Optimization of the Predicting Model for Dye-Based Inkjet Printer

Takayuki Ogasahara
CANON INC.
Tokyo, Japan

Abstract

It is very important to fully understand the relationship between ink amounts placed on the paper and resultant colors for a dye-based inkjet printer (IJ). In the field of printing, many predicting models such as the Neugebauer model (NM), the Yule-Nielsen Neugebauer model (YNNM), and the Cellular Neugebauer model (CNM) have been proposed. However, it is very difficult to precisely predict the resulting printed colors as reflectances or tristimulus values from ink amounts because of the nonlinear relationship between them.

In the previous study, the CNM only achieved sufficient prediction accuracy among a variety of predicting models, when the set of primaries was 5^N (N is the number of colorants used). In this paper, it is necessary to print and measure many primaries for prediction of reproduced tristimulus values. For example, 6-colorant prediction needs $5^6 = 15{,}625$ primaries.

The purpose of the present study is to further decrease the number of Neugebauer primaries that the CNM needs to predict with sufficient prediction accuracy. Further, the novel approach is to propose by taking into account dot gain for the present-day subtractive color IJ.

Introduction

Recently, IJ technology has been rapidly advancing. Among a variety of factors controlling image quality of IJs, granularity and tone reproduction have been improved considerably by ink dilution and small droplet technology. Further, quality of a coated paper for a dye-based IJ has also been improved drastically. In particular, ink amounts absorbed in the paper has been increased for larger color gamut, and ink absorption speed has been improved for high-speed printing.

However, improvement of image quality for the coated paper makes it difficult to predict reproduced tristimulus values from ink amounts easily. The used IJ has actually become 2.8 dots per pixel at 100% area coverage, so it can be expected that dot gain becomes much larger in the coated paper.

In the field of printing, there are many models used to predict reproduced tristimulus values from ink amounts, include the NM and the YNNM.[1-4] Among a variety of predicting models, the previous study[5] revealed in that the CNM only achieved sufficient prediction accuracy of $\Delta E_{94} \cong 1.0$, and that the set of primaries was 5^N.

The purpose of the present study is to further decrease the number of Neugebauer primaries that the CNM needs to predict keeping good prediction accuracy. The present study has focused on 3-colorant prediction by the CNM. For the prediction by $3^3 = 27$ and $4^3 = 64$ primaries, all sets of area coverages have been calculated for each colorant, including 0%, 12.5%, 25%, 37.5%, 50%, 62.5%, 75%, 87.5%, and 100%. Further, the YNNM has been modified taking into account dot gain in a coated paper for the present-day dye-based IJ.

Predicting Models

Yule-Nielsen[6] modified the NM[7] that has been widely used for modeling binary color printers to predict results in the presence of light scattering. The YNNM is written as follows:

$$\hat{R}_\lambda(\lambda) = \left(\sum_i p_i R_{\lambda,i,\max}^{1/n}(\lambda) \right)^n \quad (1)$$

where $\hat{R}_\lambda(\lambda)$ is the predicted spectral reflectance, $R_{\lambda,i}(\lambda)$ represents the measured spectral reflectance of Neugebauer primaries, and n is the Yule-Nielsen factor. Typically n is determined through minimizing some metrics such as ΔE_{94} or spectral reflectance RMS error. p_i is the weight applied to the i^{th} Neugebauer primary. If the dot locations for colorants are placed using a random or rotated screen,[8,9] the Demichel equation[10] is assumed to hold, and the primary set is shown below for a set of 2 colorants:

$$\begin{aligned} p_1 &= (1 - a_{colorant(1)})(1 - a_{colorant(2)}) \\ p_2 &= a_{colorant(1)}(1 - a_{colorant(2)}) \\ p_3 &= (1 - a_{colorant(1)})a_{colorant(2)} \\ p_4 &= a_{colorant(1)}a_{colorant(2)} \end{aligned} \quad (2)$$

where $a_{colorant}$ is the area covered by primary colorant. This area can often be calculated by regression.

