Spectral Color Reproduction Based on a Six-Color Inkjet Output System

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Abstract

The accuracy of a six-color inkjet printing system was tested using object-color spectral datasets known to both span and exceed the system's spectral gamut. The theoretical basis of the system is the Yule-Nielsen modified spectral Neugebauer equation implemented in an iterative optimization process minimizing spectral RMS error. Results of the end-to-end system based on the reproduction of 170 object colors compiled by Vrhel, *et al*. show a mean ΔE^*_{94} of 3.2 while 384 randomly selected printed color samples (in-gamut) were reproduced with a mean ΔE^*_{94} of 0.9.

Introduction

It is well know that four-color printing systems are highly metameric compared with objects undergoing graphic reproduction. Previous research concerned with increasing the number of inks from four has been done with the goal of gamut expansion, not metamerism minimization. Two notable exceptions to this were Kohler and Berns[1] and Tzeng and Tzeng and Berns.[2,3] Tzeng's system made use of six inks. However because of ink limiting constraints and concerns with the optimization difficulties of a 64-primary (2^6) system, ten four-color models were used rather than a single six-color model. This approach could reduce the full metameric-minimizing potential of a six-ink printer. Thus, it was of interest to remove the ink-limiting constraint and evaluate the full six-color model. It is hoped that this approach will fully utilize the spectral gamut of the printer resulting in the least metameric matches while maintaining high colorimetric accuracy. This paper will describe experiments with a custom six-color inkjet printing system in which color separations are generated based on the Yule-Nielsen modified spectral Neugebauer equation as a forward-prediction model. Several sets of object-color reflectance spectra were used to test for colorimetric and metameric qualities. The performance of the system in reproducing each set is analyzed and a statistical summary is presented.

Yule-Nielsen Spectral Modified Neugebauer Equation

The Yule-Nielsen modified spectral Neugebauer equation (YNSN) was used in this research. It is defined in equations (1) and (2) for the general case of K inks under the Demichel constraints:[4-6]

$$\hat{R}_\lambda = \left(\sum_{i=1 \to 2^K} w_i R_{\lambda,i,\max}^{1/n} \right)^n \quad (1)$$

$$w_i = \prod_{j=1 \to K} \begin{pmatrix} \text{If ink } j \text{ is in Neugebauer Primary } i\text{, then } a_j \\ \text{Else, } (1-a_j) \end{pmatrix} \quad (2)$$

where, n is the empirically fit Yule-Nielsen n-value accounting for physical and optical ink and paper interactions; $R_{\lambda,i,\max}$ is the spectral reflectance of the i^{th} Neugebauer primary; w_i is the Demichel weighting of the i^{th} Neugebauer primary defined by the product of the effective area coverages, a_j, for each ink.

System Description

The printing system was designed around a Epson Stylus Photo 1200 printer. A continuous-feed ink system manufactured by MIS Associates was selected to facilitate high-volume printing and ease refilling of the ink supplies. A set of CMYK archival ink was ordered from the same source. At the time the system was assembled, printer compatible orange and green inks were just coming onto the market. Inks extracted from the bulk cartridges of a Roland Hi-Fi Jet printer were placed in the channels normally occupied by light magenta and light cyan. To control the printer, a modified Linux printer driver was utilized. The driver accepts one byte per pixel; binary control over the inks is achieved by toggling corresponding bits within the bytes. To print multilevel images, a channel-independent Floyd-Steinberg dithering algorithm was used. Since the six-color YNSN model is not directly invertible, a constrained minimization routine in MATLAB, *fmincon*, was used to iteratively find the area coverages that minimized RMS error between the sample spectra and model predictions. A flowchart of the complete end-to-end system is shown in Figure 1.

