Extending Color Gamut and Improving Color Constancy for Printing Through Synthetic Ink Design

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Abstract

A computer simulation was performed to investigate optimal multiple ink sets in order to maximize color gamut and minimize color inconstancy for printing. A new mathematical function was used to simulate ink reflectance spectra. Each reflectance curve was determined by three parameters: center wavelength, width, and sharpness. The effects of these parameters on color gamut and color constancy were explored. The results showed that these three properties of ink spectra have similar effects on color gamut. However, for color inconstancy, the center wavelength and width were more important than the sharpness of the ink spectra.

1. Introduction

A printer's color gamut is the volume of the color solid defined colorimetrically produced by a particular set of ink and paper, which contains all the colors that the printer can produce. For colors that are out of gamut, color-mapping algorithms are required, which by definition, result in reduced accuracy. A large color gamut is always desirable for color reproduction.

Color constancy is the general tendency of the color of an object to remain constant when the level and color of the illumination are changed.[1] It is a result of both physiological and psychological compensations. Conversely color inconstancy is the undesirable change in color caused by changes in illumination. Color inconstancy is a very important factor to evaluate for the image quality of prints since prints are viewed under many different lighting conditions. As a consequence, in addition to color gamut expansion, color constancy should be an ink-design criterion.

In this research, optimal ink sets for maximizing the color gamut and minimizing the color inconstancy were explored. This paper is divided into four sections. In the first part, a new method is described to synthesize ink spectra in reflectance space. In the second section, the theoretical ink optimization for maximizing gamut is presented. In the third section, the theoretical ink design for improving color constancy is described. In the forth section, an ink parameter sensitivity analysis on gamut volume and color constancy is explored.

2. Spectral Reflectance of Hypothetical Inks by Trapezium Function

In order to perform ink curve optimization, several different functions were considered to model ink spectra, including a Gaussian function, a symmetric cubic-spline function, and a trapezium function.

First, Gaussian functions were used to simulate hypothetical ink curves along with smoothing.[2] Six parameters, two sets each of height, width, and peak wavelength, were necessary to simulate one ink curve in reflectance space. The advantage of this model is that it is very flexible when simulating different ink curves. The disadvantage is that the model has so many parameters that convergence and optimization speeds were slow.

Second, a symmetric cubic-spline function was used to optimize spectral dye curves.[3,4] The symmetric cubic-spline function has several advantages for simulating spectral ink curves. First, its curve shape is natural for simulating spectral ink curves without any truncation, so that the smoothness procedure, which was applied to the Gaussian function, can be avoided. Second, convergence is enhanced since the symmetric cubic-spline function requires fewer parameters. However, the symmetric cubic-spline function has several deficiencies. This function cannot create a single peak, spectral ink curve in reflectance space. As a consequence, green inks cannot be simulated, for example. This limits the range of inks that can be chosen. Another deficiency of this function is that its sharpness is determined by its width. Narrower curves are sharper and, conversely, wider curves are flatter. Therefore, the effects of width and sharpness on gamut volume or color inconstancy cannot be separated because they are not independent parameters.

In order to overcome the deficiencies described above, a new method was developed to synthesize ink spectra in reflectance space. The spectral reflectance of each ink was modeled by a trapezium function with three parameters: center wavelength, bandwidth and sharpness rate. The trapezium function is shown in Eq. 1:

$$R=\begin{cases} k*(x-p+w)+y_0 & x<p \quad R_{\min}<R<R_{\max} \\ -k*(x-p+w)+y_0 & x\geq p \quad R_{\min}<R<R_{\max} \\ R_{\max} & R>R_{\max} \\ R_{\min} & R<R_{\min} \end{cases} \tag{1}$$

where k represents the sharpness rate described by Eq 2, p is the center wavelength and w is the half width at half height y_0.

$$k=\frac{R_{\lambda 2}-R_{\lambda 1}}{\lambda 2-\lambda 1} \tag{2}$$

where λ1 and λ2 are wavelengths of the slope of the ink curve.

