

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/253737942>

Expanded Neugebauer model for printer color formation

Article in Proceedings of SPIE - The International Society for Optical Engineering · December 1998

DOI: 10.1117/12.334599

CITATIONS

3

READS

378

2 authors, including:



Huanzhao Zeng

42 PUBLICATIONS 231 CITATIONS

SEE PROFILE

An expanded Neugebauer model for printer color formation

Huanzhao Zeng^{* a}, Peter G. Anderson^b

^a8715 Edulis Court, San Diego, CA 92129

^bComputer Science Dept., Rochester Institute of Technology, Rochester, NY 14623

ABSTRACT

A model to predict colorimetric value for color printers is presented. The Neugebauer narrow-band color mixing model was applied with modifications. While sixteen primaries are used for four-color printing process in Neugebauer model, we used two data sets in our model, one with eighty-one CMYK primaries and the other with one hundred twenty-five CMY primaries. Two Yule-Nielsen factors were applied to optimize the CMYK set and the CMY set separately. The Yule-Nielsen factors were optimized by minimizing $\Delta E^*_{L^*a^*b^*}$ or ΔE^*_{94} . The Neugebauer colorimetric quality factor (CQF) was applied as a weighting function to optimize dot areas. By optimizing primaries and applying the CQF weighting function, the average color error and the maximum color error decrease significantly.

Keywords: color calibration, colorimetric, halftone, color printing, color difference

1. INTRODUCTION

In 1936, Murray and Davies¹ published a model to predict the tone reproduction of binary printing process. This model was extended by Neugebauer² in 1937 for color halftoning. However, variation from this linear optical model is often significant. Yule and Nielsen³ modified the tone reproduction model in which they incorporated an empirical factor n to fit the non-linear relationship between total reflectance and dot area. Viggiano^{4, 5} further improved the model by applying the Yule-Nielsen factor n into the Neugebauer narrow-band model. This model and its variations have been widely used to model binary color printers⁶⁻¹⁵. Another model, Kubelka-Munk equation was also used for printer color formation by many authors¹⁶⁻²⁰. Arney's model²¹ preserves the linearity of the Murray-Davies equation, and explains the reflectances of paper and inks as functions of dot areas. Balasubramanian²² extended the Neugebauer model into a cellular framework model in which the primary colors are not limited to sixteen. Due to the increase number of primaries in the cellular model, it yields more accurate result from a finer interpolation. Zeng²³ applied the Neugebauer colorimetric quality factor (CQF)^{24, 25} to optimize the dot areas of colorants for the narrow-band Neugebauer model and for the cellular model. By using this model, the color error decreases significantly.

In this paper, a model modified from Neugebauer model is presented in which variable primaries can be used. By optimizing the number and the locations of the primaries, optimizing the Yule-Nielsen n factors, and applying Neugebauer CQF weighting, very small color error can be achieved.

2. THE NEUGEBAUER EQUATION AND YULE-NIELSEN MODIFICATION

The simplest tone reproduction model, the Murray-Davies model, can be expressed by the following equation

$$R = (1 - a) R_0 + a R_i, \quad (2.1)$$

where R is the total reflectance, R_0 is the reflectance of the base which is usually paper, R_i is the reflectance of ink, and a is the relative dot area of the ink ($0 \leq a \leq 1$).

The narrow-band equation based on this model can be written as

$$R(\lambda) = (1 - a) R_0(\lambda) + a R_i(\lambda), \quad (2.2)$$

* Correspondence: Email: ICCandCRD@aol.com.

where $R(\lambda)$ is the total reflectance at wavelength λ , $R_0(\lambda)$ is the reflectance of paper at wavelength λ , and $R_i(\lambda)$ is the reflectance of ink at wavelength λ .

In the case of a four-color printing process, a color is the combination of four colorants, cyan (C), magenta (M), yellow (Y), black (K), and white paper (W). The Neugebauer equation for a four-color binary printing process is given by

$$R(\lambda)_{CMYK} = \sum_{i=1}^{16} a_i R_i(\lambda), \quad (2.3)$$

where $R(\lambda)_{CMYK}$ is the total spectral reflectance in a given wavelength λ , i is the i -th Neugebauer primary, $R_i(\lambda)$ is the spectral reflectance of the i -th primary in the given wavelength λ , and a_i is the relative area of the i -th primary. The a_i s are given by

$$\begin{aligned} a_0 &= (1-c)(1-m)(1-y)(1-k) \\ a_1 &= c(1-m)(1-y)(1-k) \\ a_2 &= m(1-c)(1-y)(1-k) \\ a_3 &= y(1-c)(1-m)(1-k) \\ a_4 &= k(1-c)(1-m)(1-y) \\ a_5 &= cm(1-y)(1-k) \\ a_6 &= cy(1-m)(1-k) \\ a_7 &= ck(1-m)(1-y) \\ a_8 &= my(1-c)(1-k), \\ a_9 &= mk(1-c)(1-y) \\ a_{10} &= yk(1-c)(1-m) \\ a_{11} &= cmy(1-k) \\ a_{12} &= cmk(1-y) \\ a_{13} &= cyk(1-m) \\ a_{14} &= myk(1-c) \\ a_{15} &= cmyk \end{aligned} \quad (2.4)$$

where c , m , y , and k are dot areas of cyan, magenta, yellow, and black colorants, respectively.