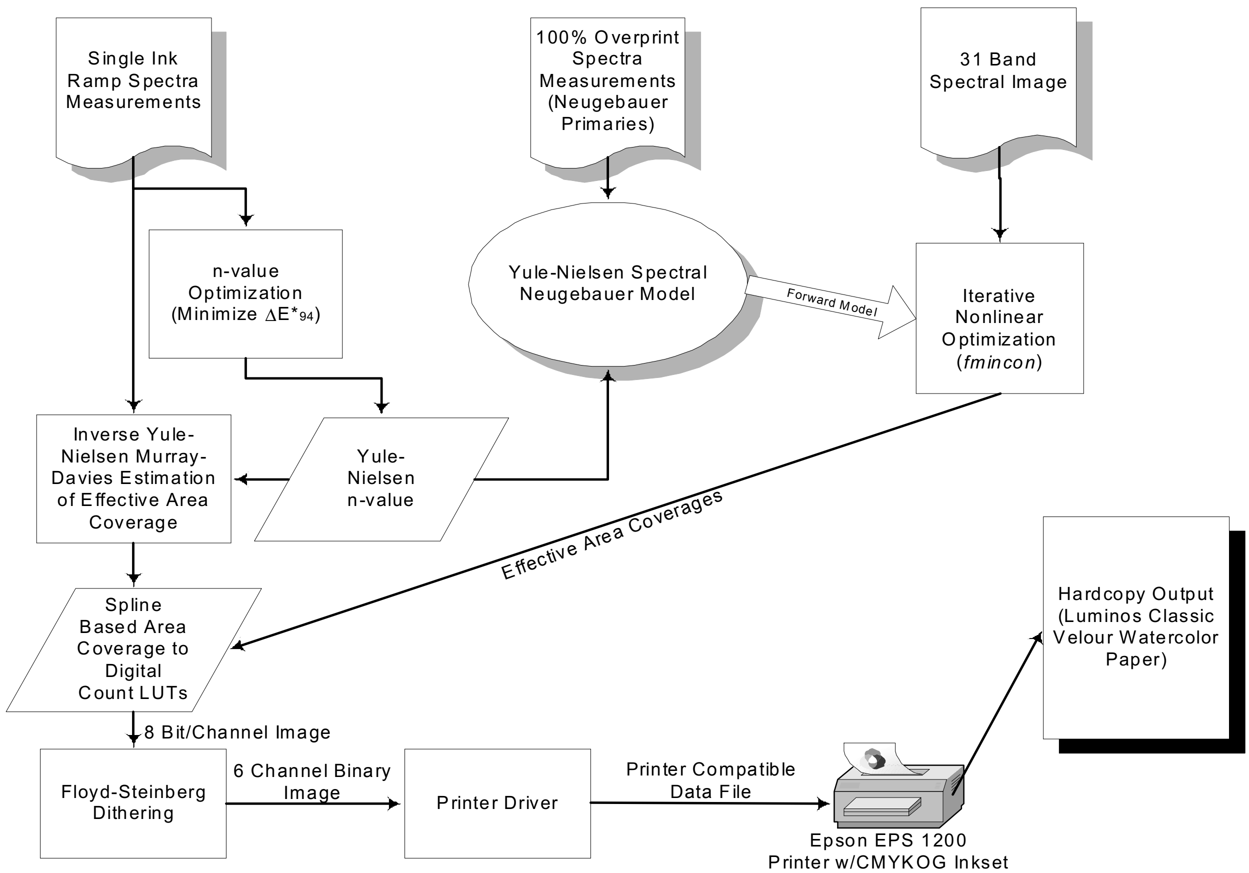

Figure 1 – Flow diagram of six-color inkjet printing system.

Printer Characterization

The YNSN forward model only requires measurements of the full coverage single inks, their overprints and paper as input. For a six-ink printer, this equals just 64 samples. However, to convert from printer digital counts to effective area coverages, single-ink ramp measurements are also necessary. All of these measurements were carried out using a GretagMacbeth Spectrolino spectrophotometer. The Spectrolino has a 4mm aperture with a 45º/0º ring optic geometry and measures from 380 to 730nm in 10nm steps. After the single-ink ramps were printed and measured, they were used to select the Yule-Nielsen n-value that minimized the average ΔE^*_{94} between measured and estimated spectra for all of the ramp data. The effective area coverages of the single-ink ramps were estimated using the inverse Yule-Nielsen Murray-Davies model with the optimized n-value. The ramp area coverages and their corresponding printer digital counts were placed into a lookup table (LUT) used in conjunction with spline interpolation to convert effective area coverages to printer digital counts.

Testing of System Accuracy

The accuracy of the forward model was tested by generating 384 random six-ink combinations, constrained to 300% maximum area coverage. These were printed and measured spectrally. The sample digital counts were also run through the YNSN forward model. The measured spectra were then fit with the iterative nonlinear optimization and the resulting digital counts were reprinted and measured. The flow diagram of this experiment is shown in Figure 2. A summary of the colorimetric and metameric performance of the system is presented in Table I. The metameric index (MI) in the table was based on a parameric correction such that a perfect match is achieved for illuminant D65.[7] The MI was a ΔE^*_{94} calculated for illuminant A and the 1931 standard observer. Because the samples of the random target are within gamut and non-metameric, the model exhibited excellent performance except for some samples near the gamut boundary. This is shown in Figure 3. Measured spectra from a GretagMacbeth ColorChecker and 170 object colors compiled by Vrhel, *et al.*[8] were evaluated to test how the system might perform in a complete imaging system. The ColorChecker and Vrhel datasets contain samples that are highly metameric and out of gamut. Thus, as expected the performance worsens. Both datasets were run through the inverse models, printed and measured. The colorimetric and metameric performance is summarized in Table II. For both datasets the mean error was acceptably small while the maximum error corresponds to highly saturated and fluorescent samples. A colorimetric error plot of the Vrhel dataset results is shown in Figure 4. Note that the samples with large errors are outside the six-color gamut. During optimization gamut mapping is performed automatically by minimizing RMS spectral error. Out of gamut samples are brought to the gamut's edge. The colorimetric consequences of this "spectral gamut mapping" are also seen in Figure 4. Essentially, lightness is preserved with uncontrolled changes in hue and chroma. In future implementations, appearance based mapping will be used. A CIE ΔE^*_{94} histogram for the Vrhel dataset is given in Figure 5. Most of the samples have quite acceptable performance.