Spectral reflectance factors larger than a defined maximum, R_{max} were truncated and set to this maximum value. Spectral reflectance factors smaller than a defined minimum were truncated and set to the minimal value R_{min}. Then the curve was smoothed in the region of truncation. In this research, the maximum and minimum reflectance factors were, respectively, 0.9 and 0.0032, based on typical glossy paper measured with a bidirectional spectrophotometer.

In general, the spectral ink curve can be divided into two groups – one with one peak wavelength such as a green ink and the other with two peak wavelengths such as a magenta ink. These two groups can be created by selecting positive or negative k values. If k is negative, the spectral reflectance curve has two peak wavelengths as shown in Figure 1. If k is positive, one-peak spectral reflectance curves are created as shown in Figure 2. Note that the center wavelength and the width have different interpretations in the one and the two peak curves.

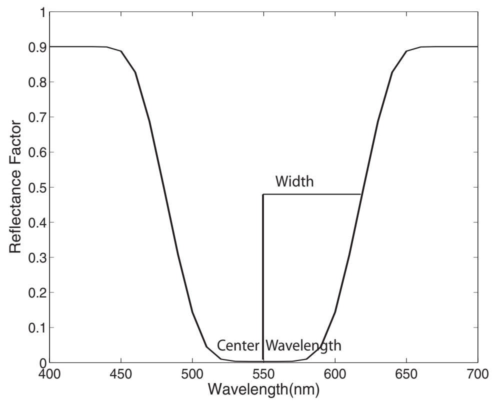

Figure 1. The ink spectral reflectance curve produced by the trapezium function with two peak wavelengths. The sharpness rate k was set to -0.02, the peak wavelength to 550nm, and the bandwidth to 60.

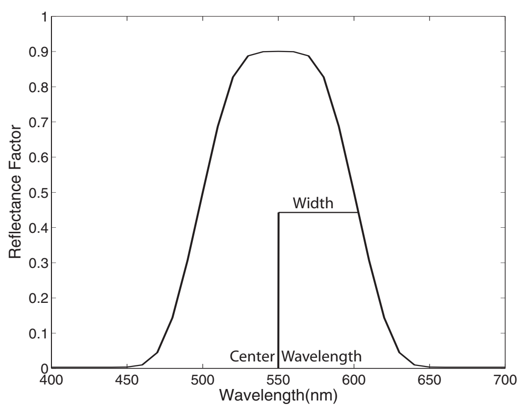

Figure 2. The ink spectral reflectance curve produced by the trapezium function with a single peak wavelength. The sharpness rate k was set to 0.02, the peak wavelength to 550nm, and the bandwidth to 60.

This trapezium function cannot simulate different spectral ink curves as well as Gaussian functions. However, based on previous research,[2] we found that these optimized inks were not as complicated as real ink curves. The ink curves are close to block ink curves so they are able to provide the higher lightness and chroma necessary for large gamut volumes.[2] The purpose of this theoretical research is to provide direction for ink design rather than producing real inks. Therefore, a simple model can be used to optimize the ink curves.

3. Optimizing the Ink Spectra for Maximizing Color Gamut

In this section, ink combinations were optimized for maximizing the gamut volume with the new trapezium ink spectra simulation function.

1) Method

In order to evaluate different ink sets, a virtual printing model was used to predict the spectra of overprints with different ink amounts from the ink and substrate spectra. This virtual model was developed in our previous research.[2] The color gamut created by a specific ink set can be calculated with factorial area coverage data. For example, we selected 11 steps from 0% to 100% area coverage in intervals of 10% for each ink. By combining these steps of four colors, there were 11^4=14,641 samples. According to the area coverage, corresponding spectral reflectance were calculated by the virtual printer model, and tristimulus values calculated for illuminant D50 and the 1931 observer. In order to evaluate the effect of printing gamut size, the tristimulus values were transformed to a more uniform color space, CIE94 corrected CIELAB space.[2] The color gamut was assumed as a convex hull and calculated with the MATLAB built-in Quick hull algorithm.

