Optimization of Color Dyes for Spectral and Colorimetric Color Reproduction

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Abstract

In general, subtractive color dyes used for current ink jet printers (IJs) are selected from among many potential dyes. However, such trial-and-error approaches are inefficient, and there remain questions as to how to guarantee a truly optimum dye set. Thus, development of a computer simulation system to choose the optimum subtractive color dyes is an important goal. Recently, IJs have been rapidly advancing. Among a variety of factors controlling image quality of dye-based color IJs, color gamut has been improved considerably by increasing the number of inks.

In the previous study, the models were studied from the viewpoint of prediction accuracy for colorimetric color reproduction. Among the models, KM that relies only on the reflectances of the primary colors approximately reproduced the color gamut. Based on the result above, this study has been solved the optimum color dyes for spectral and colorimetric color reproduction by means of a computer simulation. The former is to obtain the optimum dye set for minimizing RMS spectral reflectance error between measured and reproduced spectral reflectances for Macbeth Color Checker that is composed of 24 printed color squares, and the latter is to obtain the optimum dye set for maximizing the size of color gamut between L=40 and L*=80 under D65 and $2°$ observer.*

Introduction

Development for the optimum subtractive color dyes will rely on the full understanding of the relationship between dye amount placed on the paper and resultant color. The optimum subtractive color dyes in a photographic color film have previously been studied by means of a computer simulation.[1-2] The obtained results have showed that it is very effective to use computer simulation for development of the optimum subtractive color dyes. In a photographic color paper, Williams and Clapper proposed a transformation formula considering the multiple internal reflections in a gelatin layer.[3-5]

In the previous studies,[6-11] the authors verified predicting models for dye-based color IJs, and calculated the color gamut by means of a computer simulation. Among predicting models, KM approximately reproduced the color gamut of the coated paper used in a dye-based color IJ between $L^*=40$ and $L^*=90$. The purpose of this study is to search for the optimum dye sets between three dyes and six dyes for spectral and colorimetric color reproduction. KM that can be calculated easily has been used as a predicting model that predicts reproduced spectral reflectances and tristimulus values from dye amount printed on the coated paper, and the optimum dye sets for minimizing RMS spectral reflectance error and maximizing the size of color gamut among many dye sets have been solved by a constrained nonlinear optimization.

Predicting Models

In the previous study,[9] some models were studied from the viewpoint of prediction accuracy for the reproducible color gamut of the coated paper in a dye-based color IJ. Among the models, KM that relies only on the reflectances of the primary colors approximately reproduced the color gamut between $L^*=40$ and $L^*=90$.

KM,[12-15] which was developed as a series of equations useful for predicting reflectance in many types of colorant systems, is often used as an approach for translucent and opaque media. In particular, KM for transparent film on opaque support is written as follows:

$$\hat{R}_\lambda(\lambda) = R_{\lambda,paper}(\lambda)\exp\left\{-2\left(\sum_i c_i k_{\lambda,i}\right)\right\} \quad (1)$$

$$k_{\lambda,i} = -0.5\ln\{R_{\lambda,i}(\lambda)/R_{\lambda,paper}(\lambda)\} \quad (2)$$

where $\hat{R}_\lambda(\lambda)$ is the predicted spectral reflectance, $R_{\lambda,i}(\lambda)$ is the measured spectral reflectance of primaries, and $R_{\lambda,paper}$ is the spectral reflectance of the paper. c_i represents concentration, and $k_{\lambda,i}$ defines the absorption coefficient of the i-th colorant.

In this study, it is assumed that dye amount placed on the coated paper and resultant color are the ideal relationship that there are not multi-reflection and surface reflection. Thus, this study has used KM for prediction of spectral and colorimetric color reproduction.

Experimental Results

In this paper, hypothetical absorption bands are used by numerically fitting suitable functions to actual absorption bands. An absorption band is based on symmetric cubic spline function by using the two primary parameters of the peak wavelength and width[16].

The color gamut and RMS spectral reflectance error obtained by the absorption bands that are defined by symmetric cubic spline function have been studied by means of a computer simulation. The dye-based color IJ simulation was built from the use of the Kubelka-Munk equation. The Simplex method[18] was employed to depict color gamut. A color gamut can be calculated at seven lightness levels of $L^*=$ 30, 40, 50, 60, 70, 80 and 90 under D65 and $2°$ observer.[1] RMS spectral reflectance error was employed to evaluate spectral color reproduction. RMS spectral reflectance error was calculated in steps of 10 nm in the ranges between 400 nm and 700 nm.

