Improving the Color Constancy of Prints by Ink Design

Yongda Chen, Roy S. Berns, and Lawrence A. Taplin, Munsell Color Science Laboratory,
Chester F. Carlson Center for Imaging Science, Rochester Institute of Technology, Rochester, New York, USA

Abstract

A computer simulation was performed to investigate optimal four- and five-ink sets in order to minimize color inconstancy while maintaining a large color gamut. The effect of including a spectrally-flat black ink on color constancy was explored. The relationship between ink shape and the color constancy of prints was also analyzed. The results show that the ink shape in the middle wavelength region is very important for the color constancy of prints. The minimum and maximum color inconstancy indices that the different ink sets can achieve, which were optimized by different objective functions, were explored. The results show that color constancy can be improved by both ink design and lookup table creation.

Introduction

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. There does not yet exist a computational theory sufficient to explain the mechanism of color constancy of human vision. For many applications, it is very important that colored materials exhibit color constancy. However they often deviate significantly in hue when viewed under different light sources. In fact, color inconstancy is unavoidable. That means the perceived color always changes under different illuminants.

Color inconstancy is a very important factor to evaluate for the image quality of prints since prints are viewed under many different lighting conditions. The color constancy of neutral has always been a design criterion for photographic dyes.[2] Ohta[3] explored the optimum combination of cyan, magenta, and yellow dyes to create stable grays under different illuminants. Because of the popularity of ink-jet printing technologies, fortuitous color constancy is less commonplace. The practices of only using CMY for pictorial images and using dye-based black inks with long wavelength reflectance "tails" result in appreciable color inconstancy. As a consequence, in addition to color gamut expansion,[4-6] color constancy should be an ink-design criterion.

This paper is divided into two sections. In the first section, the theoretical ink design for color constancy was described. In the second section, color constancy properties of lookup tables combined by the optimized ink sets were evaluated.

Optimizing the Ink Spectra while Minimizing Color Inconstancy

As mentioned above, color inconstancy depends on the ink spectral properties and can be minimized by optimizing the ink spectral properties while maintaining a relative large color gamut.

Method

In this section, the different parts of the optimization algorithm are described. These metrics and models include the color inconstancy metric, theoretical ink curve function, printing model, gamut calculation, and optimization objective function.

Color Inconstancy Index

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 perceptually uniform color-difference equation. The calculation of the color inconstancy index is described in references 1, 7 and 8: Tristimulus values are calculated for illuminants of interest from an object's spectral reflectance. Using a chromatic-adaptation transform such as CIECAT02,[9] corresponding colors are calculated from each illuminant to D65. The corresponding-color tristimulus values are converted to CIELAB using D65 as the reference white. A weighted CIE94 color difference is calculated with $k_L = k_C = 2$ between pairs of corresponding colors. In this manner, hue inconstancy is penalized twice as much as lightness or chroma inconstancy. As a rule-of-thumb, samples with excellent color constancy have CII values below unity.

Absorption Bands of Hypothetical Inks by Symmetric Cubic Spline Function

In order to perform ink curve optimization, several different functions were considered to model ink spectra, including a Gaussian function, symmetric cubic-spline function, triangular function, line function, etc. All of these functions can model both one and two peak reflectance curves. At first, the Gaussian functions were used to simulate hypothetical ink curves.[5] 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. Moreover, some parameters became useless in some situations. The width and the peak wavelength were not useful when the height is zero, for example.

From previous research, 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.[5] 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.