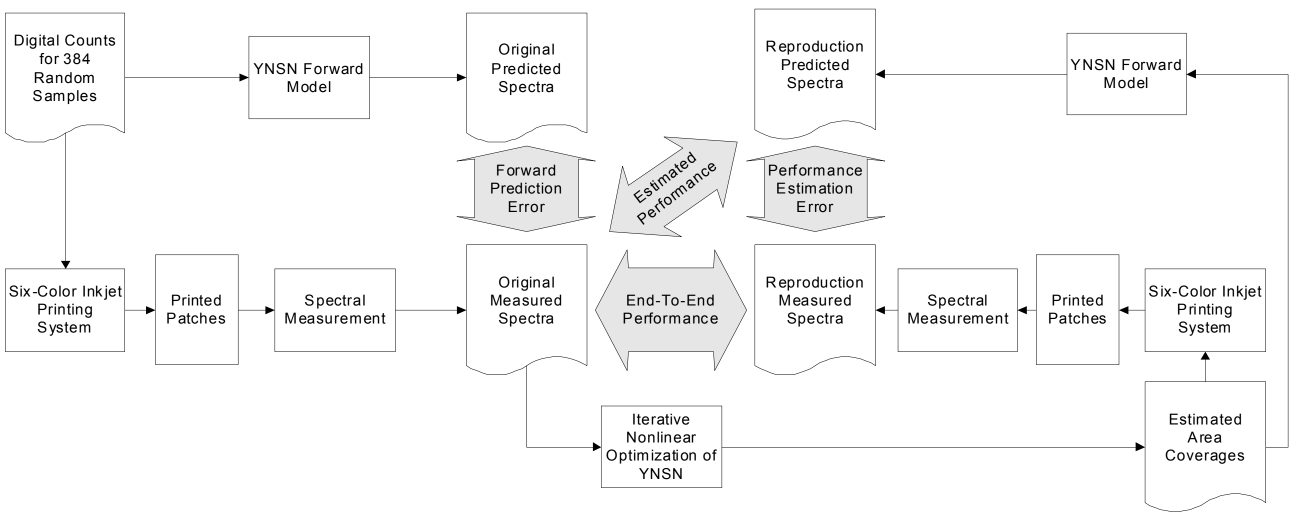

Figure 2- Flow diagram for experiment comparing results for 384 random printed color samples.

Table I – Four colorimetric and metameric comparisons of 384 random printed color sample spectra. (see Figure 2).

	ΔE^*_{94}, 2º Obs. Ill. D65			Metameric Index (Ill. A)			
Spectral Comparison	**Mean**	**StdDev**	**Max**	**Mean**	**StdDev**	**Max**	**Spectral RMS**
Forward Model Error	1.3	0.8	6.4	0.2	0.2	1.3	0.012
Estimated Performance	0.3	0.4	5.1	0.1	0.1	0.4	0.006
Estimation Error	1.0	0.4	3.2	0.2	0.1	0.6	0.009
End-To-End Performance	0.9	0.5	5.4	0.1	0.1	0.7	0.008

Table II – Estimated and actual colorimetric and metameric performance of printing system for ColorChecker and Vrhel data.

	ΔE^*_{94}, 2º Obs. Ill. D65			Metameric Index (Ill. A)			
Sample Set	**Mean**	**StdDev**	**Max**	**Mean**	**StdDev**	**Max**	**Spectral RMS**
ColorChecker Predicted	2.3	2.0	7.2	0.6	0.6	2.1	0.031
ColorChecker Printed	2.6	1.9	6.7	0.6	0.5	2.0	0.033
Vrhel Predicted	2.9	3.0	15.9	0.6	0.6	3.3	0.032
Vrhel Printed	3.2	3.0	15.2	0.6	0.5	3.1	0.035

The measured system performance for the Color Checker compares favorably with the results obtained by Tzeng using the standard CMYKGO primaries on the Dupont Waterproof system where he obtained a mean ΔE^*_{94} of 1.94.[3]