Then it needs to select the optimum dyes set for maximizing the size of color gamut and minimizing RMS spectral reflectance error among many dye sets. This problem is classified as a constrained nonlinear optimization, and is solved by the direction-set method.[17-20] In an attempt to obtain the optimum dye set in symmetric cubic spline function, the value of the peak wavelength of absorption band changes in steps of 10 nm in the ranges between 400 nm and 700 nm. Peak density of each dye was assumed to be 2.0 by taking into account the actual absorption band.

The Optimum Dye Sets for Minimizing RMS Spectral Reflectance Error

Figure 1 shows the spectral reflectances of the optimum combinations of three dyes and six dyes for minimizing RMS spectral reflectance error. It can be seen in Fig. 1 that the peak wavelengths of absorption bands that are composed of the optimum combination of six dyes are scattered over the wavelength region between 400 nm and 700 nm.

Figure 2 shows predicted spectral reflectances obtained by the optimum combinations of three dyes and six dyes, and measured spectral reflectances for 8(9-16) examples out of 24 samples of Macbeth Color Checker. Figure 3 also shows predicted spectral reflectances obtained by the optimum combinations of three dyes and six dyes, and measured spectral reflectances for 8(17-24) examples out of 24 samples of Macbeth Color Checker. It can be seen in Figs. 2 and 3 that a change from three dyes to six dyes gives RMS spectral reflectance error a large decrease as 50%. In particular, the optimum combination of six dyes largely improved RMS spectral reflectance error of the secondary colors as No. 5(blue), No. 7(orange), No. 13(blue) and No. 18(cyan including secondary absorption). Also it can be seen in Figs. 2 and 3 that both combinations reproduce stability of gray balance. The result above shows that RMS spectral error is largely improved by increasing the number of dyes.

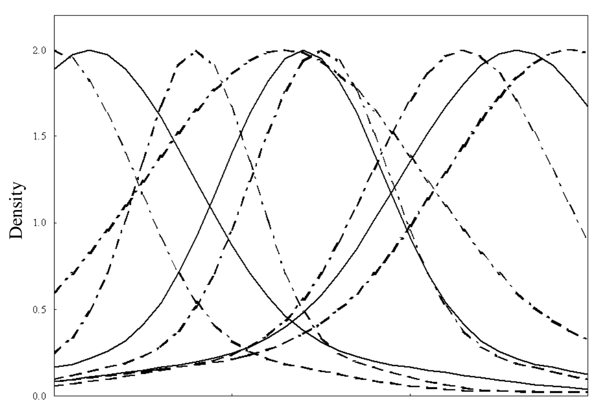

Figure 1. Spectral reflectances of the optimum combinations of three dyes (solid lines) and six dyes (dotted lines) for minimizing RMS spectral reflectance error.

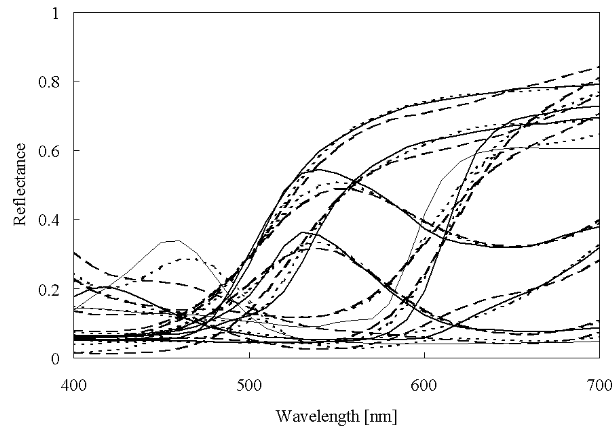

Figure 2. Reproduced spectral reflectances by the optimum three dyes (broken lines) and the optimum six dyes (dotted lines), and measured spectral reflectances (solid lines) for 8(9-16) examples out of 24 samples of Macbeth Color Checker.