The Murray-Davies equation is valid only for zero optical gain behavior. Yule and Nielsen improved the Murray-Davies equation by incorporating an n factor to curve-fit the optical gain. Thus, equation (2.1) becomes

$$R^{1/n} = (1-a) R_0^{1/n} + a R_i^{1/n}. \quad (2.5)$$

This is the Yule-Nielsen equation. Viggiano extended the Yule-Nielsen effect to the Neugebauer equation to predict the color of halftone printing by equation (2.6).

$$R(\lambda)_{CMYK}^{1/n} = \sum_{i=1}^{16} a_i R_i(\lambda)^{1/n}. \quad (2.6)$$

Both the dot area a_i and the Yule-Nielsen n factor are usually determined at the same time. If spectral reflectances are measured from 400 nm to 700 nm with intervals of 10 nm, there are 31 equations to determine two variables, a_i and n . And the n value must be the same for all dot areas. Therefore, criteria, such as minimizing the color difference or minimizing the difference between the predictive reflectance and the corresponding measured reflectance, must be set so that a_i and n could be decided.

Zeng²³ has developed a model to optimize dot areas. By using this model, the dot area a_i in equation (2.6) is treated as a function of wavelength, λ , as shown in (2.7).

$$R(\lambda)_{CMYK}^{1/n} = \sum_{i=1}^{16} a_i(\lambda) R_i(\lambda)^{1/n} \quad (2.7)$$

The dot area, a_i , is optimized by the following equation (2.8), and n is optimized by minimizing $\Delta E^*_{L^*a^*b^*}$ or ΔE^*_{94} ^{25,26}.

$$a_i = \sum_{\lambda} w(\lambda) a_i(\lambda), \quad (2.8)$$

where $w(\lambda)$ is a weighting function which is determined based on the human color vision characteristics.

Neugebauer's colorimetric quality factor (CQF) is used as the weighting function $w(\lambda)$. The CQF has been used to determine how close a spectral response is to a color mixture function^{24, 25}. The CQF is the nonlinear combination of the orthonormal set of the CIE 1931 2-degree color matching functions. Fig. 1 shows the CQF function. Since human eyes are quite insensitive to the wavelengths below 400 nm and wavelengths above 700 nm, the weights in these areas are nearly zero. Three peaks approximately correspond to the most sensitive wavelengths of the three cone types of the human eye^{26, 27}.

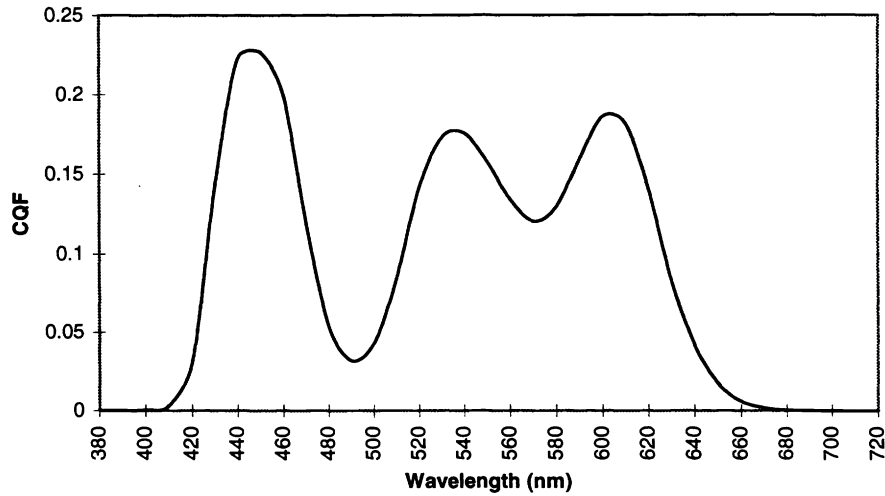


Fig. 1 Neugebauer's colorimetric quality factor (CQF).

For binary printers, each channel can only print a dot or print nothing. In other words, each channel prints only two different dots, 0% dot or 100% dot. Therefore a four-color printer can only print sixteen different colors. This is the reason that the primaries are sixteen in the Neugebauer model. Balasubramanian expanded the Neugebauer model into a cellular framework model in which the values between 0% and 100% can also be used as primaries. Geometrically, this is equivalent to performing pentahedral interpolation in 4-D CMYK color space. If primaries are the combinations of C, M, Y, and K being 0, 0.5, and 1 (the in-between value is not necessary to be exactly 0.5), the total primaries are 3^4 which is 81. If two in-between values are used, the total primaries are 4^4 which is 256. If three intermediate values are used, the total primaries are increased to 5^4 which is 625. By analyzing the patches of 81, 256, and 625 primaries, we found that there are a lot of dark or almost black patches. The reason is that all values of K are used to mix with any CMY values. If we do not mix all CMY with every K, color patches more uniformly distributed in a visually uniform color space can be obtained. By using these more uniform color patches as primaries, we can build a more accurate color model with a smaller data set, and also have color errors distributed more uniformly.