To better predict reflectance, the CNM[11] restricts the effective area coverage used by the NM within narrow limits geometrically as shown in Fig. 1, and in Eq. 2 it can be written as follows:

$$a'_{eff} = \frac{a_{eff} - a_{eff,lower}}{a_{eff,upper} - a_{eff,lower}} \quad (3)$$

where a'_{eff} is normalized effective area coverage based on the upper and lower bounding area coverage of the cell.

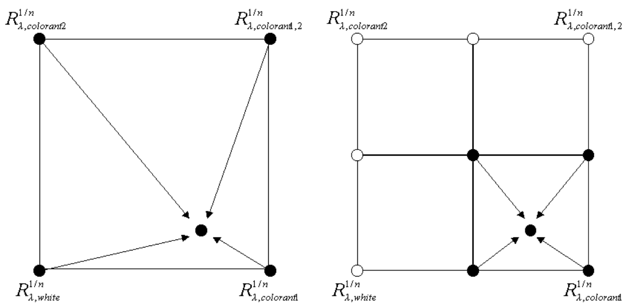

Figure 1. Illustration of two-colorant model. Left side is the NM that has 4 primaries and area coverages of 0% and 100%. Right side is the CNM that has 3^2 = 9 primaries and area coverages of 0%, 50%, and 100%. Solid circles show the Neugebauer primaries.

Experimental Results

A CANON S900 was used as a dye-based IJ. Its printing resolution is $1200dpi \times 1200dpi$. In this present study, three inks: cyan (C), magenta (M), and yellow (Y), and a coated paper (Professional Photo Paper) were used. A GretagMacbeth SpectroScan spectrophotometer was used to make all the spectral measurements. The predicting models described above were used and compared for YNNM ($n = 10.0$) and CNM ($n = 10.0$)

3-Colorant Prediction by the CNM

In the previous study[5], the CNM only resulted in the target prediction accuracy of $\Delta E_{94} \cong 1.0$ when the number of primaries was 5^N. Area coverages of 0%, 25%, 50%, 75%, and 100% were selected for each colorant.

The purpose of this study is to decrease the number of primaries (less than 5^N) and keep the present prediction accuracy. This study has focused on 3-colorant prediction by $3^3 = 27$ and $4^3 = 64$ primaries, and all sets of area coverages at detailed intervals of 12.5% have been calculated for each colorant: 0%, 12.5%, 25%, 37.5%, 50%, 62.5%, 75%, 87.5%, and 100%. Optimization of area coverage has been obtained by minimizing ΔE_{94} and RMS. 400 random printed samples that were composed of C, M, and Y were used. The results are summarized in Table 1 and Figs. 2 to 4.

It can be seen in Table 1 that optimum $4^3 = 64$ primaries[*1] arrived at sufficient prediction accuracy as $\Delta E_{94} \cong 1.0$ and $RMS \cong 0.009$. However, optimum $3^3 = 27$ primaries[*2] could not achieve the same level of prediction accuracy. A decrease from four to three in Y primary ($4 \times 4 \times 3 = 48$ primaries)[*3] improved the target prediction accuracy with $\Delta E_{94} \cong 1.17$ and $RMS \cong 0.009$. Further, prediction by $4^3 = 64$ primaries could get a performance of $\Delta E_{94} \cong 1.19$ and $RMS \cong 0.009$ when each colorant had the same area coverage of 0%, 25%, 62.5%, and 100%.

Table 1. 3-colorant prediction accuracy by the CNM

The set of primaries	$4^3 = 64$	$3^3 = 27$	$4 \times 4 \times 3 = 48$
Average ΔE_{94} D65	1.00	1.62	1.17
Standard deviation	0.56	1.00	0.75
Maximum	3.52	4.68	4.46
Minimum	0.15	0.18	0.22
Average ΔE_{94} A	1.08	1.74	1.17
RMS spectral error	0.009	0.016	0.009

The sets of area coverages are shown below:

*1. (C M Y) = (0%, 25%, 62.5%, 100%) (0%, 50%, 75%, 100%) (0%, 25%, 62.5%, 100%)

*2. (C M Y) = (0%, 50%, 100%) (0%, 62.5%, 100%) (0%, 62.5%, 100%)