Because minimizing RMS spectral error does not minimize colorimetric error, the diagonal of the Matrix R operator[9] for D65 and the CIE 1931 2-degree observer was included as a spectral weighting factor. Using this technique, certain wavelength regions were given a greater importance when spectral matching, hypothesized to improve colorimetric accuracy. The hypothesis was supported by the results shown in Table III. The predicted colorimetric error, particularly for the ColorChecker and Vrhel datasets has been improved over the un-weighted results given in Table II. These results look promising; other weighting functions will be evaluated in the future, for example those proposed by Viggiano.[10]

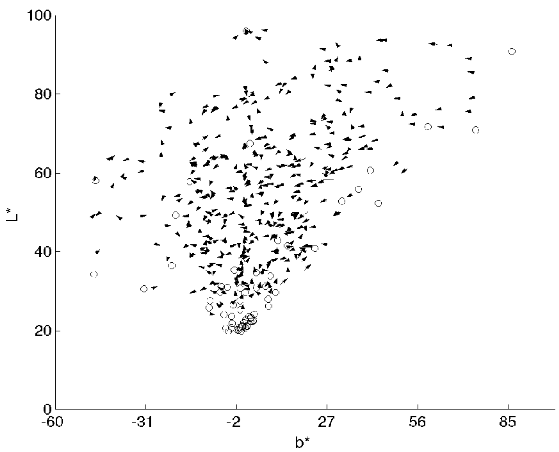

Figure 3-CIELAB Colorimetric error plot for predicted spectra of 384 random printed color samples. The locations of the 64 Neugebauer primaries are marked with open circles

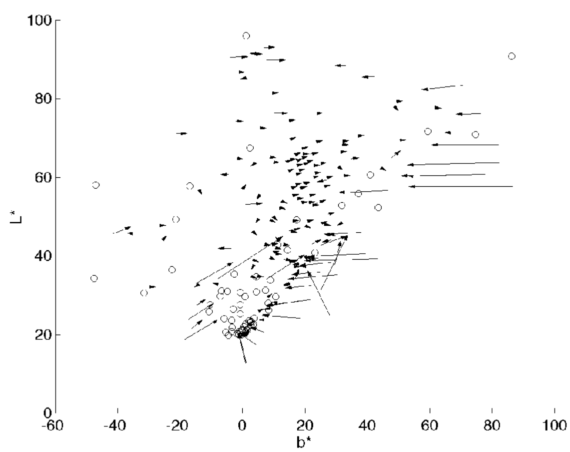

Figure 4 – CIELAB Colorimetric error plot for Vrhel object spectra predictions. Open circles mark Neugebauer primaries.

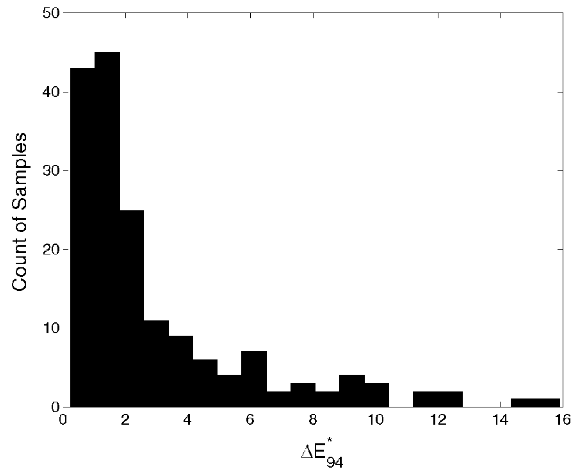

Figure 5 – Predicted spectra ΔE^*_{94} histogram for Vrhel samples.

Table III – Colorimetric and metameric performance of system predictions for three sample sets with the addition of Matrix R spectral weighting function.

	ΔE^*_{94}, 2° Obs. Ill. D65			Metameric Index (Ill. A)			Spectral RMS
Sample Set	**Mean**	**StdDev**	**Max**	**Mean**	**StdDev**	**Max**	
384 Random Samples	0.2	0.3	2.5	0.1	0.1	0.7	0.006
ColorChecker	1.2	1.4	5.1	0.7	0.7	2.6	0.050
VrhelObject Spectra	1.7	2.7	13.9	0.8	0.7	4.3	0.044

Conclusion

A six-color-inkjet-based-spectral-color-reproduction system has successfully been constructed and tested. A high degree of colorimetric accuracy is achievable for both metameric and non-metameric input spectra. This initial system made extensive use of MATLAB. While providing eased prototyping and debugging capability, it's speed was a significant limitation. Further research is being conducted with this spectral printing system, all source code will be written in C and additional consideration given to the selection of the nonlinear optimization algorithm.

Acknowledgements

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Biography

Lawrence A. Taplin received his B.S. degree in Computer Science from the University of Delaware in 1996 and is working towards the completion of a M.S in Color Science at the Rochester Institute of Technology. His thesis topic is the spectral modeling of a six-color inkjet printer. He is a member of IS&T.

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