Estimation of the Neugebauer Model of a Halftone Printer and Its Application

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Abstract

For color output devices of printing, the halftone printing technique is widely used to implement color printers. In this paper, the modeling problem of a halftone printer is studied. We use an optimization algorithm and an interpolation method to solve the modeling problem. The result is applied to softproof.

Introduction

Based on the Spectral Yule-Nielsen modified Neugebauer equation, the modeling problem can be solved by the sequential quadratic programming (SQP) method. With linear interpolation, we form a 4-D look-up table for the color patches on IT8.7/3 test chart. This leads an low average error 1.3212 and a successful application of softproof.

Basic Theory and Motivation

Based on the additive characteristics of light reflectance, the main theory of the Neugebauer equations[1] is that the total reflectance of color mixing is the sum of each of Neugebauer primary colors weighted by its relative area. Due to the effects of the penetration of light into the paper and multiple reflectance within the paper, the Neugebauer equation is not good enough to satisfy the measurement data. In order to consider those factors, Yule and Nielsen modified the primary Neugebauer equation and the spectral Yule-Nielsen modified Neugebauer equation is

$$R_{total}^{(1/n)}(\lambda,C,M,Y,K) = \sum_{i=1}^{16} A_{w(i)}(C,M,Y,K) R_{w(i)}^{(1/n)}(\lambda)$$

where n is the Yule-Nielsen value and $R_{total}(\lambda,C,M,Y,K)$ is the spectral reflectance of the color mixing at wavelength λ for any, fixed C, M, Y, and K values. The term $R_{w(i)}(\lambda)$ is the spectral reflectance that is measured with respect to the i-th primary color at wavelength λ of 100% area and $A_{w(i)}(C,M,Y,K)$ is the relative dot areas of the i-th primary color for any fixed C, M, Y, and K values, and w = [p, c, m, y, r, g, b, cmy, k, ck, mk, yk, rk, gk, bk, cmyk].

Based on the Neugebauer equations, there have had many studies for various types of Neugebauer models. In the application of color mixing models of a halftone color printer, Henry R. Kang[3] shows that the Neugebauer model is a suitable color mixing theory for a halftone color printer. Robert and Raja investigate the accuracy of various types of Neugebauer models in predicting the colorimetric response of a halftone color printer. Robert and Raja[4] investigate the accuracy of various types of Neugebauer models in predicting the colorimetric response of a halftone color printer. Their experimental results show that the model based on the Yule-Nielsen modified Neugebauer equation always has a better prediction performance.

For those experiments of various types of Neugebauer model, the Demichel's dot overlap model is usually employed to calculate the areas of Neugebauer primary colors. However, the Demichel's idea do not always match the pixel patterns of a halftone color printer. In Figure 1, we show the situation where the Demichel's dot overlap model may fail for some pixel patterns of a halftone two-color printer.
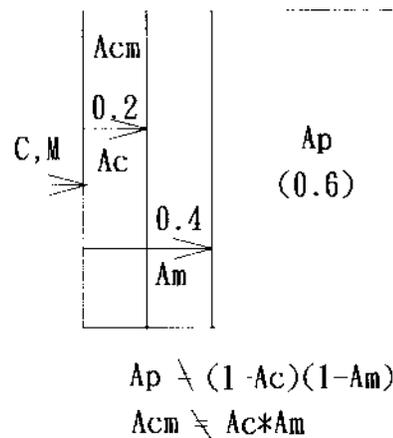

Figure 1. The Demichelë's law is not suitable in this printing pattern.

By considering six possible patterns, S.L. Chang[5] has proposed a method to calculate the areas of

Neugebauer Primary Colors (NPAs) based on the Newton's minimization method and reduced the average error $\Delta E^* ab$ to 1.82. In order to relax the assumptions of possible printing patterns and reduce computation complexity for the optimization problem proposed in S.L. Chang, we shall reform another optimization problem to estimate the NPAs. We estimate the areas of the Neugebauer primary colors for the spectral Yule-Nielsen modified Neugebauer equations based on the sequential quadratic programming (SQP) method.[6] In order to reduce the scale of the optimization problem, we set a suitable constraint which will be described later.

In our experiment, we employ an SQP algorithm to estimate the areas of Neugebauer primary colors of the 163 sampled color patches. Then, for the overall IT8.7/3 test chart, we build a 4-D look-up table between the values (C, M, Y, K) and the areas of Neugebauer primary colors instead of Demichel's dot overlap model. With respect to the IT8.7/3 test chart, we reduce the average prediction error ΔE^*ab to 1.3212, standard deviation of ΔE^*ab to 0.7033 and maximum of ΔE^*ab to 4.9496 respectively.