The maximum printing gamut for the optimized ink sets were first calculated. The objective function can be expressed as:

$$\underset{R_{\lambda,ink}}{Maximize} \quad [V(R_{\lambda,pred})] \tag{3}$$

where $R_{\lambda,pred}$ is calculated from the virtual printer model by ink set $R_{\lambda,ink}$ which were synthesized by Eq. 1. Preliminary research indicated that the optimal ink curves for maximum gamut volume were so sharp that they became block inks. Therefore, the sharpness rate was limited to 0.02 in order to simulate the sharpness of real ink.

2) Experimental

First, three-ink combinations were optimized. Figure 3 shows the optimized spectral reflectances for the three inks. The optimized results correspond with previous research.[5,6] These results confirm that for three-color subtractive systems, the optimum colorants can only be cyan, magenta and yellow.

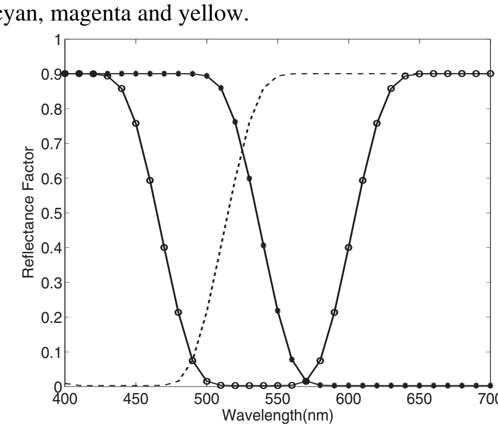

Figure 3. Three optimized ink reflectance spectra for maximum color gamut.

The four-chromatic ink combinations were optimized for maximizing the printing gamut. This optimization resulted in two different ink combinations, which achieved similar gamut volume. The first optimal four-ink set, shown in Figure 4, was generated by cyan, magenta, yellow, and purple. The second optimal four-ink set, shown in Figure 5, was generated by cyan, magenta, yellow, and green. Different inks combinations will increase the printing gamut in different directions. Therefore, depending on the application, one may be more desirable.

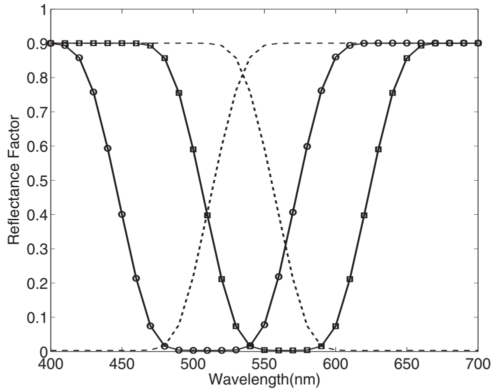

Figure 4. *The first optimized four-ink set for maximum color gamut.*

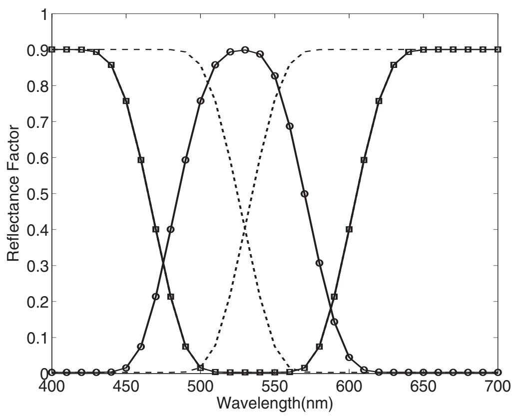

Figure 5. The second optimized four-ink set for maximum color gamut.

