Simple Spectral Color Prediction Model using Multiple Characterization Curves

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effective coverage map

Abstract

Color prediction models are of high interest for color printing industry. Our previous work proposed a simple color prediction model which used an effective coverage map based on CIEXYZ. By applying the model to different printers and halftoning methods we verified the good performance of the method. Considering the requirement of accurate spectral or reflectance match in the digital printing industry, an investigation to extend our basic color prediction model form CIEXYZ to spectral data is presented in this paper. The whole procedure is simple to understand and easy to be carried out. The experiments show that the extended model works well in predicting the spectrum of a specific combination of printed inks.

Introduction

Color prediction is an important part of the color reproduction. The typical application of color prediction includes print device calibration, investigation of the behavior of print process, as well as color management. Various color prediction models have been proposed in literature (Wyble, 2000). The simplest models are based on Murray-Davies and Neugebauer Model. The Yule-Nielsen model (Ruckdeschel, 1978; Viggiano, 1990) is a very popular model which was improved and modified by many researches since it was presented. The improved and modified by many researches since it was presented. The improved Yule–Nielsen Modified Spectral Neugebauer Model is a well known model (Hersch, 2005) amongst the refined models. Other models based on analysis of the actions of light and substrates, such as Clapper-Yule model (Clapper and Yule, 1953), Kubelka-Munk model (Emmel and Hersh, 1999) etc, have also been proposed.

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Since dot gain has a great impact on the print result, it is a crucial part of color prediction models. Dot gain composes of physical and optical dot gain, physical dot gain refers to ink spreading while optical dot gain is due to the light scattering (Namedanian and Gooran, 2011). In Yule-Nielsen Model, an exponent, which is also referred to as the n-factor, is used to numerically simulate the optical dot gain. Since the spectral reflectance measured by physical instruments includes the effects of both optical and physical dot gain, the n-factor practically is a fitting factor and sometimes it is hard to obtain an optimal n- factor to make the model match the measurement data.

A simple and new color prediction approach was proposed in our previous work (Gooran, et al., 2009). In that basic model, for each involved ink (cyan, magenta or yellow) three characterization curves were obtained by CIEX, CIEY and CIEZ values, which differentiates our basic model from most of the other dot gain related models that using single dot gain curve. By using the three characterization curves, the effective coverage corresponding to reference coverage are obtained by interpolation. Then Demichel's equations (Demichel, 1924) are used to figure out the effective coverage of primary and secondary colors involved in the color patch. Then by using the simple Neugebauer equation we can predict the printed color.

However, according to our previous experiments, the effective coverage of a certain amount of primary ink changes without obeying any observable rule when ink superposition happens (Qu and Gooran, 2011). By using several training patches, an effective coverage map was created to characterize the effective coverage values of the involved inks with higher accuracy. How to build this effective coverage map was introduced in our previous papers (Qu and Gooran, 2012a, 2012b).

In this work, the extension of our color prediction model to a spectral color prediction model is presented. More than three characterization curves based on the spectral data at different wavelength bands are used. This means that the visible wavelength interval is divided into more than three subintervals. For each subinterval one effective characterization curve is defined based on Murray-Davies equation. The effective coverage map is also applied to the spectral form to investigate the accuracy of our spectral color prediction model.

One motivation to extend our model from color (CIEXYZ or CIELab) prediction to spectral prediction is that spectral or reflectance match ensures the color equivalence and avoids the problem with metameric match. A correct and reliable spectral prediction model provides advanced color separation for multi spectral color reproduction.

In the following text, a brief introduction of the model based on CIEXYZ will be given at first, and then how to extend the model to spectral form is described. Finally, the experiments that were carried out to evaluate the extended model are described and the results are illustrated.

Color prediction Model Based on CIEXYZ

In order to characterize the dot gain behavior of the primary ink printed on paper (single ink print) Equation (1) is used. This equation is used for a cyan patch with a reference coverage of cref. Similar equations are used for magenta and yellow.

$$
\begin{aligned}
Xc_{mea} &= c_{eff}^{X} \cdot X_c + (1 - c_{eff}^{X}) \cdot X_p \\
Yc_{mea} &= c_{eff}^{Y} \cdot Y_c + (1 - c_{eff}^{Y}) \cdot Y_p \\
Zc_{mea} &= c_{eff}^{Z} \cdot Z_c + (1 - c_{eff}^{Z}) \cdot Z_p
\end{aligned}
\qquad (1)
$$

Where c_{eff}^{X}, c_{eff}^{Y} and c_{eff}^{Z} are the effective coverage of cyan corresponding to the reference coverage value c_{ref}. X_p, Y_p and Z_p are CIEXYZ tri-stimulus value of paper. Xc, Yc and Zc are CIEXYZ tri-stimulus value of full tone cyan. The measured CIEXYZ values of each halftone cyan patch are Xc_{mea}, Yc_{mea} and Zc_{mea}.

