 dominant colors, known as the Neugebauer primaries, namely white (W), cyan (C), magenta (M), yellow (Y), red (R), green (G), blue (B), and black (K) for a 3 colorant CMY binary(bi-level) color printer. These primaries correspond to one, two, and three color overprints of the colorants C, M, Y or to no colorant on paper (W). Geometrically, Neugebauer primaries can be interpreted as the vertices of a unit cube in the CMY colorant space with the vertices $\{0,0,0\} \equiv W$, $\{1,0,0\} \equiv C$, $\{0,1,0\} \equiv M$, $\{0,0,1\} \equiv Y, \ldots, \{1,1,1\} \equiv K$. An alternative labelling of these primaries is therefore W, C, M, Y, MY, CY, MY, and CMY respectively.

The spectral Neugebauer equation for a three colorant binary printer is

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

where $R(\lambda)$ is the predicted spectral distribution as a function of wavelength λ of a given patch printed using 3 colorants, $R_i(\lambda)$ is the spectral distribution of the patch with only the i-th Neugebauer primary on it, the weight w_i is the fractional proportion of the i-th Neugebauer primary in the given patch and $N = 2^3 = 8$. This equation can be generalized to predict the spectral distribution of a patch printed using a binary printer with L colorants where $N = 2^L$, the Neugebauer primaries correspond to $1, 2, \ldots, L$ layer overprints of the colorants or to no colorant on paper.

An important optical phenomenon that the linear Neugebauer model fails to account for is optical dot gain. Optical dot gain is defined as the change in measured reflectance due to interactions between the colorants and the paper substrate, mainly due to lateral scattering of light in the substrate. Yule and Nielsen [2] modified the Neugebauer equation to take into account optical dot gain for a monochrome printer and empirically found the following power law expression

$$R(\lambda)^{\frac{1}{n}} = w_B R_B(\lambda)^{\frac{1}{n}} + w_W R_W(\lambda)^{\frac{1}{n}}, \qquad (2)$$

where $R_B(\lambda)$ and $R_W(\lambda)$ are the spectral distributions of the black ink and white paper respectively. The factor n is called the Yule-Nielsen factor and is derived from the best fit of the model to the training data set.

Viggiano [5] extended the Yule-Nielsen equation (2) to the case of color halftones and obtained the following Yule-Nielsen modified spectral Neugebauer equation.

$$R(\lambda)^{\frac{1}{n}} = \sum_{i=1}^{N} w_i R_i(\lambda)^{\frac{1}{n}}. \qquad (3)$$

It has been shown that inclusion of the Yule-Nielsen factor significantly improves the fit of the model to the training data set [3], [4].

2.1. Model Based Characterization

Numerous researchers have studied the application of the color mixing models described above and other color mixing models to the problem of characterization of CMY and CMYK color printers. Rolleston and Balasubramanian [6] compared the performances of colorimetric and spectral, Yule-Nielsen modified and simple, non-cellular and cellular Neugebauer equations. Kang [7] also compared the accuracy of spectral Neugebauer and Yule-Nielsen modified spectral Neugebauer equations along with three other color mixing models: Clapper-Yule multiple internal reflections model, Beer-Bouger law and Kubelka-Munk theory. Balasubramanian [4] analyzed the effects of using the cellular framework and incorporating the Yule-Nielsen factor in the spectral Neugebauer equations.

Chang *et al* [8] devised a method based on Newton's minimization technique to estimate the fractional proportions of the Neugebauer primaries more accurately using additional non-primary Neugebauer colors. Lee [9] exploited an optimization technique called sequential quadratic programming to estimate the Yule-Nielsen modified spectral Neugebauer model parameters for a color halftone printer. Balasubramanian [10] carried out a weighted least squares regression over the training set of spectral distribution measurements to create a Yule-Nielsen modified spectral Neugebauer model.

Hua and Huang [11] utilized a model which they called the advanced cellular YNSN (Yule-Nielsen modified spectral Neugebauer) model, where the weighting coefficients w_i in (3) showing the fractional proportions of the Neugebauer primaries are functions of wavelength λ instead of constants. Agar and Allebach [12] developed an iterative method for color printer characterization based on cellular Yule-Nielsen modified spectral Neugebauer equations.

