Prediction of Color in Halftone Prints using Core-Fringe Model

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Abstract

It is well known that the chromaticity coordinate points of a single ink halftone ramp are in a curve on the CIE xy chromaticity diagram. This non-linear behavior is caused by a color component, which is neither the color of paper nor the color of ink. This third component can result from both variation of ink layer thickness and light scattering in paper.

In the current study, we used a halftone dot structure model to simulate the variation of ink layer thickness and then estimated the colorimetric characteristics of single ink halftone print.

Our model assumes that a halftone dot consists of two regions. One region is a central area of the dot that has the same thickness of ink layer as that of the solid print, and is referred as “core”. The other region is the marginal area of the dot that has thinner ink layer than that of the solid print, and is referred as “fringe”. Using this model, we calculated the reflectance spectra and chromaticity coordinates for single ink halftone ramps and then compared them with the measured values. Consequently, the model could describe the non-linear behavior of single ink halftone prints as well as predict the reflectance spectra more precisely than the Murray-Davies model.

Introduction

Many models have been proposed to predict the colors of halftone images.[1] Murray-Davies model or Neugebauer model are typical linear models that are often used to characterize color printers or lithographic printing. These linear models are simple and plain for color reproduction, but have disadvantage of low accuracy of color prediction as described below.

In single ink halftone printing, one would expect that colors of printed samples be reproduced in an additive mixture of two primary colors, that is, color of ink and color of paper. Therefore the chromaticity coordinate points of the reproduced single ink halftones should be on a straight line that connects the two primary colors, the paper color and the ink color, on the CIE xy chromaticity diagram. However, it is reported that the points are actually in a curve rather than on the straight line on the chromaticity diagram.[2] This non-linear behavior suggests an existence of another color component that is involved in color reproduction of the single ink halftone, which is neither the color of paper nor the color of ink. The above linear models cannot represent this non-linearity, because they are based on linear addition of only the colors of ink and paper for single ink halftones.

Some previous studies suggest that this third component can result from mechanical and/or optical phenomena related to halftone dots.[3,4] Variation of ink layer thickness are typical of mechanical phenomena, and light scattering in ink and paper are typical of optical phenomena.

In this report we propose a model that can describe the effect of the variation of ink layer thickness on the colorimetric characteristics of single ink halftone prints and then evaluate the model performance in predicting color.

Core-Fringe Model

The halftone dot structure model we propose here is illustrated in Fig.1. This model is based on an assumption that a halftone dot consists of two regions with different thickness of ink layer. One of the regions is a central area of the dot that has the same thickness of ink layer as the solid print, and is referred as “core”. The other one is the marginal area of the dot that has thinner ink layer than the solid print, and is referred as “fringe”. In this model, the spectral reflectance, $R(\lambda)$, of a halftone tint can be expressed as follows,

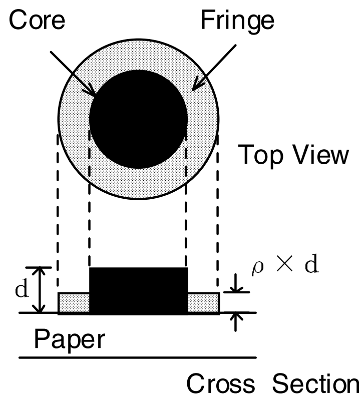


Figure1. Halftone dot structure of core-fringe model

$$R(\lambda)=a_c R_c(\lambda)+ a_f R_f(\lambda) +(1-a_c -a_f) R_p(\lambda), \qquad (1)$$

where $R_c(\lambda)$, $R_f(\lambda)$ and $R_p(\lambda)$ are the spectral reflectance of the core, fringe, and paper, respectively. a_c and a_f are the respective area fractions of the core and fringe.

The $R_c(\lambda)$ and $R_p(\lambda)$ can be obtained by measuring the solid print and paper, but $R_f(\lambda)$ cannot be obtained from measurement because both the region and the ink layer thickness for the fringe are unknown. Then we assumed that the density of the fringe obeyed the Beer-Lambert's law, and calculated the values of $R_f(\lambda)$ from Eq. 2,

$$R_f(\lambda)=(R_c(\lambda)/R_p(\lambda))^{\rho}\cdot R_p(\lambda), \quad (2)$$

where ρ is the ratio of fringe ink thickness to core ink thickness, and has to be determined in some mathematical way. Substituting Eq. 2 into Eq. 1 gives us the following form,

$$R(\lambda)=a_c R_c(\lambda)+ a_f R_c(\lambda)^{\rho} R_p(\lambda)^{1-\rho} +(1-a_c-a_f) R_p(\lambda). \quad (3)$$

It is very difficult to find the precise values for the a_c and a_f, because typical measurement techniques of dot areas use optical principles and thus cannot clearly separate the core and the fringe regions due to light scattering. Similarly, measuring the value of ρ is also difficult. Then we used a non-linear optimization technique to estimate the values of a_c and a_f together with the value of ρ.