*3. (C M Y) = (0%, 25%, 62.5%, 100%) (0%, 50%, 75%, 100%) (0%, 62.5%, 100%)

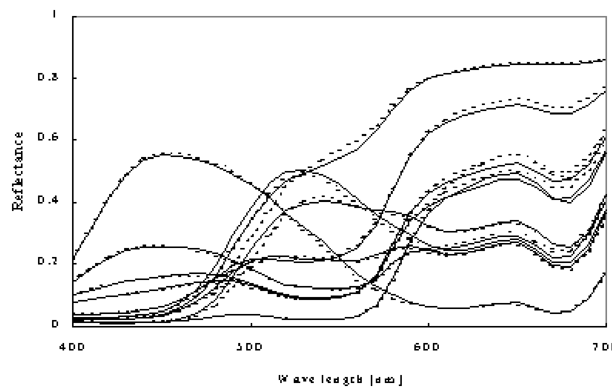

Figure 2. Measured spectral reflectances (solid lines) and predicted spectral reflectances obtained by the CNM used 4x4x4 primaries (dotted lines) for 10 examples out of 400 samples.

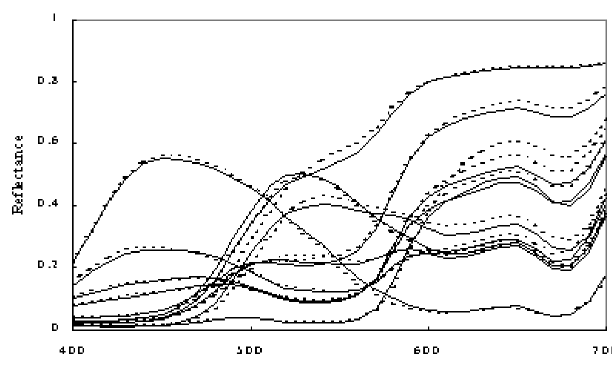

Figure 3. Measured spectral reflectances (solid lines) and predicted spectral reflectances obtained by the CNM used 3x3x3 primaries (dotted lines) for 10 examples out of 400 samples.

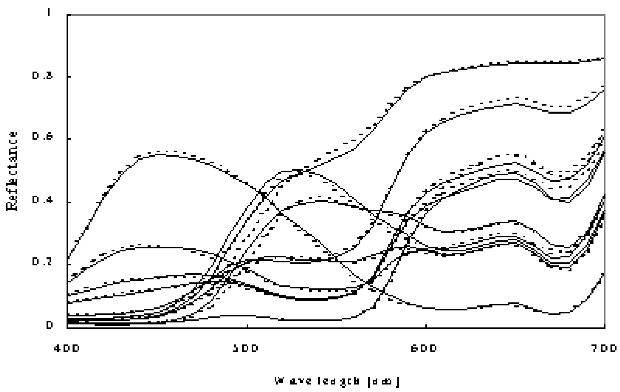

Figure 4. Measured spectral reflectances (solid lines) and predicted spectral reflectances obtained by the CNM used 4x4x3 primaries (dotted lines) for 10 examples out of 400 samples.

A Limitation of Prediction by the YNNM

For 3-colorant precise prediction, the CNM needs at least $4 \times 4 \times 3 = 48$ primaries. However, if it is not necessary to achieve sufficient prediction accuracy, the YNNM that needs $2^3 = 8$ primaries can easily predict reproduced tristimulus values. For example, prediction accuracy of 33-step ramps of cyan (C) is $\Delta E_{94} \cong 4.00$ and $RMS \cong 0.032$.

The dot diameter of the used IJ is $40\mu m$ [12], so the area of a droplet on the paper can be calculated by the equation of $\pi r^2 = \pi \times \left(20 \times 10^{-3}\right)^2$. Dot area factor af is defined as the area covered by printed dots, and hence the dot area factor of the 100% area coverage for 1200 dots per inch is written as follows:

$$af = \frac{1200 \times 1200 \times \pi r^2}{25.4 \times 25.4} = 2.80 \qquad (4)$$

The relationship between dot area factor and the values of ΔE_{94} and spectral reflectance RMS error has been studied for prediction of 33-step ramps of each colorant and is shown in Fig. 5. The Neugebauer primary was taken as spectral reflectance of each dot area factor. It can be seen in Fig. 5 that when the value of $af \leq 2.0$, it is possible to achieve prediction accuracy of $\Delta E_{94} \leq 1.0$ and $RMS \leq 0.010$.