If we use n^4 (n is 3, 4, 5, ...) primaries for four-color printers, we still use equations (2.7) and (2.8) for color modeling. Primaries to predict an unknown color are still sixteen. The difference between this model and the original Neugebauer model is that the sixteen primaries in Neugebauer model are not changed for any input CMYK values, while the sixteen

primaries in the cellular model are determined based on the input CMYK values. For example, if cyan dot area $c = 0.45$, an cyan dot areas in the primaries just below 0.45 is 0.4 and just above 0.45 is 0.6, c is re-scaled to $c' = \frac{0.45-0.4}{0.6-0.4} = 0.25$ (see Fig. 2).

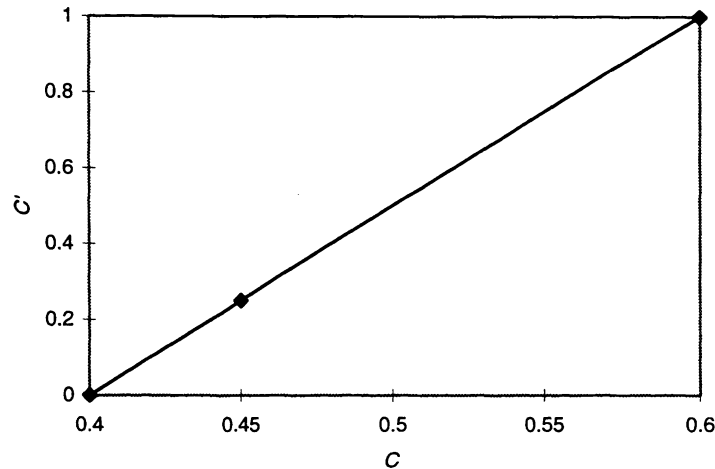


Fig. 2 Re-scale cyan dot areas in the expanded Neugebauer model.

By using n^4 primaries, there are more dark colors than light colors for modeling. Thus dark colors are over-weighted in the modeling. It would be good to choose primaries so that their colors are distributed in the whole printer color gamut as uniformly as possible in a visually uniform color space, such as CIE L*a*b* color space. However, before we model the color behavior of a printer, it is impossible to find the CMYK set so that colors of this set distribute uniformly in CIE L*a*b* color space. Nevertheless, we know that uniformly sampling in the CMYK color space is not good because it makes denser sampling in dark and black areas than in the light area. A general idea is to apply all combinations among CMY, but apply very few combinations of high K value with high CMY values. Following is an example to choose primaries.

We used eighty-one (which is 3^4) primaries by sampling in CMYK color space and found that the maximum color error is still very large. We suspected that the samplings are not dense enough in some areas in CIE L*a*b* color space. So we decided to use more primaries. We used five sampling points for each of CMY with K being 0 (herein, ink value 1 means 100% dot area and 0 means 0% dot area) so that we could get a more accurate conversion from CMY to spectral reflectance or from CMY to CIE XYZ. Therefore the primaries for CMY are 5^3 which is 125. Due to high dot gain in ink jet printers, we sampling denser in low digital value areas so that we can get a more uniform distribution in CIE L*a*b* color space. For CMYK, we use 81 primaries. The total primaries are 206 which are the sum of the primaries of the 5^3 sampling for the CMY set and the 3^4 sampling for the CMYK set. For an input color, if K is not zero, the 16 primaries to be used in equation (2.7) will be picked from the 81 CMYK primaries; if K is zero, the 8 primaries to be used in equation (2.7) (for K equals zero, the primaries are reduced to 8 in equation (2.7)) will be picked from the 125 CMY primaries.

There are a few reasons that we designed above primaries. The first is that if we used five steps for all CMYK, the total primaries would be 625 in which there would be a lot of dark and black color patches which were not necessary to be used. The second reason is that CMY to CIE XYZ conversion is more important than CMYK to CIE XYZ conversion for the process to generate ICC profiles and color rendering dictionaries in our processing flow. When generating printer calibration tables, we converted device XYZ to the XYZ of CMY and the XYZ of K, then converted the XYZ of CMY to CMY and the XYZ of K to K. The third reason is that we used regular sampling points instead of arbitrary grid points so that the program could runs more efficiently. We can use grid points with any CMYK values as primaries, but the program will takes more time to search the primaries to be used in equation (2.7).

3. EXPERIMENTAL RESULTS

An X-Rite 938 spectrophotometer was used to measure all patches. The measuring geometry is 0/45. All samples were printed by a Hewlett-Packard 2000CP wide-format ink jet color printer in 600 DPI resolution printing mode. The HP high-gloss paper and indoor ink set were used. A target was designed to analyze the page to page color difference of the printer. We started with 6^3 CMY uniformly sampling color patches. Then we used gray component replacement to convert CMY into CMYK, therefore we had 216-patch CMYK target finally. After more than fifteen minutes of warm-up and printing, we printed this 216-patch CMYK target twice and measured CIE $L^*a^*b^*$ values of both targets. The average and maximum color errors²⁸⁻³² are 0.8 and 2.9 $\Delta E^*_{L^*a^*b^*}$, respectively, or 0.5 and 1.2 ΔE^*_{94} , respectively. The histogram of $\Delta E^*_{L^*a^*b^*}$ is shown in Fig. 3. These are the page to page color differences of the printer.