Model based characterization of printers with more than four colorants has also been studied. Ostromoukhov [13] generalized the compound Neugebauer model to multicolor printing with odd number of colorants. Meireson and Van De Capelle [14] proposed a new mathematical expression for the color mixing in color printers with more than 4 colorants that is motivated by the Yule-Nielsen modified spectral Neugebauer model and the Kubelka-Munk theory. P. Hung [15] discussed the variable reduction method and the division method for colorimetric characterization beyond three colorants.

2.2. Model Based Separation

Color separation can be broadly defined as the computation of the amounts of the colorants that need to be printed in order to create a desired color. Since the commonly used color spaces have three degrees of freedom, the color separation problem for printers having 4 or more colorants is a mathematically under-constrained optimization problem and requires additional constraints such as upper bounds on total colorant amount and preference of colorants. Previous studies utilizing spectral models for color separation include Mahy and Delabastita's method based on inversion of Neugebauer equations [16] and Tzeng and Berns' [17] approach of spectral model based six color separation to minimize metamerism in the printing of a spectral image.

Our proposed method constitutes the second step of a 2-step color separation process for $CMYKcm$ printers. We propose a model based 4 dimensional color separation of $CMYK$ into $CMYKcm$ following the first stage of initial $CMYK$ color separation. Our method allows the use of commercially available packages for the first step and for color printer profile generation. Our approach assumes that the gamut of a $CMYKcm$ printer is approximately equal to the gamut of its $CMYK$ printer subset.

3. Our Method

Given a 6 colorant $CMYKcm$ color printer, we first characterize this printer. We begin with printing the 64 (2^6) Neugebauer primaries for the $CMYKcm$ printer and measuring their spectral distributions. We then print a training target of primary (containing only one colorant) and secondary (containing two colorants) ramps of 21 patches going from 0% to 100% coverage, in increments of 5%.

We measure the spectral distributions of these samples and using the Yule-Nielsen modified spectral Neugebauer equation (3) and the spectral distributions of the 64 Neugebauer primaries, we then find the Yule-Nielsen factor n that minimizes RMS (root-mean-squared) ΔE_{1976} prediction error between the predicted and the measured spectral distributions for the $CMYKcm$ training target.

Once we determine the Yule-Nielsen factor and hence the spectral model for the printer, we use the model to find the color separation function to go from $CMYK$ to $CMYKcm$. As stated above, since the error we are trying to minimize is the Euclidean distance in the 3 dimensional $L^*a^*b^*$ color space, there is not a unique optimal mapping from the 4 dimensional $CMYK$ space into the 6 dimensional $CMYKcm$ space and additional constraints are required. It is commonly accepted in the color printing community that giving preference to colorants with L^* values closer to that of the paper substrate (*i.e* higher L^* values) results in smoother and visually more pleasing color halftones. Therefore, we find the mapping using the following greedy approach. Given a point in the $CMYK$ space to be mapped to a point in $CMYKcm$ space, we try to maximize the use of the colorants in the following order; yellow, light cyan, light magenta, cyan, magenta, and black. We measure the spectral distribution of the patch with the given $CMYK$ 4-tuplet. Then, for each possible $CMYKcm$ 6-tuplet we predict the spectral distribution using the spectral model of the printer. We choose the $CMYKcm$ 6-tuplet that results in minimum ΔE from the patch with given $CMYK$ 4-tuplet. To ensure a monotonic mapping, we only accept 6-tuplets that result in a L^* value greater than the measured L^* value. Furthermore, we do not allow the use of the cyan or the magenta colorant before using the maximum amount of the light cyan or the light magenta colorant, respectively.

4. Experimental Results

We tested our method on an Indigo Ultrastream 2000 liquid electrophotography based digital color printing press with $CMYKcm$ inks. Our training spectral data for the $CMYKcm$ printer consisted of the 420 spectral distributions of the color patches on the primary and secondary ramps and 64 spectral distributions of the Neugebauer primaries. For the fractional proportions of the primary colorants in Eq. 3 (w_i for $i = C, M, Y, K, c, m$), we used the entries in the dot area control look-up-tables on the printer. We computed the remaining w_i's assuming the statistical independence of the colorant layers. Through a least squares regression in $R(\lambda)$, the optimal value for n was found to be 1.14, resulting in an RMS ΔE of 3.05. Figure 1 shows the histogram of the ΔE errors for the training color patches.