If a group of cyan patches with reference coverage c_{ref} increasing from 0 to 100% are available, the measurement data of them enable us to obtain three different characterization curves for cyan. Similarly, three characterization curves are obtained for magenta or yellow.

Instead of using an optimized single dot gain curve together with the n-factor, the three curves introduced above were used taking into account the fact that in the measurement of CIEXYZ values, there is actually optical dot gain included in the data.

Hence the calculated c_{eff}^{X}, c_{eff}^{Y} and c_{eff}^{Z} for a certain c_{ref} include both physical and optical dot gain. The difference between calculated c_{eff}^{X}, c_{eff}^{Y} and c_{eff}^{Z} for a certain c_{ref} proves that it is not completely correct to define only one characterization curve for each ink to be used in Neugebauer's equations when calculating the resulting colour values.

The three characterization curves for cyan enable us to calculate the effective coverage of cyan corresponding to any reference coverage c_{ref} by interpolation. However, as mentioned before when cyan is printed together with magenta or yellow or both, the effective coverage of cyan may vary irregularly. The effective coverage map was then proposed aiming to figure out correct effective coverage for each involved ink (Qu and Gooran, 2012a). The map is put in a coordinate system whose three axes refer to the reference ink coverage of the three primary inks. Therefore each point in the coordinate system presents a color patch and its three coordinates correspond to the three reference ink coverage. If we choose some training points in this coordinate system and fill them with 9 values which are the reliable three effective coverage values for each ink based on CIEX, Y, Z respectively

(c^X_{eff}, c^Y_{eff}, c^Z_{eff}, m^X_{eff}, m^Y_{eff}, m^Z_{eff} and y^X_{eff}, y^Y_{eff}, y^Z_{eff}), is built. Given any ink combination, the effective coverage of each ink based on CIEX, Y, Z could be estimated and used to predict the CIEXYZ values of the color resulted from the given ink combination.

Color prediction Model Based on Spectral data

Since CIEX, Y and Z approximately stand for three special wavelength bands along the visible wavelength interval, the extension of our model from CIEXYZ to the spectral form is carried out by applying several spectral data at certain wavelength subintervals instead of CIEX, Y and Z. The used spectral data have their wavelength range from 380 nm to 730 nm by step of 10 nm in this paper; therefore thirty six dot gain characterization curves are used.

Replacing CIEXYZ values with spectral data R which consists of thirty six subintervals, Equation (1) becomes Equation (2), where we take magenta instead of cyan as the example.

$$R^i_{mea} = m^i_{eff} \cdot R^i_m + (1 - m^i_{eff}) \cdot R^i_p \qquad i = 1, 2, 3, \ldots, 36 \tag{2}$$

(R^1_{mea}, R^2_{mea}, ..., R^{36}_{mea}) are the measured spectra of a halftone magenta patch; are the measured spectra (R^1_m, R^2_m, ..., R^{36}_m) of the full-tone magenta while(R^1_p, R^2_p, ..., R^{36}_p) are the measured spectra of unprinted paper. (m^1_{eff}, m^2_{eff}, …, m^{36}_{eff}) are the effective coverage of magenta corresponding to each wavelength subinterval.

In order to obtain the characterization curves based on spectral data for a certain ink, say magenta, a number of magenta patches with different reference coverage values are printed. Equation (2) is used to calculate the values of (m^1_{eff}, m^2_{eff}, …, m^{36}_{eff}) for each patch with a certain reference coverage m_{ref}. Figure 1 shows the measured spectrum of full tone magenta (left) and the characterization curves for magenta when it is printed on paper (right). The used spectral data are at thirty six subintervals in this case. To have an unambiguous illustration, Figure 1 only presents six curves, of which two are picked from short (430nm, 450nm, red curves), two from medium (530nm, 570nm, green curves) and two from longer (660nm, 670nm, blue curves) wavelength bands respectively. It is shown that the characterization curves behave differently at different wavelength sub-intervals; for magenta, the characterization curves at medium wavelength bands have more dot gain than that at short or longer wavelength bands. The thirty six characterization curves for cyan and yellow can be obtained similarly.