Prediction of 33-step Ramps by the Modified YNNM

Base on the result above, it is impossible for the YNNM to precisely predict reproduced tristimulus values, when dot area factor is more than 2.0. It is assumed that only the Yule-Nielsen factor cannot correct dot gain in this area that changes from halftoning to continuous tone. Therefore, a predicting model is proposed by taking into account dot gain. The modified YNNM is written as follows:

$$D'_{\lambda,i}(\lambda) = 1.0 - \left(1.0 - D_{\lambda,i}(\lambda)\right)^b \qquad (5)$$

$$b = f(c) \qquad (6)$$

$$R'_{\lambda,i}(\lambda) = 10^t, t = -D'_{\lambda,i}(\lambda) \qquad (7)$$

$$\hat{R}_{\lambda}(\lambda) = \left(\sum_i p_i \left(R'_{\lambda,i}(\lambda)\right)^{1/n}\right)^n \qquad (8)$$

where $D_{\lambda,i}(\lambda)$ is the measured spectral density of the Neugebauer primary, $D'_{\lambda,i}(\lambda)$ is the modified spectral density of the Neugebauer primary, and $R'_{\lambda,i}(\lambda)$ is the modified spectral reflectance of the Neugebauer primary. The value of b can be obtained by the Simplex method through minimizing spectral reflectance RMS errors, and the same value is used for each colorant unless dye concentration of each colorant is greatly different. The values of b and $D'_{\lambda,i}(\lambda)$ after normalizing to 1.0 peak density are shown in Figs. 6 and 7.

Compared with the result obtained by the YNNM ($\Delta E_{94} \cong 4.00$), the modified YNNM achieved a good performance in Table 2.

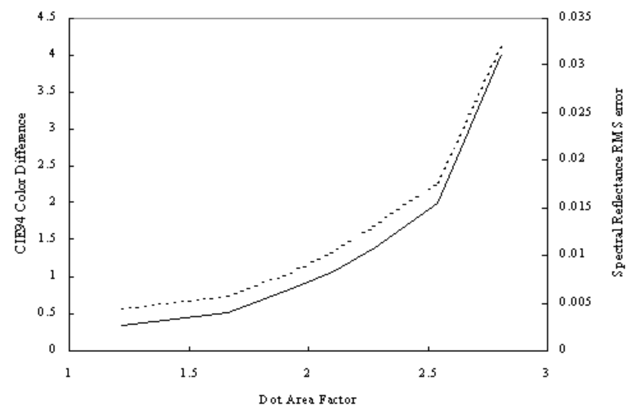

Figure 5. The relationship between dot area factor and ΔE_{94} (solid line) and RMS (dotted line).

Table 2. Prediction accuracy of 33-step ramps by the modified YNNM

The set of primaries	C	M	Y
Average ΔE_{94} D65	1.45	0.94	0.65
Standard deviation	0.59	0.47	0.27
Maximum	2.47	1.54	0.98
Minimum	0.28	0.12	0.18
Average ΔE_{94} A	1.54	0.74	0.67
RMS spectral error	0.011	0.011	0.015

Conclusion

For 3-colorant prediction by the CNM, the set of optimum $4^3 = 64$ primaries achieved the target prediction accuracy of $\Delta E_{94} \cong 1.0$ and $RMS \cong 0.009$. A decrease from four to three in Y primary ($4 \times 4 \times 3 = 48$ primaries) resulted in the reduced target prediction accuracy with metrics values as $\Delta E_{94} \cong 1.17$ and $RMS \cong 0.010$. Further, the set of $4^3 = 64$ primaries achieved a performance of $\Delta E_{94} \cong 1.19$ and $RMS \cong 0.009$ when each colorant has the same area coverages of 0%, 25%, 62.5%, and 100%. Based on the results above, the CNM can precisely predict reproduced tristimulus values when the set of primaries is more than 4^N, and area coverages of each colorant are selected at the same intervals for a dye-based IJ.