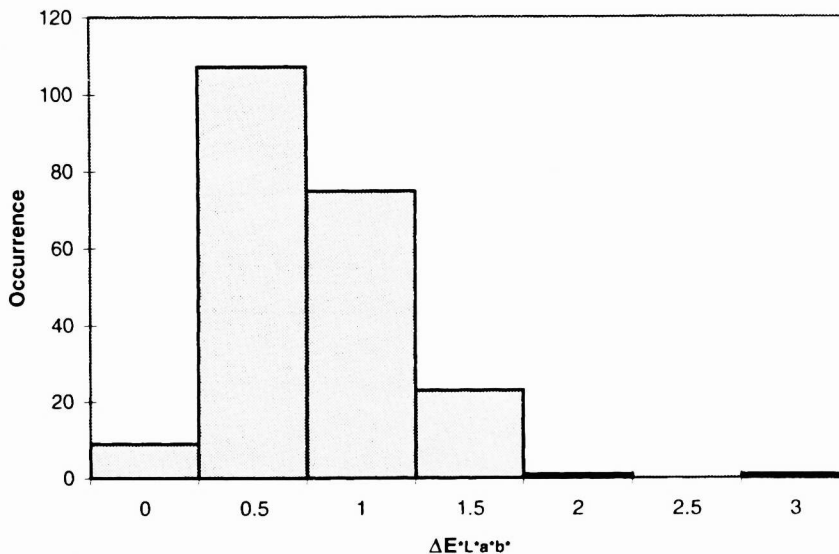


Fig. 3 The histogram of the page to page color difference of the testing printer.

The 4 by 18 ramps of cyan, magenta, yellow, and black primaries were printed and the spectral reflectances were measured. The dot areas were calculated using equations (2.7) and (2.8). Four one-dimensional lookup tables to determine CMYK dot areas from CMYK digital counts were obtained by linear interpolation.

The 81 CMYK primaries and the 125 CMY primaries (206 totally) which are designed in the previous section were printed, and their spectral reflectances were measured.

Two test color sets were printed to analyze color errors of the model. One is 6^3 uniformly sampling CMY patches and the other is CMYK patches which is converted from this CMY set.

The Yule-Nielsen factor n for the 81 CMYK primaries was optimized by minimizing the average $\Delta E^*_{L^*a^*b^*}$ or ΔE^*_{94} using C, M, Y, and K ramps and 125 CMY primaries. The Yule-Nielsen factor n for the 125 CMY primaries was optimized by minimizing the average $\Delta E^*_{L^*a^*b^*}$ or ΔE^*_{94} using C, M, and Y ramps. We also used test color sets (216 CMY patches and 216 CMYK patches) to optimize n factor so that we could analyze the differences in determining n factor by using different color sets.

3.1 Determine Yule-Nielsen n Factor and Dot Areas for the 81 Primaries

Dot areas were calculated by equations (2.7) and (2.8). C, M, Y, and K ramps, and 125 CMY primaries were used to optimize Yule-Nielsen n value. Since the 81 primaries had been used in Neugebauer equation, they were not used to calculate color error for optimizing n factor. The optimized n value is 5.0 by minimizing $\Delta E^*_{L^*a^*b^*}$. The average $\Delta E^*_{L^*a^*b^*}$ and average ΔE^*_{94} versus n value are shown in Fig. 4. The average color error in n being 5.0 is 1.4 $\Delta E^*_{L^*a^*b^*}$ or 0.9 ΔE^*_{94} . The dot area

versus digital value for n being 5.0 is shown in Fig. 5. We found that there is almost no difference in optimizing n value by minimizing average $\Delta E^*_{L^*a^*b^*}$ or by minimizing average ΔE^*_{94} .