The goal of this optimization is to minimize the spectral error of the model. Then the least square algorithm was used. Let $R_i(\lambda_j)$ and $R_i'(\lambda_j)$ be the predicted reflectance value and the measured reflectance value, respectively, at the jth wavelength λ_j for the ith halftone patch. Sum, D, of squared difference between $R_i(\lambda_j)$ and $R_i'(\lambda_j)$ for all the patches is given as follows,

$$D=\Sigma\,\Sigma\,(R_i'(\lambda_j)-R_i(\lambda_j))^2. \quad (4)$$

The values of a_c, a_f and ρ were determined so that the D could be minimized.

Experimental

Samples for measurement were made by printing clustered dot halftone in Cyan, Magenta, and Yellow ink on a coated paper at 175-LPI. The nominal values of dot area fractions of the samples were 0 to 1 at intervals of 0.1 in this study. These dot area values were modified by a microscopic image analysis as described later.

Measurements of the spectral reflectance of the samples were made using Gretag Spectrolino, a spectro-colorimeter, with a sampling width of 10nm between 380nm to 730nm. For analysis the spectral reflectance data from 400nm to 700nm was used. Measuring geometry was 45/0 and black backing was used.

For measurement of dot area, an image of each halftone sample was captured with a microscope, Nikon OPTIPHOT, equipped with a 3-chip color CCD camera, Fujix HC-2500, and then was analyzed using an image analysis software, Mitani MacScope. Analysis for measurement of the dot area was carried out by Otsu method.[5] Optimization was done using Microsoft Excel®.

Results

Table 1 shows the estimated values of ρ for the samples. The similar values of ρ imply that the fringe thickness is nearly constant for all the inks used in this study. The values close to 0.5 seem to be reasonable because an actual ink layer thickness varies continuously from the ink thickness of the solid print to no ink.

Table 1. Estimated values for ρ.

	Cyan	Magenta	Yellow
ρ	0.38	0.40	0.36

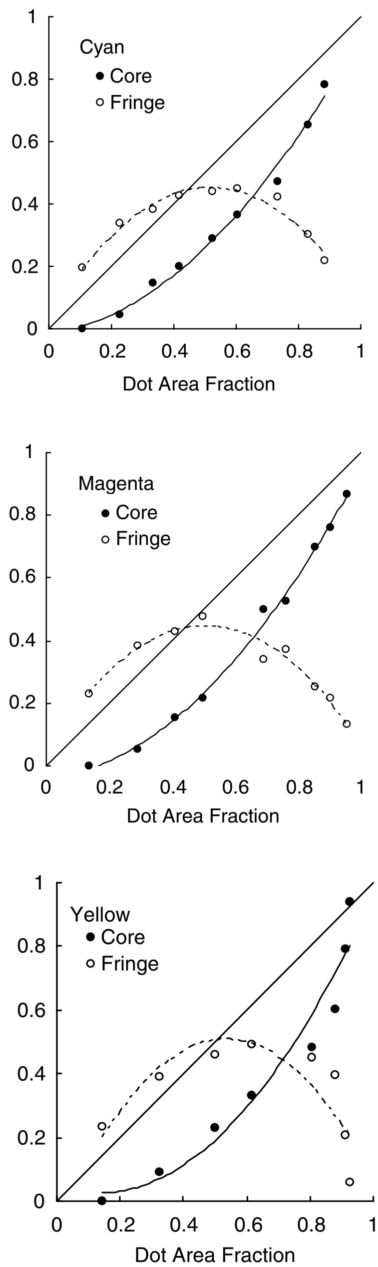
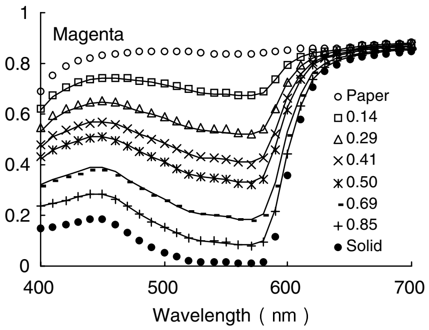


Figure 2. Core and fringe areas versus dot area.