In our model, we use all the thirty six curves to predict the spectrum of the printed color. When there is only one primary ink involved, given any reference coverage of the primary ink, we can calculate the possible effective coverage by interpolation along these curves.

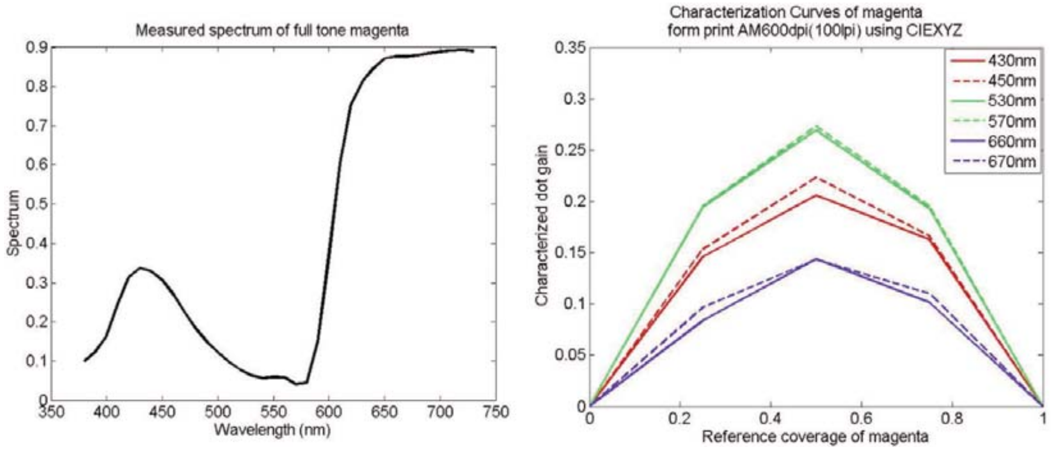

Figure 1. *Left, the measured spectrum of full tone magenta; Right, characterization curves using spectral data for magenta printed by a laser printer using AM600dpi_100lpi (only six curves are illustrated here).*

When more inks are involved, two approaches are applied to predict the test color. The first approach is to use the thirty six characterization curves of each ink directly, ignoring ink superposition. We call this approach 'based on spectrum, without effective coverage map '. The second approach applies the effective coverage map in the spectral form. The mapping based on spectral data for each training point in the effective coverage map is similar to that using CIEXYZ values which was described in references (Qu and Gooran, 2012a, 2012b). The mapping based on CIEX was carried out by matching the values of c_{eff}^{X}, c_{eff}^{Y} and c_{eff}^{Z} (for simplicity, only the calculation using CIEX values is presented here) under certain assumption to fulfill Equation (3). The calculation was carried out three times using CIEX, Y and Z values respectively.

$$\begin{aligned}
&c^{X} = c_{eff}^{X} \bullet (1-m_{eff}^{X}) \bullet (1-y_{eff}^{X}) && m^{X} = m_{eff}^{X} \bullet (1-c_{eff}^{X}) \bullet (1-y_{eff}^{X}) \\
&y^{X} = y_{eff}^{X} \bullet (1-m_{eff}^{X}) \bullet (1-c_{eff}^{X}) && r^{X} = m_{eff}^{X} \bullet y_{eff}^{X} \bullet (1-c_{eff}^{X}) \\
&g^{X} = c_{eff}^{X} \bullet y_{eff}^{X} \bullet (1-m_{eff}^{X}) && b^{X} = c_{eff}^{X} \bullet m_{eff}^{X} \bullet (1-y_{eff}^{X}) \\
&k^{X} = c_{eff}^{X} \bullet m_{eff}^{X} \bullet y_{eff}^{X} && p^{X} = (1-c_{eff}^{X}) \bullet (1-m_{eff}^{X}) \bullet (1-y_{eff}^{X}) \\
&X_{mea} = c^{X} \bullet X_{c} + m^{X} \bullet X_{m} + y^{X} \bullet X_{y} + r^{X} \bullet X_{r} + g^{X} \bullet X_{g} + b^{X} \bullet X_{b} + p^{X} \bullet X_{p} + k^{X} \bullet X_{k}
\end{aligned} \tag{3}$$

The assumption that was set during the mapping is as follows: For a couple of training patches that have the same reference coverage of certain ink, say cyan, the corresponding effective coverage of cyan might be different from each other because of ink superposition. However for this couple of patches the effective coverage of cyan should be close to each other since they were produced by using the same amount of ink cyan.