From experience, the symmetric cubic-spline function can provide better convergence properties. Only two parameters, peak wavelength and width, are necessary to model one ink curve. However the symmetric cubic-spline function only can simulate single peak spectra in density space. As a consequence, it cannot directly model the green ink curve. Therefore, in this research the green ink was not considered. The spectral density of a theoretical ink was modeled by a symmetric cubic spline function[10,11,] with the peak wavelength and width, shown in Eq. 1:

$$\begin{aligned}
&D_{\lambda,ink} = \frac{\left\{w^3 + 3w^2\left(w-|\lambda|\right) + 3w\left(w-|\lambda|\right)^2 - 3\left(w-|\lambda|\right)^3\right\}}{6w^3} \quad \text{for..}|\lambda| < w \\
&D_{\lambda,ink} = \frac{\left(2w-|w|\right)^3}{6w^3} \quad \text{for..} w < |\lambda| < 2w \qquad\qquad (1) \\
&D_{\lambda,ink} = 0 \qquad \text{for..} 2w < |\lambda| \\
&R_{\lambda,ink} = 10^{D_{\lambda,ink}}
\end{aligned}$$

where $D_{\lambda,ink}$ represents the spectral density of the inks, $R_{\lambda,ink}$ represents the spectral reflectance of the inks, λ is the peak wavelength of an absorption band, *w* is the width of an absorption band, and the peak densities are normalized to 2.5, corresponding to the minimum reflectance, 0.0032.

Virtual Printing Model and Printing Gamut

In order to evaluate different ink sets, the spectra of overprints with different ink amounts should be predicted from the ink and substrate spectra. Therefore a virtual model was developed in our previous research. [5] The virtual model can be divided into two parts. In the first part, Kubelka-Munk turbid media theory[12] was used to predict the spectra of overprints with full area coverage, or Neugebauer primaries, with the assumption that transparent ink-jet inks would penetrate the paper support and yield a homogenous colored layer. In the second part, the Yule-Nielson modified Spectral Neugebauer model (YNSN)[13] was used to predict the spectra of samples from ink amounts of different inks based on the spectra of Neugebauer primaries. The Yule-Nielsen exponent, n value, was chosen as ten based on previous research.[14]

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 reflectances were calculated by the virtual printer model, 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.[5] The color gamut was assumed as a convex hull and calculated with the MATLAB built-in Quick hull algorithm[15] and notated as $V(R_{\lambda,pred})$. $R_{\lambda,pred}$ was calculated from the virtual printing model. Function V(x) was used to calculate the gamut volume produced by the Lab values in CIE94 corrected CIELAB space.

Objective Function for Minimizing the Color Inconstancy Index

A computer simulation was developed by the authors to investigate the optimum ink combinations for maximizing color gamut.[5] At that time, color gamut was the only optimization objective. In this research, color inconstancy was used as the optimization objective and color gamut was used as a constrained condition. The optimization objective is minimizing the color inconstancy of prints between two illuminations by investigating optimum ink reflectance spectra. The objective function is expressed in Eq. 2.

$$\begin{aligned}
&I = \frac{\sum_{i=1}^{n} CII(R_{\lambda,pred,i})}{n} \\
&\underset{R_{\lambda,ink}}{Minimize} \quad [I] \qquad\qquad (2) \\
&Subjectto \qquad V(R_{\lambda,ink}) \geq \left(100-m\right) * V(R_{\lambda,ink})_{maximum}
\end{aligned}$$

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, $V(R_{\lambda,pred})_{maximum}$ created by the same ink primaries.

This problem is classified as a constrained nonlinear optimization and was solved by the sequential quadratic programming (SQP) method. The MATLAB built-in optimization algorithm, *fmincon*, was utilized. The optimization results were verified with different starting values to insure the results were truly optimal.

Experimental

Effect of Black Ink on the Color Constancy of Prints

As is well known, the traditional ink set CMYK includes black ink and can provide stable neutral colors. However we do not know if it can improve the color constancy of chromatic prints. Therefore a computer simulation was performed to investigate the effect of black ink on color constancy. Based on the different ink sets, additional ink was optimized for minimizing the mean color inconstancy index for grid samples in the colorant space. The optimization results always converged to a spectrally-flat black ink curve. The mean color inconstancy index of all samples decreased significantly for different ink sets. Therefore, it can be concluded that black ink can improve color constancy significantly.

Optimize the Ink Sets for Maximizing Color Gamut

According to the description in the method, the maximum printing gamut for the optimized ink sets were first calculated. The objective function can be expressed as:

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

The three- and four-chromatic ink combinations were optimized maximizing the printing gamut. When calculating the printing gamut, the black ink was added into the three- and four-chromatic ink combinations. Figures 1 and 2 show the optimized spectral density for three and four chromatic inks.