Figure 2 shows the area fractions of core and fringe versus the dot area fraction. In the figure, the symbols represent the estimated values for the area fractions of core and fringe, and the straight line with a slope of unity corresponds to the case where the core area is equal to the dot area. For all the inks, almost every plotted point for the core is below the straight line, and the core area fraction rises exponentially with the dot area fraction. Meanwhile, the plotted points for the fringe show a tendency to vary convexly with the dot area fraction, like a typical "dot gain" curve. The reason fringe is predominant at lower dot area fraction is probably that the ink layer of a small dot is considerably thin due to poor ink trapping compared to the solid print. Each solid curve is an approximation by a quadratic function for the estimated value of the core area fraction, and each dashed curve is for the fringe area fraction. For Cyan and Magenta, these approximations are good but not so good for Yellow.



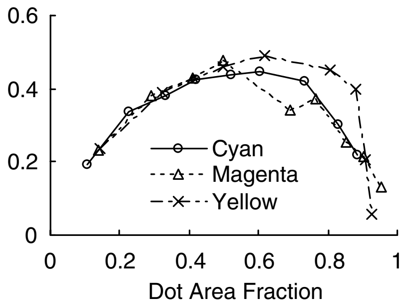


Figure 3. Fringe area versus dot area.

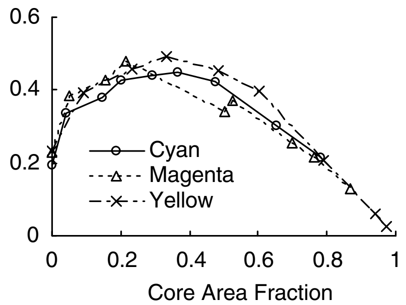


Figure 4. Fringe area versus core area.

Figure 3 shows the relationships between the dot area fraction and the fringe area fraction for all the inks. Those relationships are almost the same under 0.5 but distinctly differ over 0.5 of dot area fraction, particularly between Yellow ink and the other two inks.

The relationships between the core area fraction and the fringe area fraction for all the inks are shown in Fig. 4, where the difference between the inks is not as much as in Fig. 3. It is characteristically found that the fringe area has the maximum at less than 0.4 and also has the value of more than 0.2 even at 0 of the core area fraction.

Discussion

As shown in Fig. 2, the area fractions of core and fringe can be expressed with quadratic functions of the dot area fraction. Thus the reflectance spectra of the core-fringe model can be expressed with the dot area fraction instead of the core and fringe area fractions. Given y is the area fraction of core or fringe of a dot and x is the area fraction of the dot, the above functions can be expressed as

$$y=px^2+qx+r, \tag{5}$$

where p, q, and r are constants.

Table 2 shows the values of p, q, and r of the quadratic functions represented by the solid and dashed curves in Fig. 2. Using Eq. 5 with these values, we calculated the values of core and fringe area fractions for each sample and then calculated the corresponding spectral reflectance value. Results from this calculation are shown in Fig. 5.

Table 2. Coefficients values of quadratic functions used for approximation.

	Core			Fringe		
	p	*q*	*r*	*p*	*q*	*r*
Cyan	0.81	0.14	-0.02	-1.56	1.62	0.04
Magent	0.88	0.11	-0.04	-1.56	1.58	0.05
Yellow	1.25	-0.34	0.05	-2.02	2.16	-0.07

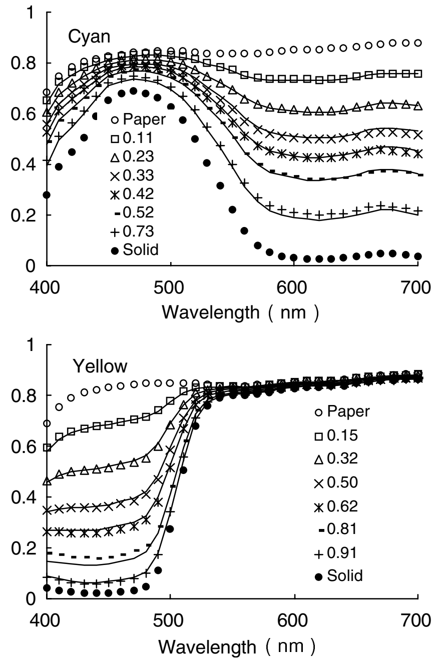


Figure 5. Predicted reflectance spectra.