Take the training patch (c_{ref}=0.5, m_{ref}=0.25, y_{ref}=0) as an example, and recall that c_{eff}^{X} refers to the effective coverage for cyan based on CIEX. Although c_{eff}^{X} (when c_{ref}=0.5, m_{ref}=0.25, y_{ref}=0) differs from the c_{eff}^{X} (when c_{ref}=0.5 and $m_{ref} \neq 0.25$ or $y_{ref} \neq 0$), it should be close to c_{eff}^{X} (when c_{ref}=0.5, m_{ref}=0.5, y_{ref}=0) and c_{eff}^{X} (when c_{ref}=0.5, m_{ref}=0.25, y_{ref}=0.25) because they have the same reference coverage for cyan. Similarly, the effective coverage for 25% magenta m_{eff}^{X} (when c_{ref} =0.5, m_{ref} =0.25, y_{ref} =0) differs from but should be close to m_{eff}^{X} (when c_{ref} =0.25, m_{ref} =0.25, y_{ref} =0) and (when c_{ref} =0.25, m_{ref} =0.25, y_{ref} =0.25).

In this paper Equation (3) is replaced by Equation (4) using the spectral data at a certain wavelength band which is called the *i*-th sub-interval (i =1, or 2 …or 36) in the following text.

$$\begin{aligned}
&c^i = c_{eff}^i \bullet (1-m_{eff}^i) \bullet (1-y_{eff}^i) && m^i = m_{eff}^i \bullet (1-c_{eff}^i) \bullet (1-y_{eff}^i) \\
&y^i = y_{eff}^i \bullet (1-m_{eff}^i) \bullet (1-c_{eff}^i) && r^i = m_{eff}^i \bullet y_{eff}^i \bullet (1-c_{eff}^i) \\
&g^i = c_{eff}^i \bullet y_{eff}^i \bullet (1-m_{eff}^i) && b^i = c_{eff}^i \bullet m_{eff}^i \bullet (1-y_{eff}^i) \quad i=1,2,3...36; \qquad (4) \\
&k^i = c_{eff}^i \bullet m_{eff}^i \bullet y_{eff}^i && p^i = (1-c_{eff}^i) \bullet (1-m_{eff}^i) \bullet (1-y_{eff}^i) \\
&R_{mea}^i = c^i \bullet R_c^i + m^i \bullet R_m^i + y^i \bullet R_y^i + r^i \bullet R_r^i + g^i \bullet R_g^i + b^i \bullet R_b^i + p^i \bullet R_p^i + k^i \bullet R_k^i
\end{aligned}$$

c^i, m^i, y^i, r^i g^i, b^i, k^i and p^i are the fractional coverage for the primary and secondary colors. Rimea refers to the i-th sub-interval of the measured spectrum of a certain training patch. $R^i{}_c$, $R^i{}_m$, $R^i{}_y$, $R^i{}_r$, $R^i{}_g$, $R^i{}_b$, $R^i{}_p$ and $R^i{}_k$ are the *i*-th sub-interval of the spectra for each full tone primary and secondary colors. c_{eff}^i , m_{eff}^i and y_{eff}^i are effective ink coverage values obtained in the mapping. Recall that one calculation is only dealing with certain sub-interval data, we use thirty six sub-intervals in this paper, therefore the calculation is repeated thirty six times to obtain c_{eff}^i , m_{eff}^i and y_{eff}^i i =1, 2, …, 36 for each training point in the map.

Given any reference ink combination, using the 'based on spectrum, without effective coverage map' approach, (m_{eff}^1 , m_{eff}^2 , …, m_{eff}^{36}) are obtained by interpolation along the curves shown in Figure 1 for magenta while (c_{eff}^1 , c_{eff}^2 , …, c_{eff}^{36}) and (y_{eff}^1 , y_{eff}^2 , …, y_{eff}^{36}) are obtained by interpolation along the similar characterization curves for cyan and yellow respectively.