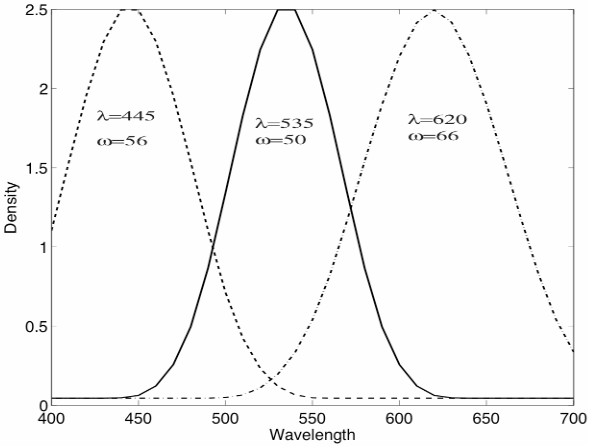

Figure 1. *Three optimized ink density for maximum color gamut.*

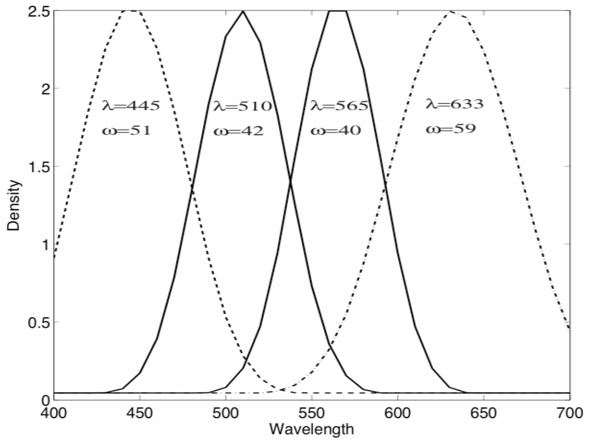

Figure 2. *Four optimized ink density for maximum color gamut.*

The Optimum Three Chromatic Inks Plus Black Ink Set

The black ink was added into the ink sets as a constant ink because of its important in color constancy. The other three inks were optimized according to Eq. 2 in which the compromise percent in gamut, *m,* was changed from 0% to 20% in 1% intervals. Figure 3 shows that the mean color inconstancy index decreased as the compromise in color gamut increased. Figure 4 shows the comparison of spectral density between the three-ink set with maximum gamut and the optimum three-ink set with minimum color inconstancy while limited to 10% gamut compromise. In Fig. 4, the peak wavelength of absorption band for cyan and yellow ink moved to longer and shorter wavelengths, respectively. The bandwidth of magenta was extended significantly and the ink shape becomes flatter.

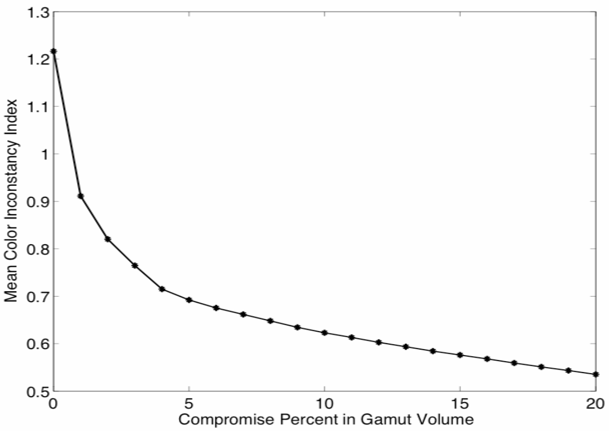

Figure 3. *The mean color inconstancy index of prints as the compromise gamut increase for three chromatic inks*