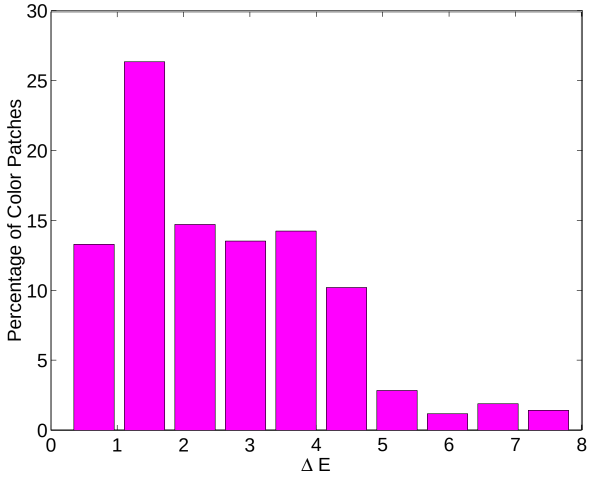

Figure 1: *Histogram of the ΔE errors for the training set.*

We tested the accuracy of our model based color separation algorithm on the CGATS standard IT8.7/3(1993) $CMYK$ test target. First, we measured the spectral distributions of the IT8.7/3 $CMYK$ test patches. Then, for each $CMYK$ test patch we found the optimal $CMYKcm$ 6-tuplet using our method, printed it and computed the ΔE from the test patch. The RMS ΔE for 928 patches was found to be 4.31. Figure 2 displays the histogram of the ΔE errors for the test color patches.

We also implemented a commonly used separation technique to map $CMYK$ space to $CMYKcm$ space: one dimensional separation of C into Cc and M into Mm while keeping M, Y, and K constant. We have printed and measured a 25x25 uniform grid of patches with C and c coverages ranging from 0% to 100% in each dimension, and similarly a 25x25 uniform grid of patches with M and m. Using these measurements, we empirically found

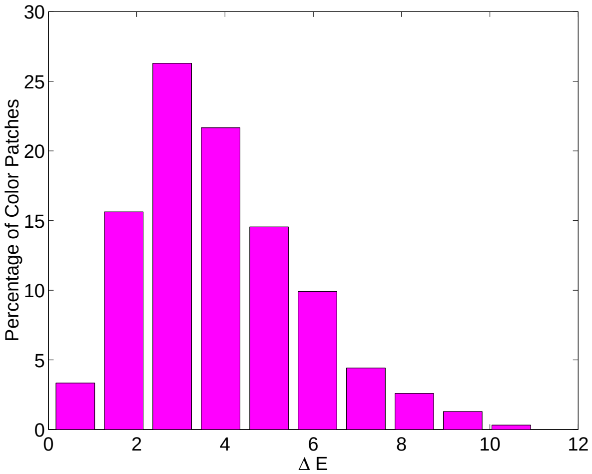

Figure 2: Histogram of the ΔE errors for the IT8.7/3 $CMYK$ test target using $CMYK \mapsto CMYKcm$ separation

the monotonic increasing functions $f_C : C \mapsto Cc$ and $f_M : M \mapsto Mm$, minimizing ΔE errors for a cyan ramp and a magenta ramp, respectively. The functions f_C and f_M were again obtained in a greedy fashion, keeping C and M at 0, while increasing c and m until c and m reach their maximum value, at which point we began increasing C and M. We tested the accuracy of this algorithm also on the IT8.7/3 $CMYK$ test patches and obtained an RMS ΔE error of 4.44. Figure 3 displays the histogram of the ΔE errors for the test color patches for this separation technique.