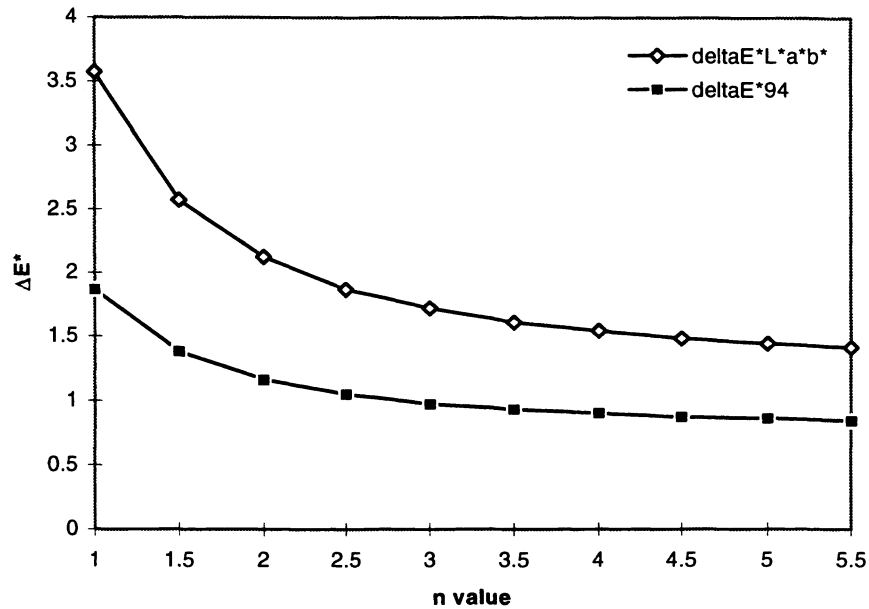


Fig. 4 Average color error versus Yule-Nielsen value n for the 81 CMYK primaries.

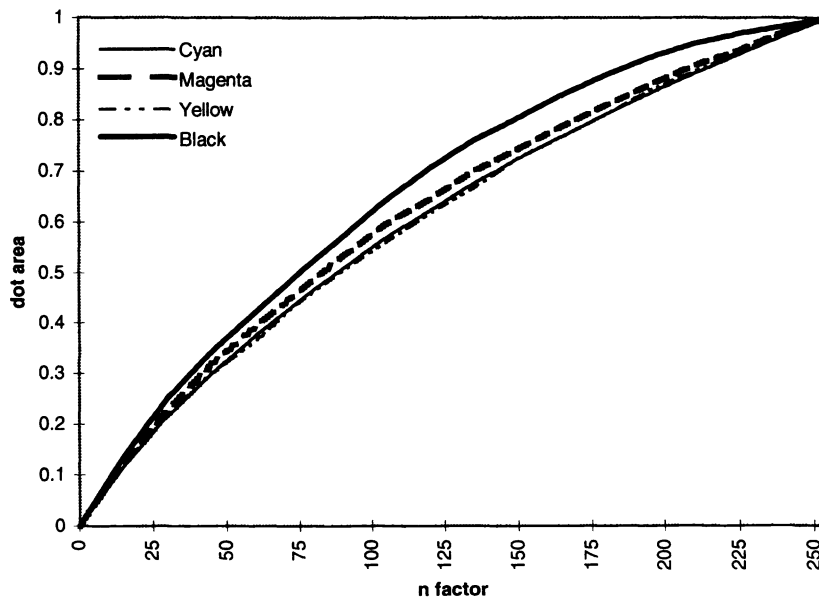


Fig. 5 CMYK dot areas versus CMYK digital values for Yule-Nielsen value $n=5$.

We also used the CMYK test color set (216 patches) to optimize n value. The n value was found to be 4.5. The average color error for 216 CMYK color patches is 2.1 $\Delta E^*_{L^*a^*b^*}$ or 1.3 ΔE^*_{94} for n as 4.5 and 5. This verifies that using the CMYK ramps and the 125 primaries to optimize n value for the 81 primaries is appropriate.

3.2 Determine Yule-Nielsen n Factor and Dot Areas for the 125 Primaries

Dot areas were calculated with the Neugebauer CQF weighting by equations (2.7) and (2.8). C, M, and Y ramps were used to optimize the Yule-Nielsen n factor. The optimized n value is 2.5 by minimizing $\Delta E^*_{L^*a^*b^*}$. The average $\Delta E^*_{L^*a^*b^*}$ and average ΔE^*_{94} versus n value are shown in Fig. 6. The average color error in n being 2.5 is $0.8 \Delta E^*_{L^*a^*b^*}$ or $0.5 \Delta E^*_{94}$. The dot area versus digital value for n being 2.5 is shown in Fig. 7.

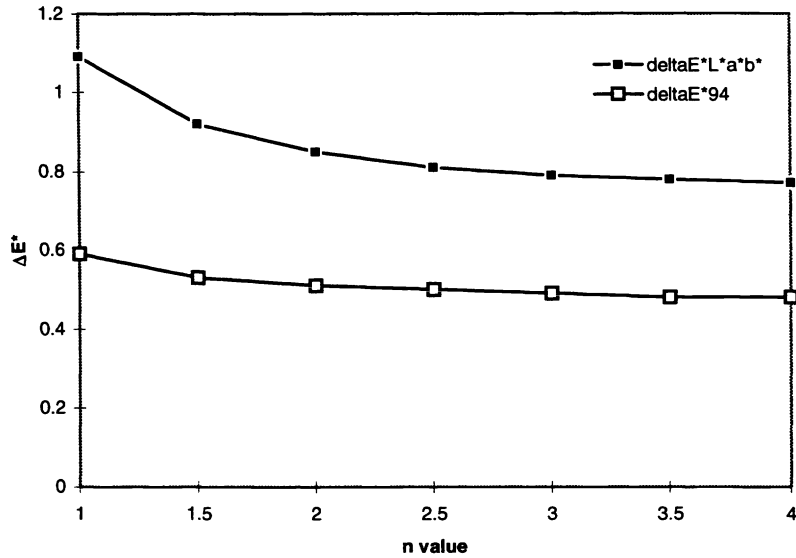


Fig. 6 Average color error versus Yule-Nielsen value n for the 125 CMY primaries.