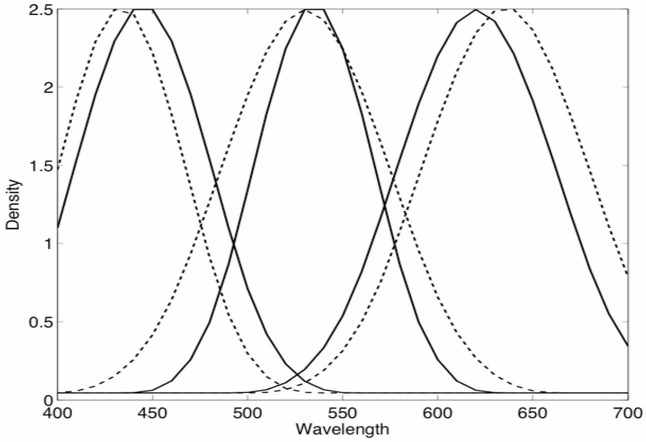

Figure 4. *Spectral Density Comparison between chromatic three-ink combination with maximum gamut (solid line) and optimum ink set for color constancy (dotted line) with 10% gamut volume compromise.*

The Optimum Four Chromatic Ink plus Black Ink Set

Based on the four-chromatic ink set with the maximum printing gamut, four chromatic inks, besides black ink, were optimized according to Eq. 2. The compromise percent in gamut *m* was also changed from 0% to 20% in 1% intervals. Figure 5 shows that the mean color inconstancy index of samples in five-colorant space decreased as the compromise in color gamut increased. Comparing Fig 3 and Fig 5, we found that the five-ink combination optimized for maximizing the printing gamut provided worse color constancy than the four-ink combination. The width of the ink spectral curve for the five-ink combination is narrower than that for the four-ink combination as shown in Fig 1 and 2. The spectral curve of the five-ink combination is sharper than that of the four-ink combination. Generally, the narrower and sharper ink curves result in greater color inconstancy.

Figure 6 shows the comparison of spectral density between the four-chromatic ink set with maximum gamut and the optimum four-chromatic ink set with minimum color inconstancy while limited by the 10% gamut compromise. From Fig 6, we find that the ink shapes of cyan and yellow changed only slightly, whereas the ink shapes of magenta and purple changed significantly. Their peak wavelengths moved and their absorption bands widened significantly, especially for the original purple ink. The original purple ink will become a spectrally-flat black ink as the compromise in gamut continues to increase and the original magenta ink will move to the middle wavelength and be widened. From Figs 4 and 6, it can be concluded that the color constancy properties of an ink set are determined principally by the ink shapes in the middle wavelength region.

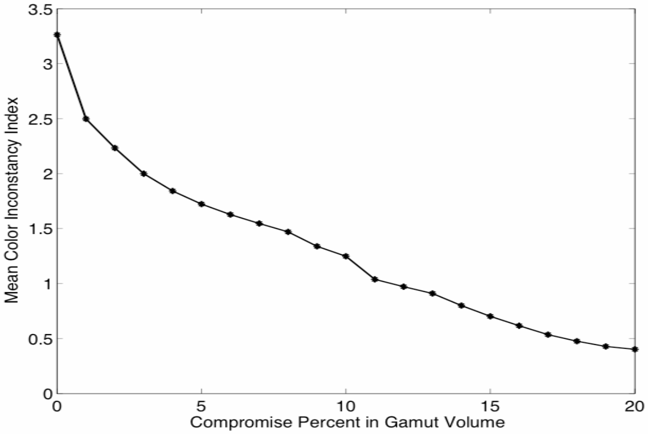

Figure 5. *The mean color inconstancy index of prints as the compromise gamut increase for four inks.*