Experimental Setting

Our objective is to estimate the Neugebauer model of a four-color halftone printing device. The printer under test is the Fuji Color Art. A total 163 color patches chosen from the IT8.7/3 test chart are printed by this printer. The 163 sample colors are chosen as the combination of [K∈{0,20}, C,M,Y∈ {0,40,70,100}], [K∈{60}, C,M,Y∈ {0,40,100}] and [K∈{100},C,M,Y∈{0,100}]. We then use a spectrodensitometer, X-Rite 938, to measure the spectrum and tristimulus values for these 163 printed samples. The spectral data for each sampled color patch is measured from 400nm to 700nm with frequency interval 10nm. Thus the spectral data of each color patch consists of 31 points.

Formulation of Optimization Problem For Model Estimation

In this section, we formulate an optimization problem to estimate the areas of Neugebauer primary colors. For simplicity of notation, we shall use A_i as the abbreviation of $A_{w(i)}(C,M,Y,K)$. We denote the sum of the areas containing cyan ink as A_c; similarly, the sum of the areas of the magenta, yellow, and black ink are represented by $\overline{A}_m, \overline{A}_y, \overline{A}_k$. Finally, we define $\overline{A}_{c,ideal}$ as the ideal dot area which is occupied by cyan ink. Similarly, $\overline{A}_{m,ideal}$, $\overline{A}_{y,ideal}$, $\overline{A}_{k,ideal}$ are defined as the ideal dot areas that are occupied by magenta, yellow, and black inks respectively. For example, if the input valve of C (Cyan) is 20, then $\overline{A}_{c,ideal}$ will be 0.2.

Estimation of Optimization Problem For Model Estimation

For any fixed C, M, Y, K values, the NPAs of the printed color patch will be estimated based on the spectral Yule-Nielsen modified Neugebauer equation:

$$R_{total}^{(1/n)}(\lambda,C,M,Y,K) = \sum_{i=1}^{16} A_{w(i)}(C,M,Y,K) R_{w(i)}^{(1/n)}(\lambda)$$

$$= A_1 * R_p^{(1/n)}(\lambda) + A_2 * R_p^{(1/n)}(\lambda) + \cdots\cdots + A_{16} * R_{cmyk}^{(1/n)}(\lambda)$$

For any fixed sampled color, we define the matrices A, B and Q as:

$$B(C,M,Y,K) = \begin{bmatrix} R_{total}^{(1/n)}(\lambda_1,C,M,Y,K) \\ R_{total}^{(1/n)}(\lambda_2,C,M,Y,K) \\ \vdots \\ R_{total}^{(1/n)}(\lambda_m,C,M,Y,K) \end{bmatrix}$$

$$Q = \begin{bmatrix} R_p^{(1/n)}(\lambda_1) R_c^{(1/n)}(\lambda_1)\cdots\cdots R_{cmyk}^{(1/n)}(\lambda_1) \\ R_p^{(1/n)}(\lambda_2) R_c^{(1/n)}(\lambda_2)\cdots\cdots R_{cmyk}^{(1/n)}(\lambda_2) \\ \vdots \\ R_p^{(1/n)}(\lambda_m) R_c^{(1/n)}(\lambda_m)\cdots\cdots R_{cmyk}^{(1/n)}(\lambda_m) \end{bmatrix}$$

$$A = \begin{bmatrix} A_1, A_2, \cdots\cdots A_{16} \end{bmatrix}^T$$

Now, with the Spectral Yule-Nielsen equations, we can formulate the optimization problem for any fixed C, M, Y, and K value as follow:

$$\arg\min_A \frac{1}{2}\|QA - B\|_2^2$$

Subject to the following constraints
Constraint 1. $0 \le i \le 1$; i = 1, • • •,16
Constraint 2. A1 + A2 + • • • • • • + A16 = 1
Constraint 3.

$$\left|\overline{A}_c - \overline{A}_{c,ideal}\right| \le \varepsilon * \overline{A}_{c,ideal}$$

$$\left|\overline{A}_m - \overline{A}_{m,ideal}\right| \le \varepsilon * \overline{A}_{m,ideal}$$

$$\left|\overline{A}_y - \overline{A}_{y,ideal}\right| \le \varepsilon * \overline{A}_{y,ideal}$$

$$\left|\overline{A}_k - \overline{A}_{k,ideal}\right| \le \varepsilon * \overline{A}_{k,ideal}$$

where ε is a small number. In our experiment, ε is set as 0.05.

For the above optimization problem with fixed Yule-Nielsen value n, there are several methods, such as methods of Penalty and Barrier function and feasible directions,[7] to estimate the area vector A. Here, among the methods of feasible directions, we employ the sequential quadratic programming (SQP)[8] method that has more high successive and convergent rate to solve the optimization problem. The overall optimization program consists of an inner loop and an outer loop. For a fixed Yule-Nielsen value n, the inner loop uses the SQP method to estimate the NPAs of the sampled color patches. Then a line search method, such as bisection method, is used in the outer to loop find the best value n loop which results in the lowest fitting error.