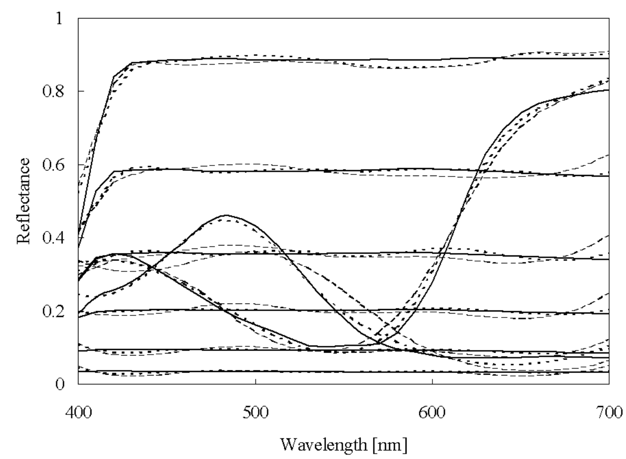

Figure 3. Reproduced spectral reflectances by the optimum three dyes (broken lines) and the optimum six dyes (dotted lines), and measured spectral reflectances (solid lines) for 8(17-24) examples out of 24 samples of Macbeth Color Checker.

The Optimum Dye Sets for Maximizing the Color Gamut

Figure 4 shows the spectral reflectances of the optimum combinations of three dyes and six dyes for maximizing the color gamut. It can be seen in Fig. 4 that all peak wavelengths of absorption bands that are composed of the optimum combinations of three dyes and six dyes exist at less than 620 nm. Based on the result above, it can be assumed that the absorption band having the peak wavelength at over 620 nm is not very effective to maximize the color gamut.

Figures 5-7 show the color gamuts obtained by the optimum dye sets between three dyes and six dyes at L^*=40, 60 and 80. It can be seen in Figs. 5-7 that the blue, red and green areas of color gamuts obtained by the optimum dye sets were largely expanded by increasing the number of dyes. A change from three dyes to four dyes gave a large increase as 130%, and two changes from four dyes to five dyes and from five dyes to six dyes gave a small increase as 110%.

Focused on the relationship between the color gamut and lightness, it can be seen in Figs. 5 and 6 that it gives reproducible color gamut a large increase at L^*=40 and 60 respectively by increasing the number of dyes. However, Figure 7 shows that it gives reproducible color gamut a small increase at L^*=80 by increasing the number of dyes, and the areas of the color gamuts obtained by the optimum dyes sets shift from the red area to the green area by increasing the number of dyes. The result above shows that it is a very effective way to increase the number of dyes for maximizing the color gamut.

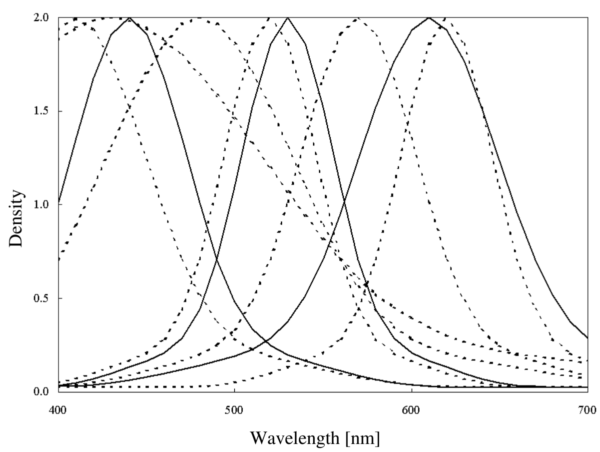

Figure 4. Spectral reflectances of the optimum combinations of three dyes (solid lines) and six dyes (dotted lines) for maximizing the color gamut.