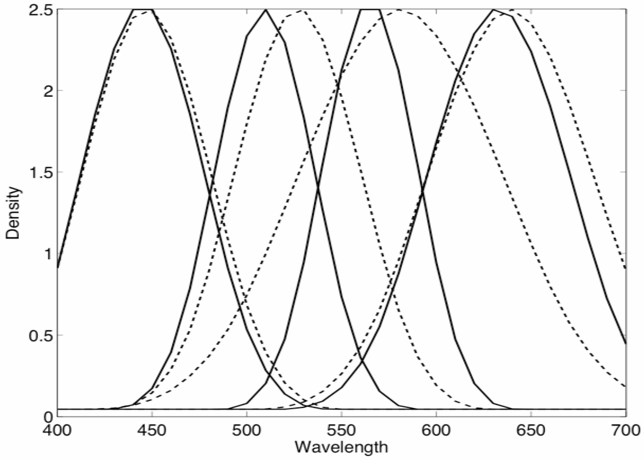

Figure 6. *Spectral density comparison between four-ink combination with maximum gamut (solid line) and optimum ink set for color inconstancy index (dotted line) with 10% gamut volume compromise.*

Properties of Color Lookup Table Created by Optimized Ink Sets

For multiple-ink printing, the identical color can be produced by different ink combinations. The different ink combinations have different color constancy properties as determined by their spectra. Therefore, color inconstancy can also be decreased by the proper color separation algorithm.[15] The lookup table combined with color constant ink sets can provide not only high colorimetric reproduction accuracy but also high image quality. In this section, the color inconstancy properties of the color lookup table combined by the ink sets optimized above are explored.

Method

The virtual printing model was combined with an optimization algorithm to perform the colorimetric reproduction of a test target. With the similar colorimetric reproduction accuracy, the maximum and minimum color inconstancy index, which each ink set can achieve, were estimated. This is a multiple objectives optimization problem. The weights were used to combine the different objectives and transfer it as a single objective optimization problem. The objective function is described as Eq 4. The MATLAB built-in optimization algorithm, sequential quadratic programming, was utilized.

$$\underset{ink\_amounts}{Minimize}\left[w1*I+w2*\overline{\Delta E_{00}}\right] \tag{4}$$

where *ink_amounts* represents the ink amounts for different inks and is the optimized parameter. Function I is the average color inconstancy index of predicted samples. $\overline{\Delta E_{00}}$ is the mean color difference between predicted and original samples under illuminant D50. The objective function is minimized by searching the appropriate ink amounts, *ink_amounts*. That means the proper ink amounts were found to make the reproduction colorimetrically matching the original target and possessing the minimum color inconstancy index at the same time. The weights, *w1* and *w2*, can be adjusted to minimize or maximize the color inconstancy index of the reproduction and to guarantee colorimetric accuracy simultaneously. For color reproduction, the colorimetric accuracy is always more important than other properties. The multiple optimization rounds were performed in order to find the optimal ink combinations, which can provide high color reproduction accuracy, and maximum or minimum color inconstancy. In the first round, the weight, *w1*, was set larger than or equal to the weight, *w2,* in order to minimize or maximize the color inconstancy. This weight setting might result in the poor colorimetric accuracy for part of samples. In the following rounds, the weight, *w2*, was increased in order to improve colorimetric accuracy for these samples. This process continued until the colorimetric accuracy could not be improved further, due to some samples being out of printing color gamut.

Experimental

The test targets included a grey scale, Gretag Macbeth Color Checker, and Color Checker DC. In order to compare color inconstancy, the four ink sets were used to reproduce the test targets, virtually. They were four- and five-ink sets with maximum color gamut, as shown in Figures 1 and 2, and four- and five-ink sets optimized for minimizing color inconstancy index and containing 95% maximum printing gamut, simultaneously. First the ink amount for these four ink sets were optimized to minimize color inconstancy of reproduction and color reproduction errors. The weights *w1* and *w2* in Eq. 4 were defined as positive numbers. Then the multiple rounds optimization was performed as described above.

Table 1 shows the color inconstancy performances for four ink sets based on the objective function above. Figure 8 shows the mean color inconstancy index as bars and the minimum and 95 percentiles of color inconstancy index as error bars. The optimized ink sets for color inconstancy index can provide better color constancy performance than the ink set with maximum gamut. Moreover more inks provide more possibilities of ink combinations, so five-ink sets can provide a lower mean color inconstancy index than four-ink sets, irrespective of whether the ink sets were optimized for color constancy or maximum gamut. We also find that the compromise in gamut results in more samples out of gamut.