Construction of a 4-D Look-up Table

By the optimization method, we can establish the relationships between the (C,M,Y,K) value and their NPAs for the 163 sample colors. However, on the IT8.7/3 test chart, the relationships for the remaining 591 colors are still unknown. Therefore we use the 3-D cubic division[9] to linearly interpolate the data and construct a 4-D look-up table so the overall relationships between the (C,M,Y,K) value and their NPAs for all the colors on the test chart can be constructed.

Results of Prediction

We use 754 sample colors of the IT8.7/3 test chart to evaluate the performances of the 4-D look-up table for the transformation from CMYK to NPAs for the half-tone printer under test. For a fixed set of values (C,M,Y,K) on the test chart, i.e. for a fixed color patch, we can use the look-up table to estimate its spectral reflectance distribution based on spectral Yule-Nielsen modified Neugebauer equation. The estimated spectral reflectance distribution can then be used to calculate a set of estimated Cibola color coordinates. On the other hand, we can use a spectrodensitometer to obtain the spectral data and a set of measured CIELab color coordinates for the specified color patch. The error between the measured and the estimated CIELab color coordinates can be used to validate the 4-D look-up table. This type of error is usually called CIELab error denoted by ΔE^*ab. The analysis of ΔE^*ab for all the color patches will be helpful for understanding the distortion of the tested halftone printer from human color perception. We calculate the average, maximum, and standard deviation of the ΔE^*ab error from the 754 samples of the IT8.7/3 target. The results are shown in Table 1.

Table 1. Average, Maximum and Standard deviation of CIE L*a*b* ΔEab errors based on the spectral Yule-Nielsen modified Neugebauer equations.

YN value (n)	ΔE^*_{avg}	ΔE^*_{max}	ΔE^*_{STD}
Spectral Yule-Nielsen model	1.3212	4.9496	0.7033

In this case, we get the average ΔE^*ab error as 1.3212, and the maximum ΔE^*ab error 4.9496, and the standard derivation 0.7033. The histogram of the ΔE^*ab error based on the spectral Yule-Nielsen modified Neugebauer equations is Figure 2.
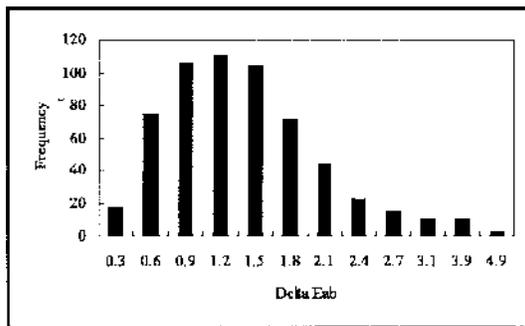

Figure 2. The histogram of the DE*ab error

In the application of the spectral Yule-Nielsen modified Neugebauer equations, Henry R. Kang[3] had used the Demichel's law for the calculation of NPAs and get the average error of CIELab as 10.60. Robert and Raja[4] had also applied the Demichel's law in the spectral Yule-Nielsen modified Neugebauer equation and obtained the minimum average error of CIELab as 2.6.

An Application to Softproof

In previous section, we have constructed a 4-D look-up table for transformation from (C,M,Y,K) values to NPAs. Now we use the constructed look-up table for softproof such that an printed image, produced by Fuji Color Art, and a related displayed file on CRT colorimetrically match as close as possible.

In our application, the white point of the printed image is X = 75.9866, Y = 79.7659, and Z = 86.5788 based on the D65 illuminate. We also have measured the white point of CRT as x = 0.348, y = 0.338, and Y = 95.3, then the X, Y, and Z values of the printed image were translated to the X, Y, and Z values of the CRT based on the CIELab model. Based on the setting, a printed image and two displayed images were generated. One of the displayed images is corrected using the two look-up tables mentioned above. The other is generated by directly transforming the (C,M,Y,K) values to (R,G,B) values and sent to the CRT. By visual match, it shows that the look-up table (LUT) of our experiment has effectively improved the accuracy in the color appearance of cross-media. The results can be used to attain the objective of WYSIWYG (What You See Is What You Get). Here, we just briefly introduce the application of softproof based on our experimental results. The study on color appearance of cross media can be referred to Mei-Chun Lo.[10]

Conclusion and Discussion

In this paper, based on the Spectral Yule-Nielsen modified Neugebauer equation, we use the SQP optimization method to estimate the NPAs of the sampled color patches. A 4-D look-up table is further constructed to represent the model of a halftone printer. For the IT8.7/3 test chart, our method results in a low average prediction error. The average error ΔE^*ab is 1.3212 when the spectral Yule-Nielsen modified Neugebauer equation is applied. We also apply our experimental results to softproof and have effectively promoted the accuracy of color reproduction for an image displayed by a CRT and that printed by a particular color printer.

We have constructed a look-up table for transformation from (C,M,Y,K) to NPAs for a tested printer. In the future, we need to construct a function or a mapping from (C,M,Y,K) to (L,a,b) to represent the model of a halftone printer from human color perception viewpoint. This is an important research topic for color reproduction and development of color management system.

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