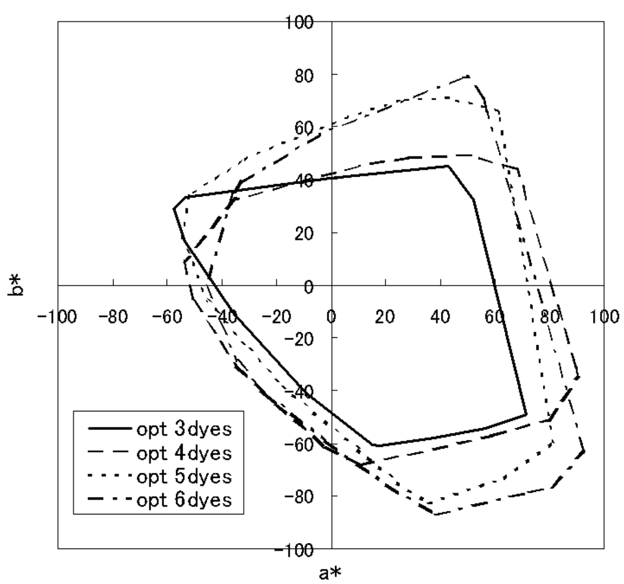

Figure 5. Color gamuts obtained by the optimum combinations of three dyes (solid line), four dyes (broken line), five dyes (dotted line) and six dyes (broken and dotted line) at L = 40 under D65 and 2° observer.*

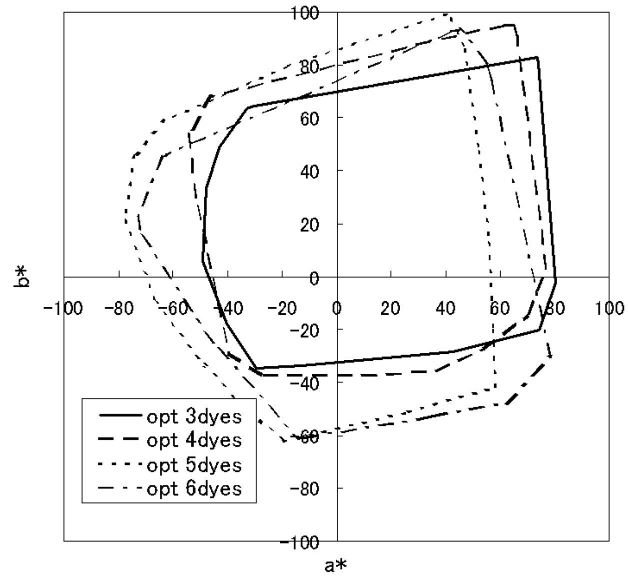

Figure 6. Color gamuts obtained by the optimum combinations of three dyes (solid line), four dyes (broken line), five dyes (dotted line) and six dyes (broken and dotted line) at L = 60 under D65 and 2° observer.*

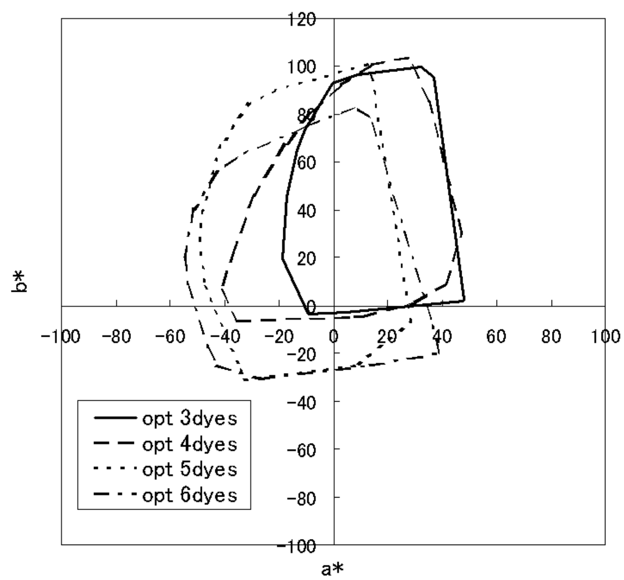

Figure 7. Color gamuts obtained by the optimum combinations of three dyes (solid line), four dyes (broken line), five dyes (dotted line) and six dyes (broken and dotted line) at L = 80 under D65 and 2° observer.*

Conclusion

The optimum dye sets obtained by means of a computer simulation showed that it is very effective to increase the number of dyes for spectral and colorimetric color reproduction. It gave RMS spectral reflectance error a large decrease as 50% by increasing the number of dyes. In particular, the optimum combination of six dyes improved RMS spectral reflectance error of the secondary colors as No. 5(blue), No. 7(orange), No. 13(blue) and No. 18(cyan including secondary absorption).

Also it gave reproducible color gamut a large increase by increasing the number of dyes. In particular, the blue, red and green areas of color gamuts were largely expanded, and it was very effective to maximize the color gamut at *L*=40* and *L*=60*, respectively.