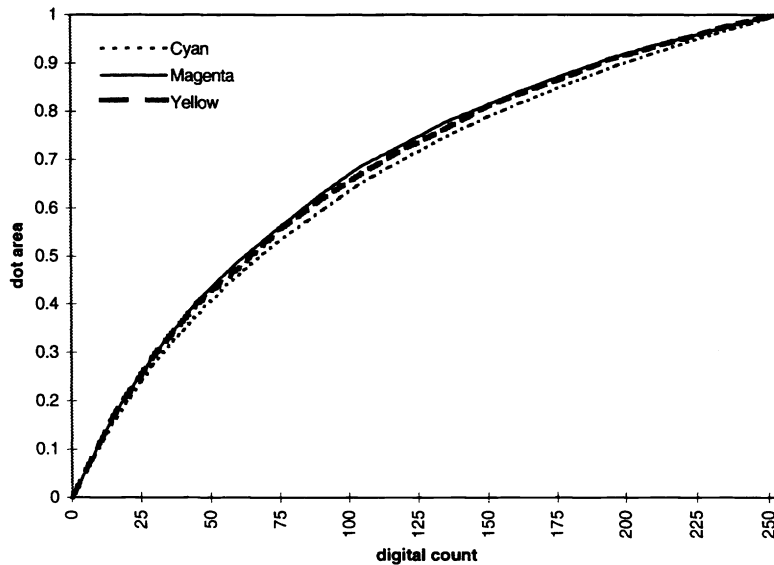


Fig. 7 CMY dot areas versus CMY digital values for Yule-Nielsen value $n=2.5$.

We also used the CMY test color set (216 patches) to optimize n factor. The n factor was also found to be 2.5. The average color error for the 216 CMY color patches are $1.5 \Delta E^*_{L^*a^*b^*}$ or $0.8 \Delta E^*_{94}$. The color errors are almost the same by using these two color sets. This verifies that using CMY ramps to optimize n factor for 125 primaries is appropriate.

A summary of the n factors and color errors using different color sets to optimize the n factors for the 81 CMYK primaries and the 125 CMY primaries is shown in Table 1.

Table 1 A comparison for optimizing n factor using different color sets

| colors set to optimize n value | 81 CMYK primaries | | 125 CMY primaries | |
|--|----------------------------------|-----------------|-------------------|----------------|
| | CMYK ramps and 125 CMY primaries | 216 CMYK colors | CMY ramps | 216 CMY colors |
| n factor | 5.0 | 4.5 | 2.0 | 2.0 |
| average $\Delta E^*_{L^*a^*b^*}$ for 216 CMYK colors | 2.1 | 2.1 | | |
| average $\Delta E^*_{L^*a^*b^*}$ for 216 CMY colors | | | 1.5 | 1.5 |

3.3 A Comparison Between Using 81 CMYK Primaries and Using 81 CMYK Primaries Plus 125 CMY Primaries

We used the 216 CMYK color patches to compare color errors between using 81 primaries and 81 primaries plus 125 primaries (206 primaries totally). By using 81 primaries with the n factor as 5.0, the average color error is $2.1 \Delta E^*_{L^*a^*b^*}$ or $1.3 \Delta E^*_{94}$, and the maximum color error is $5.5 \Delta E^*_{L^*a^*b^*}$ or $3.1 \Delta E^*_{94}$. By using the 206 primaries with the n value as 2.5 for the CMY primaries and n value as 5.0 for the CMYK primaries, the average color error is $1.8 \Delta E^*_{L^*a^*b^*}$ or $1.1 \Delta E^*_{94}$, and the maximum color error is $4.4 \Delta E^*_{L^*a^*b^*}$ or $3.1 \Delta E^*_{94}$. With the 206 primaries, the average color error is decreased by $0.3 \Delta E^*_{L^*a^*b^*}$, and the maximum color error is decreased by $1.1 \Delta E^*_{L^*a^*b^*}$.

By using the 216 CMY color patches to calculate color errors, the average color errors and maximum color errors are 1.8 and $6.3 \Delta E^*_{L^*a^*b^*}$ by using the 81 CMYK primaries, and 1.5 and $4.2 \Delta E^*_{L^*a^*b^*}$ by using the 206 primaries. With the 206 primaries, the average color error is decreased by $0.3 \Delta E^*_{L^*a^*b^*}$ and the maximum color error is decreased by $2.1 \Delta E^*_{L^*a^*b^*}$.

The above results are also listed in Table 2 and histograms of $\Delta E^*_{L^*a^*b^*}$ are shown in Fig. 8 and Fig. 9.