The lines in these figures represent the reflectance values predicted from the core-fringe model, and the symbols represent the measured values. The numbers beside some of the symbols mean the measured dot area fractions of the samples used. As seen in the figures, the model values fit the measured values well.

Table 3. Model performance for single ink halftone prints.

		Ave. ΔE^*_{ab}	Max. ΔE^*_{ab}	Spectral RMSd
Core-fringe model	Cyan	1.1	2.3	0.007
	Magenta	0.6	1.1	0.005
	Yellow	2.8	9.1	0.014
Murray-Davies model	Cyan	6.2	8.0	0.038
	Magenta	8.6	11.9	0.028
	Yellow	6.2	14.9	0.027

Table 3 shows the model performance in terms of average color differences and maximum color differences in ΔE^*_{ab}, and spectral root mean square (RMS) differences between the measured and predicted reflectance values. The performance of the core-fringe model is better than that of the Murray-Davies model. It is considered that the lower performance for the Yellow samples in the core-fringe model is due to larger errors in measurement of dot area fractions of the Yellow samples.

Then we calculated the CIE xy-chromaticity values of the samples on the basis of the above two models, and compared the calculated values with the measured values as shown in Fig. 6. Results show that the core-fringe model can express the non-linear behavior of single ink halftone prints on the CIE xy-chromaticity diagram.

The core-fringe model is a model in which the physical structure of a halftone dot was simplified. In this study, however, we determined the model parameter values, not by measurements but by an optimization method. Therefore the resulting values for the model parameters may reflect the optical properties rather than the physical structure of the halftone dot. This suggests that the estimated values for the fringe area and thickness are closely related to the light scattering in ink and paper.

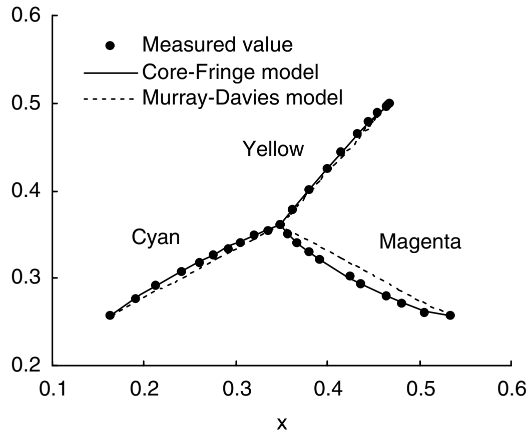


Figure 6. Predicted chromaticity coordinates.

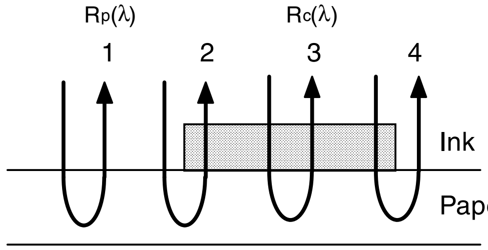


Figure 7. Light paths in halftone system

Considering that four light paths are chiefly involved in color reproduction of the single ink halftone as shown in Fig.7, path 1 and path 3 are incorporated in the core-fringe model as the spectral reflectance of the paper, $R_p(\lambda)$, and the spectral reflectance of the core, $R_c(\lambda)$, respectively, but path 2 and path 4 are not. However, the spectral reflectance for the path 2 and path 4 is identical to the spectral reflectance of the fringe with the ink layer of exactly half the core ink thickness because both path 2 and path 4 pass through the dot ink layer once. Therefore some of the fringe area fraction can be regarded as corresponding to the path fractions of the path 2 and path 4.

Conclusion

The core-fringe model could predict reflectance spectra and the chromaticity coordinates for the single ink halftone ramps used more precisely than the Murray-Davies model. This model has potentiality for characterization of printing devices. However, further study is needed to apply the model to prediction of overprint color.

References

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Biography

Yoshihiko Azuma received a Bachelors degree and a Masters degree from Tokyo Institute of Technology, Japan, in 1979 and 1981, respectively. In 1981, he joined Dai Nippon Printing Co. Ltd. and since 1995, he has been an assistant professor at Tokyo Institute of Polytechnics, Japan. His research areas are halftone color model, color transformation algorithm, cross-media color matching and color tolerance.