In a future study, the author will take into consideration subtractive color dyes currently used in dye-based color IJs including secondary absorption, and obtain the optimum dye set by means of a computer simulation. Also the predicting models will be improved prediction accuracy of reproducible spectral reflectances.

References

1. N. Ohta, "The Color Gamut Obtainable by the Combination of Subtractive Color Dyes. I. Actual Dyes in Color Film. (1) Optimum Peak Wavelengths and Breadths of Cyan, Magenta, and Yellow," Photogr. Sci. Eng., 15(5), 399-422 (1971).
2. N. Ohta, "The Color Gamut Obtainable by the Combination of Subtractive Color Dyes. I. Actual Dyes in Color Film. (3) Stability of Gray Balance," Photogr. Sci Eng., 16(3), 203-207 (1972).
3. F. C. Williams and F. R. Clapper, "Multiple Internal Reflections in Photographic Color Prints," J.Opt. Soc. Amer., 43, 595 (1953).
4. J. D. Shore and J. P. Spoonhower, "Reflection Density in Photographic Color Prints Generalizations of the Williams-Clapper Transform," JIST, 45(5), 484-488(2001).
5. D. B. Judd, "Fresnel Reflection of Diffusely Incident Light," J. Research Natl. Bur. Standards, 29, 329 (1942).
6. T. Ogasahara and N. Ohta, "Verification of the Optimum Prediction Model for Dye-Based Inkjet Printer," Proc. of the IS&T PICS 2003 Conference, Rochester, NY, 429-434 (2003).
7. T. Ogasahara, "Optimization of the Printing Model for Dye-Based Inkjet Printer," Proc. of the IS&T NIP19 Conference, New Orleans, LA, 785-788 (2003).
8. T. Ogasahara, "Verification of the Predicting Model and Characteristics of Dye-Based Inkjet Printer," J. Imaging Sci Tech., 48(2), 136-143 (2004).
9. T. Ogasahara, "Optimization of Subtractive Color Dyes for Dye-Based Color Inkjet Printer," Proc. of the 11th Color Imaging Conference, Scottsdale, AZ, 218-223 (2003).
10. T. Ogasahara, "Optimization of Subtractive Three Color Dyes for Dye-Based Color Inkjet Printer", J. Imaging Sci Tech., 48(2), 502-510 (2004).
11. T. Ogasahara, "Optimization of Subtractive Four Color Dyes for Dye-Based Color Inkjet Printer", J. Imaging Sci Tech., 48(2), 511-518 (2004).
12. A. Beer, "Bestimmung der absorption des rothen lichts in farbigen flussigkeiten," Ann. Phys. Chem., 86(2), 78(1852).
13. G. Wyszechki and W. S. Stiles, "Color Science: Concepts and Methods," Quantitative Data and Formulae"2nd edition. New York: John Wiley & Sons, 30(1982).
14. P. Kubelka and F. Munk, "Ein Beitrag zur Optik der Farbanstriche," Z. Tech Phys. 12, 593-601 (1931).
15. H. R. Kang, "Kubelka-Munk Modeling of Ink Jet Mixing," J. Imaging Sci Tech., 17(2), 76-83(1992).
16. N. Ohta, Introduction to Color Reproduction Technology, Corona Publishing Co., Ltd., (1997)
17. W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, Numerical Recipes in C [Japanese version], Gijutsu-Hyohron Co., Ltd., 282-338 (1993).
18. R. P. Brent, Algorithms for Minimization without Derivatives, Prentice-Hall Inc., 7, (1973).
19. F. S. Acton, Numerical Methods That Work, Harper and Row, 464-467 (1970).
20. D. A. H. Jacobs, The State of the Art in Numerical Analysis, Academic Press, 259-262 (1977).

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Takayuki Ogasahara received his B.S. and M.S. degrees in nuclear engineering from Nagoya University, Japan in 1994 and 1996. Since then, he has been employed at CANON INC. His work has primarily focused on the optimization of subtractive color dyes, development of image processing and image quality issues. Between 2002 and 2004, he has been a visiting scientist at Munsell Color Science Laboratory of Rochester Institute of Technology. He is a member of the IS&T.