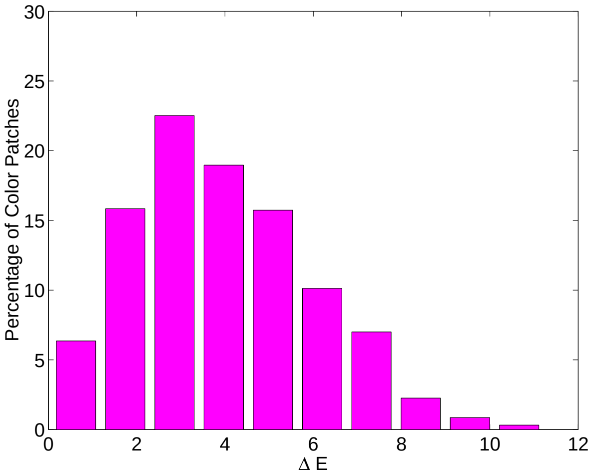

Figure 3: Histogram of the ΔE errors for the IT8.7/3 $CMYK$ test target using $C \mapsto Cc$, $M \mapsto Mm$ separation

Finally, to check the validity of our assumption that the gamut of the $CMYKcm$ Indigo Ultrastream 2000 printer is approximately equal to the gamut of its $CMYK$ printer subset, we compared these two gamuts. We first sampled the $CMYKcm$ space with a pattern similar to the one used in the IT8.7/3 $CMYK$ test target, in which we tessellated the $K = 0$, $K = 0.4$ and $K = 1$ hyperplanes with 4^5, 3^5, and 2^5 uniform grids respectively to form a test target with 1299 color patches. We then printed and measured the spectral distributions of these patches. Lastly, we compared the convex hull of the $L^*a^*b^*$ values of these patches with the convex hull of the $L^*a^*b^*$ values of the IT8.7/3 $CMYK$ test patches. This comparison depicted in Figure 4 validates our assumption that the gamut of the $CMYKcm$ Indigo Ultrastream 2000 printer (shown with the black wire mesh) is only slightly larger than its $CMYK$ sub-printer (shown with the light color solid).

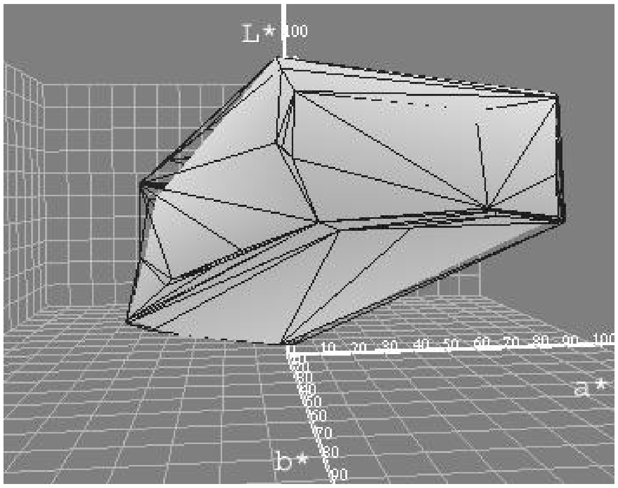

Figure 4: Comparison of the gamuts of the $CMYKcm$ Indigo Ultrastream 2000 printer (shown with the black wire mesh) with its $CMYK$ printer subset (shown with the light color solid)

5. Conclusion

We developed a spectral model based color separation method for the second step of a 2-step color separation process for $CMYKcm$ printers. We employ a model based 4 dimensional color separation of $CMYK$ into $CMYKcm$ following the first stage of initial $CMYK$ color separation. Our model based approach offers a means for studying the effect of the choice of the color separation functions and the constraints such as total colorant amount limitations and colorant preferences on the resulting spectral distributions without printing and empirical testing. Our approach permits the use of commercially available packages for the first step and for color printer profile generation. We obtained a training RMS ΔE of 3.05 for our Yule-Nielsen modified spectral Neugebauer model and a testing RMS ΔE of 4.31 for our spectral model based color separation method. The proximity of the training and testing error values shows the validity of our spectral model. Compared to the commonly used empirical one dimensional $C \mapsto Cc$ and $M \mapsto Mm$ separation method, our model based $CMYK \mapsto CMYKcm$ separation method allows more flexibility in the choice of color separation functions, and also results in a slightly smaller RMS ΔE of 4.31, as opposed to 4.44. Our approach is currently restricted to $CMYKcm$ printers and assumes that the gamut of a $CMYKcm$ printer is approximately equal to the gamut of its $CMYK$ sub-printer. This assumption hinders the generalization of our algorithm to other hi-fi color printers.

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