4. Optimizing the Ink Spectra for Minimizing Color Inconstancy

1) Method

Color inconstancy depends on the ink spectral properties and can be minimized by optimizing the ink spectra while maintaining a relative large color gamut. Generally a color inconstancy index (CII) is used as a metric to evaluate the extent of color inconstancy. The color inconstancy index is the total color difference between a sample's colorimetric coordinates under reference and test illuminants using a chromatic adaptation transformation (*e.g.*, CIECAT02) and a perceptually uniform color-difference equation (*e.g.,* CIEDE2000). The calculation of the color inconstancy index is described in references 1, 7 and 8.

The optimal ink combinations for maximizing color gamut were explored in the last section. In this section, color inconstancy was used as the optimization objective and color gamut used as a constrained condition. The objective function is expressed in Eq. 4.

$$I = \frac{\sum_{i=1}^{n} CII(R_{\lambda,pred,i})}{n} \qquad (4)$$

$$\underset{R_{\lambda,ink}}{Minimize} \quad [I]$$

$$Subject\ to \quad V(R_{\lambda,ink}) \geq (100 - m) * V(R_{\lambda,ink})_{\max}$$

where $R_{\lambda,pred,i}$ is calculated from the virtual printing model, in which the ink amounts are set to regular grid points in the colorant space. Function CII was used to calculate the color inconstancy indices of predicted reflectances between illuminants D50 and F11. Variation I represents the average color inconstancy index of the samples. The constrained condition is a compromise in color gamut created by the optimal ink primaries for color inconstancy index and should be less than a fixed *m*, of the maximum color gamut, $V(R_{\lambda,pred})_{max}$ created by the same ink primaries.

This problem is classified as a constrained nonlinear optimization and was solved by a pattern-search type algorithm.

2) Experimental

The optimal three-chromatic ink plus black ink set was optimized for minimizing color inconstancy according to Eq. 4. The spectral reflectance factors of the optimal ink set for minimum color inconstancy, for Illuminant D50 to F11, and its gamut volume limited to 5% in gamut compromise, are shown in Figure 6. The dashed lines represent the original ink set optimized for maximizing gamut volume, and the solid lines represent the ink set optimized for minimizing color inconstancy. Compared with the original ink set, the spectral ink curve widths were increased, especially for magenta ink. The sharpness rate of magenta ink was decreased.

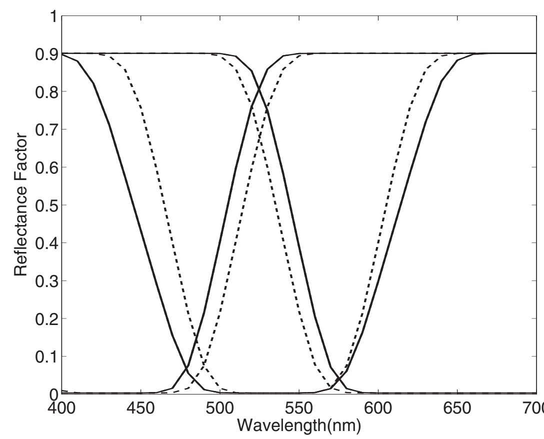

Figure 6. Spectral reflectance factor comparison between the three-ink set optimized for maximum gamut volume (dashed line) and minimum color inconstancy (solid line) with a 5% gamut volume compromise.

Table 1 shows the color inconstancy index statistics produced by the ink set optimized for gamut volume and that for color constancy. A small reduction in gamut volume resulted in a large improvement in color constancy.

Table 1. The color inconstancy indices from illuminant D50 to F11 produced by the three ink set optimized for color gamut and the three ink set optimized for color constancy.

	CII (D50 to F11)		
	Mean	Max	95% percentile
Ink set optimized for gamut volume	0.78	10.85	2.18
Ink set optimized for color constancy	0.50	4.71	1.49

5. Sensitivity analysis

In this section, the effects of the properties of spectral ink curves, such as center wavelength, width, and sharpness rate, on gamut volume and color constancy are explored. The different parameters of the magenta ink in the optimal three-ink set were changed to explore these effects. Its center wavelength and the width were changed from the optimal points within ±30 nm, in increments of 5 nm. The sharpness rate was changed from 0.008 to 0.02 in increments of 0.002.