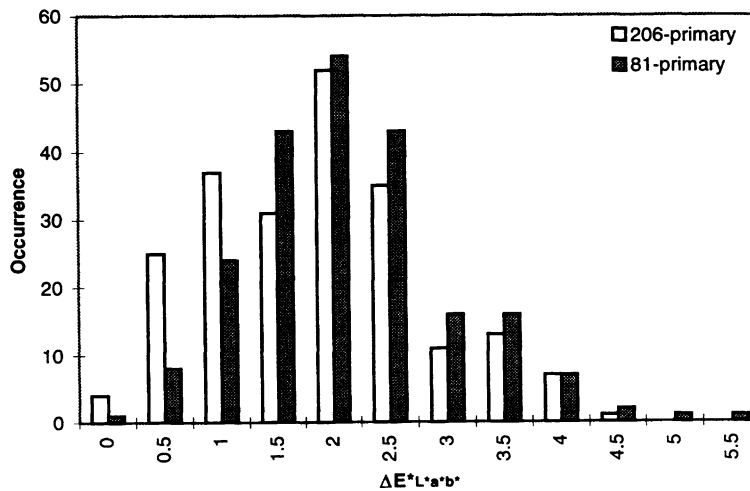


Fig. 8 The histograms of color errors by using the 81 CMYK primaries and the 81 CMYK primaries plus the 125 CMY primaries for the 216 CMYK test colors.

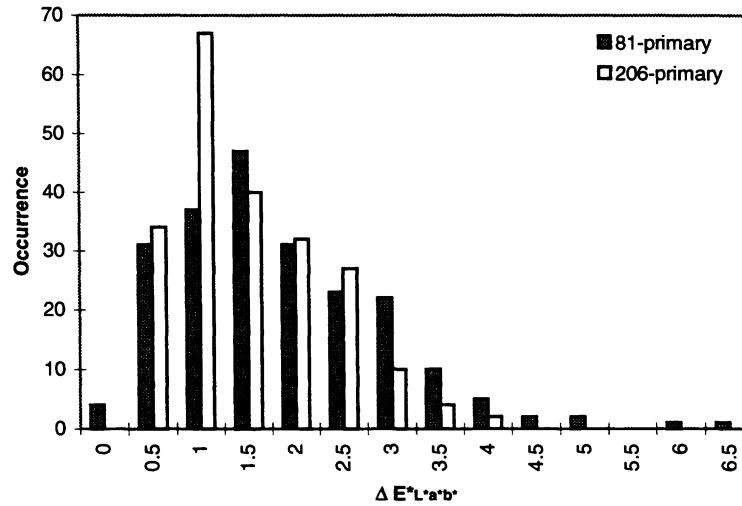


Fig. 9 The histograms of color errors by using the 81 CMYK primaries and the 81 CMYK primaries plus the 125 CMY primaries for the 216 CMY test colors.

Table 2 A comparison of average $\Delta E^*_{L^*a^*b^*}$ and maximum $\Delta E^*_{L^*a^*b^*}$

| | 216 CMY Test Color | | 216 CMYK Test Color | |
|----------------------------------|--------------------|-------------|---------------------|-------------|
| | 81-primary | 206-primary | 81-primary | 206-primary |
| average $\Delta E^*_{L^*a^*b^*}$ | 1.8 | 1.5 | 2.1 | 1.8 |
| maximum $\Delta E^*_{L^*a^*b^*}$ | 6.3 | 4.2 | 5.5 | 4.4 |

4. CONCLUSIONS

A model expanded from Neugebauer color mixing model for printer color formation was developed. Different data sets were used to model color behaviors of CMYK and CMY colors. We presented a method to design primaries so that the model predicts colorimetric values more accurately and distributes errors more uniformly. The Neugebauer CQF weights were implemented to optimize dot areas. Yule-Nielsen n factor was optimized by minimizing average $\Delta E^*_{L^*a^*b^*}$ or average ΔE^*_{94} . In our experimental verifications, we used 81 CMYK primaries plus 125 CMY primaries and two Yule-Nielsen n factors, one for the CMYK set and the other for the CMY set. If K value of an input CMYK color is not zero, the 81-primary set will be used to calculate spectral reflectance and colorimetric value; otherwise, the 125-primary CMY set will be used to calculate spectral reflectance and colorimetric value. The sampling for CMY colors is denser than the sampling for CMYK colors so that color errors can be distributed more uniformly. It also increases the accuracy of the color calibration because CMY to CIE XYZ conversion is more important for the accuracy of the color calibration for printers in our calibration process. A HP 2000CP wide-format inkjet color printer with high-glossy paper and indoor ink was used for testing. The average and maximum color errors for the 216 CMYK test colors using 206 primaries are 1.8 and 4.4 $\Delta E^*_{L^*a^*b^*}$, respectively. The average and maximum page to page color errors of this printer are 0.8 and 2.9 $\Delta E^*_{L^*a^*b^*}$, respectively. If we assume that $\Delta E^*_{L^*a^*b^*}$ is additive, the average color error of this model is about 1.0 $\Delta E^*_{L^*a^*b^*}$.