Using the 'based on spectrum, with effective coverage map' approach,(c_{eff}^1 , c_{eff}^2 , …, c_{eff}^{36}),(m_{eff}^1 , m_{eff}^2 , …, m_{eff}^{36}) and (y_{eff}^1 , y_{eff}^2 , …, y_{eff}^{36}) are obtained by cubic interpolation in the created effective coverage map.

c^i, m^i, y^i, r^i g^i, b^i, k^i and p^i, the fractional coverage for the primary and secondary colors, are then calculated using Demichel's equations. Finally the spectrum of the test color patch $(R_{cal}^1, R_{cal}^2, ..., R_{cal}^i)$ is predicted by Equation (5).

$$R_{cal}^i = c^i \bullet R_c^i + m^i \bullet R_m^i + y^i \bullet R_y^i + r^i \bullet R_r^i + g^i \bullet R_g^i + b^i \bullet R_b^i + p^i \bullet R_p^i + k^i \bullet R_k^i \quad (5)$$

i=1,2,3...36;

Experiment and conclusion

To investigate the models based on spectral data, we used Amplitude Modulated (AM, 100lpi) halftone prints at 600dpi, and a laser printer (Xerox, Phaser 6180) with uncoated office copy paper. All prints were measured by a Spectrophotometer (BARBIERI electronic Spectro LFP RT) using d65 light source for a 2° observer. The differences between the predicted and measured values were calculated using both CIELab color difference ΔE_{94} and spectral ΔRMS.

Since our model based on CIEXYZ with an effective coverage map gives very satisfying prediction results, the results obtained by using spectral data are compared with the results obtained by using CIEXYZ data, in Table 1 and Table 2.

Totally 1248 color patches were used in this paper; they were divided into 2 teams: ‘1-2 colors (244)’ refers to those 244 patches that involve only 1 or 2 inks; ‘3 colors (1004)’ refers to the 1004 patches that involve 3 inks. The training samples used to create the effective coverage map are included in those patches. Their reference coverage value of each ink was taken from [0%, 25%, 50%, 75%, 100%], therefore they are totally 5×5×5=125 patches.

ΔE_{94}	**based on CIEXYZ, with effective coverage map**			**based on spectrum, with effective coverage map**			**based on spectrum, without effective coverage map**		
AM600dpi-100lpi	Max	Mean	>4	Max	Mean	>4	Max	Mean	>4
1-2 colors (244)	3.19	0.71	0	3.18	0.72	0	3.51	1.31	0
3 colors (1004)	4.86	1.45	10	4.91	1.41	9	7.96	2.16	103

Table 1. *The CIELab ΔE94 between measured and predicted colors*

ΔRMS	**based on CIEXYZ, with effective coverage map**		**based on spectrum, with effective coverage map**		**based on spectrum, without effective coverage map**	
AM600dpi-100lpi	Max	Mean	Max	Mean	Max	Mean
1-2 colors (244)	×	×	0.152	0.039	0.170	0.059
3 colors (1004)	×	×	0.209	0.05	0.293	0.067

Table 2. *The spectral ΔRMS between measured and predicted spectral data*

Table 1 presents the color prediction error using CIELab color difference ΔE94. It shows that with the usage of effective coverage map, the performance of the approach ‘based on spectrum, with effective coverage map’ is very close to that of the model based on CIEXYZ values. The only difference is that the spectral model uses thirty six characterization curves while the CIEXYZ based model uses only three. If no effective coverage map is used, the prediction errors of the very simple approach ‘based on spectrum, without effective coverage map’ are worse when 3 inks are involved. Without effective coverage map the prediction error of color patches with 1 or 2 inks are still acceptable.

Table 2 presents the spectral ΔRMS between measured and predicted spectrum. Since the model in our pervious papers uses CIEXYZ values only, the spectral ΔRMS was not calculated. From Table 2, it can be noticed that using the effective coverage map reduces the spectral ΔRMS. It has to be mentioned that the patch with maximum ΔE_{94} (7.96) is not the same one that has the maximum ΔRMS value (0.293). This means that big ΔE_{94} not always corresponds to big ΔRMS.

The above experiment and results show that the approach using more characterization curves and the effective coverage map proposed in our previous model are viable when the calculation is dealing with spectral data. It is therefore feasible to extend our color prediction model based on CIEXYZ to the model based on spectral data. Although the mapping using spectral data is more sensitive to printer and measurement errors, it is possible to solve it by setting certain constraints during the mapping of the effective coverage map.

The work presented in this paper enriches our simple color prediction model using multiple characterization curves for each ink, which make this model functional for both CIEXYZ values and spectral data. In our future work, the focus will be the inverse model, i.e. color separation model, as well as the development of our model when more than 3 primary inks are involved.

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