First, the effects of different spectral changes for magenta ink on gamut volume were analyzed. As shown in Figure 7, shifting the center wavelength, changing the width, or decreasing the sharpness rate caused a similar decrease in gamut volume.

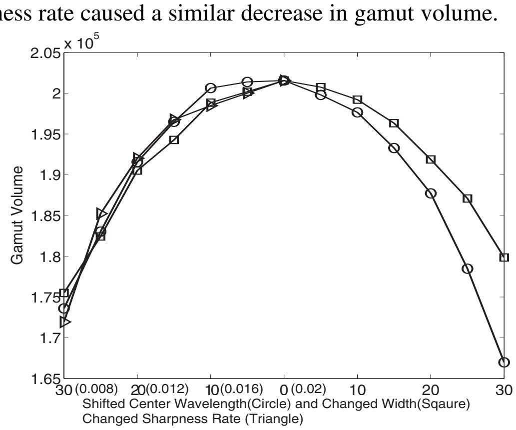

Figure 7. The effects of shifting center wavelength (circle), changing width (square), and changing sharpness rate (triangle) of magenta ink on color constancy.

Second, the effects of different spectral changes for magenta ink on color inconstancy were analyzed. The changes of color inconstancy from D50 to F11, caused by shifting the center wavelength, width, and sharpness rates of the magenta ink, are shown in Figure 8. The changes in color inconstancy caused by shifting the center wavelength and width had a much larger effect than sharpness rate. Generally the center wavelength position is the primary factor in the determining color inconstancy, followed by width, then sharpness. These trends were quite different, compared with Figure 7, in which changes in all three parameters caused a similar decrease in gamut volume.

5. Conclusions

In this research, different ink sets were optimized for maximizing color gamut with a new ink spectral synthesis function, the trapezium function. This enabled the computationally efficient (including optimization convergence) exploration of improving the color constancy of prints by ink design. The results showed that the color inconstancy of prints can be limited to a relatively smaller range by optimizing the ink set for minimal color inconstancy. The effects of ink properties on both color gamut and color constancy were analyzed. Three parameters of ink spectra, center wavelength, width, and sharpness rate, had similar effects on color gamut. Conversely, the color constancy of an ink set was mainly determined by center wavelength and width. The effect of sharpness on color constancy was negligible compared to the other effects.

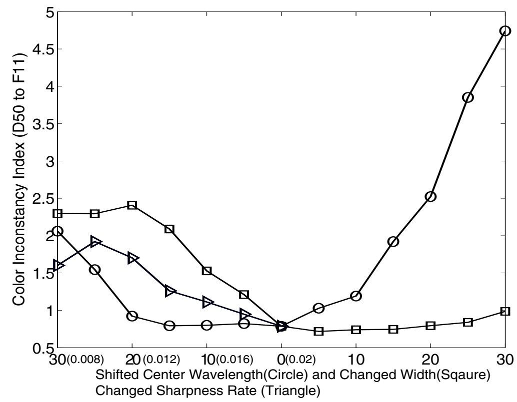

Figure 8. The effects of shifting center wavelength (circle), changing width (square), and changing sharpness rate (triangle) of magenta ink to the color constancy.

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Author Biography

Yongda Chen is a Ph.D candidate in Munsell Color Science Laboratory at Rochester Institute of Technology. He has been working with his advisor, Dr. Roy Berns, in the fields of Imaging Science and Color science. His works focus on Multi-ink Printer Characterization, Color Device Characterization, Image Quality Evaluation, Color Management, and Spectral Color Reproduction. He is expected to accomplish his Ph.D dissertation recently.