REFERENCES

1. A. Murray, "Monochrome Reproduction in Photoengraving", *J. Franklin Institute*, **221**, 721-744 (1936).
2. H. E. J. Neugebauer, "Die Theoretischen Grundlagen des Mehrfarbenbuchdrucks", *Zeitschrift fur Wissenschaftliche Photographie Photophysik und Photochemie*, **36**(4), 73-89 (1937).
3. J. A. C. Yule and W. J. Nielsen, "The penetration of light into paper and its effect on halftone reproduction", *Proc. TAGA*, 65-76 (1951).
4. J. A. S. Viggiano, "The color of halftone tints", *Proc. TAGA*, 647-661 (1985).

5. J. A. S. Viggiano, "Modeling the color of multi-colored halftones", *Proc. TAGA*, 44-62 (1990).
6. F. Clapper and J. Yule, "The effect of multiple internal reflections on the densities of half-tone prints on paper", *J. Opt. Soc. Am.* **43**, 600-603 (1953).
7. F. Ruckdeschel and O. Hauser, "Yule-Nielsen effect in printing: a physical analysis", *Applied Optics*, **17**, 3376-3383 (1978).
8. K. Haller, "Mathematical models for screen dot shapes and for transfer characteristic curves", *Advances Printing Science and Technology*, Redwood Burn Limited, Great Britain, 85-103 (1980).
9. 10. M. Pearson, "n value for general conditions", *Proc. TAGA*, 415-425 (1980).
10. 11. I. Pobboravsky, M. Pearson, and C. Daniels, "Application of a dynamic measurement technique for the investigation of the causes of dot gain in web offset lithography", *Proc. TAGA*, 481-495 (1989).
11. H. Wordel and F. Dolezalek, "The influence of instrument geometry and filter choice on density and dot area measurement", *J. Imaging Tech.* **13**, 145-150 (1987).
12. W. Naing, Y. Miyake, N. Abe, and S. Kubo, "Analysis of tone reproduction characteristics for inkjet images by a modified Yule-Nielsen equation", *J. Imaging Tech.* **14**, 6-11 (1988).
13. Y. Shiraiwa and T. Mizuno, "Equation to predict colors of halftone prints considering the optical property of paper", *J. Imaging Sci. Technol.* **37**, 385-390 (1993).
14. L. Daligault and P. Archinard, "Predictive model for color ink jet printing", *Proc. SPIE*, **1912**, 133-141 (1993).
15. P. Hung, "Colorimetric calibration in electronic imaging devices using a look-up-table model and interpolations", *J. Electronic Imaging*, **2**, 53-61 (1993).
16. E. Allen, "Colorant Formation and shading", *Optical Radiation Measurements*, Academic Press, New York, **2**, 289-336 (1980).
17. E. Allen, "Basic equations used in computer color matching, II, Tristimulus match, two-constant theory", *J. Opt. Soc. Am.* **64**, 991-993 (1974).
18. R. Berns, "Spectral modeling of a dye diffusion thermal transfer printer", *J. Electronic Imaging*, **2**, 359-370 (1993).
19. H. R. Kang, "Printer-related color processing techniques", *Proc. SPIE*, **2413**, 410-419 (1994).
20. H. R. Kang, "Applications of color mixing models to electronic printing", *J. Electronic Imaging*, **3**, 276-287 (1994).
21. J. S. Arney, "An expanded Murray-Davies model of tone reproduction in halftone imaging", *J. Imaging Sci. Technol.* **39**, 502-508 (1995).
22. R. Balasubramanian, "A printer model for dot-on-dot halftone screens", *Proc. SPIE*, **2413**, 356-364 (1994).
23. H. Zeng and B. Chin, "A printer model for color printing", *IS&T 50th Annual Conference*, 284-288 (1997).
24. H. E. J. Neugebauer, "Quality factor for filters whose spectral transmittances are different from color mixture curves, and its application to color photography", *J. Opt. Soc. Am.* **46**, 821-825 (1956).
25. P. G. Engeldrum, "Almost color mixture functions", *J. Imaging Tech.* **14**, 108-110 (1988).
26. R. W. G. Hunt, *Measuring Colour*, 2nd ed., Ellis Horwood Limited, England, pp. 39-60 (1992).
27. R. Boynton, *Human Color Vision*, Holt, Rinehart and Winston, New York, pp.159-206 (1979).
28. CIE, "Industrial colour-difference evaluation", *Technical Report 116-1995* (1995).
29. B. Beretta, "Digital color printing 1995: a retrospective from the trenches", *IS&T Eleventh International Congress on Advances in Non-Impact Printing Technologies*, pp. 437-440 (1995).
30. M. Melgosa, et al., The weighting functions for lightness in the CIE94 color-difference model, *Col. Res. Appl.* **21**, 347-352 (1996).
31. M. Luo, and B. Rigg, BFD(1:c) Colour-difference formula. Part 1. Development of the formula, *J. Soc. Dyers Colourists*, **103**, 86-94 (1987).
32. 33. M. Luo, and B. Rigg, BFD(1:c) Colour-difference formula. Part 2. Performance of the formula, *J. Soc. Dyers Colourists*, **103**, 126-132 (1987).