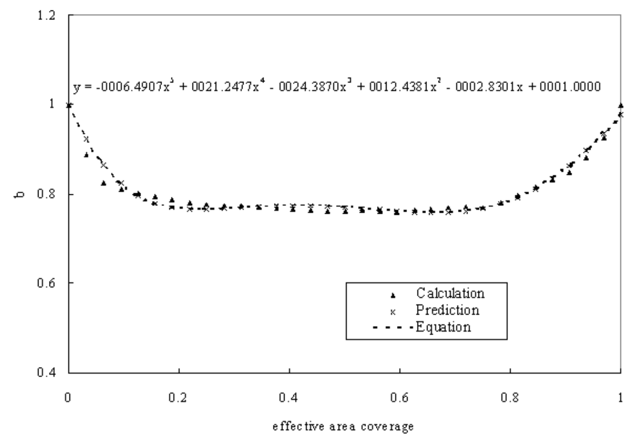

Figure 6. The value of b obtained by the Simplex method.

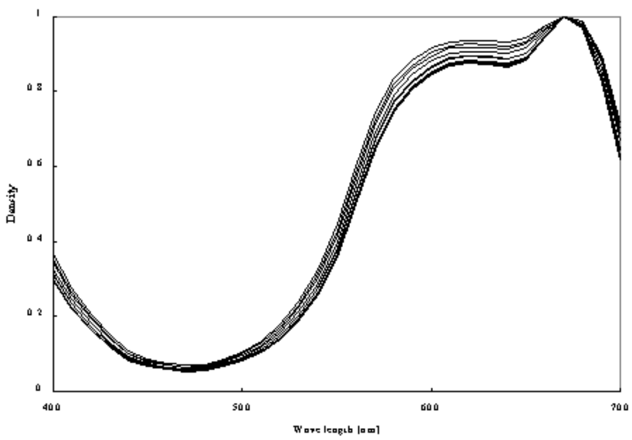

Figure 7. Modified spectral density distributions of 12-step ramps of C after normalizing to 1.0 peak density.

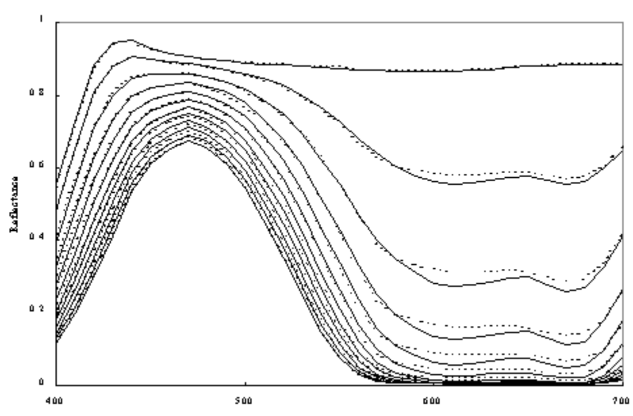

Figure 8. Measured spectral reflectances (solid lines) and predicted spectral reflectances obtained by the modified YNNM (dotted lines) for 12 examples out of 33-step ramps.

For prediction of 33-step ramps, the YNNM could not precisely predict reproduced tristimulus values from ink amounts, when dot area factor is more than 200%. Therefore, the modified YNNM was proposed by taking into account dot gain. For prediction of 33-step ramps, the modified YNNM got a good performance of $\Delta E_{94} \cong 1.01$ and $RMS \cong 0.012$. As a result of the present study, the predicting model for a dye-based IJ should use the CNM with 4^N primaries and the modified YNNM with 2^N primaries depending on the case.

Acknowledgement

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Biography

Takayuki Ogasahara received his BS and MS degrees in nuclear engineering from Nagoya University in 1994 and 1996. Since then, he has been employed at CANON INC. in VITD Lab. His work has primarily focused on the development of image processing, including optimization of subtractive color dyes, halftoning, and image quality issues. He developed some inkjet printers such as S900 and S9000. He is a member of the IS&T, and a visiting scientist at Rochester Institute of Technology. E-mail: Takayuki0513@aol.com