As pointed out before, color constancy is only one criterion for image quality. The final color lookup table depends on compromises between color constancy, color gamut, spatial image quality, ink amount, etc. Therefore the worst case, or maximum color inconstancy that these ink sets can reach, was also estimated. The weight *w1* in Eq. 4 was defined as negative number, whereas *w2* as positive number.

Table 2 shows the worst performance of color constancy for different ink sets based on the objective function above. Figure 9 shows the mean color inconstancy index as bars and the minimum and maximum color inconstancy index shown as error bars. Compared to the ink sets optimized only for color gamut, the ink sets optimized for both color constancy and color gamut can decrease the maximum color inconstancy index significantly. In other words, even though the color constancy property of the final color lookup table gets worse when the other image quality criteria were taken into consideration, the relative low color inconstancy can still be guaranteed by the optimized ink combinations.

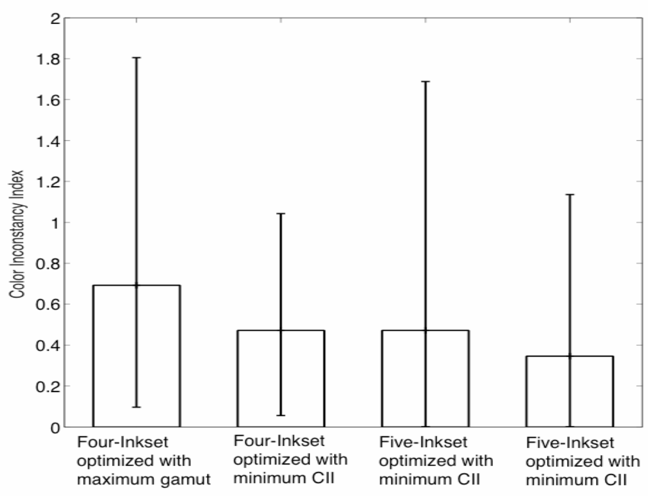

Figure 8. The mean color inconstancy index of reproduction produced by different ink sets and their 95 percentiles and minimum values expressed as error bars.

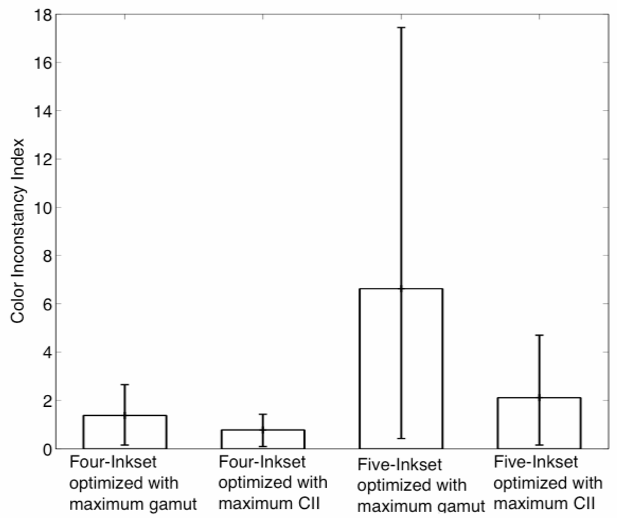

Figure 9. The mean color inconstancy index of reproduction produced by different ink sets and their 95 percentiles and maximum values expressed as error bar.

Table 1: The Property of Color Inconstancy of Predicted Reproduction Optimized for Minimizing the Color Inconstancy Index by Different Ink Sets

	Mean CII	Maximum CII	Minimum CII	95% percentile CII	Number of samples out of gamut
Four-ink set optimized with maximum gamut	0.69	3.59	0.10	1.81	8 (2.8%)
Four-ink set optimized minimizing CII while limited to 5% gamut compromise	0.47	2.72	0.06	1.04	12 (4.2%)
Five-ink set optimized with maximum gamut	0.47	8.54	0	1.69	2 (0.7%)
Five-ink set optimized minimizing CII while limited to 5% gamut compromise	0.35	2.13	0	1.14	3 (1.1%)

Table 2: The Property of Color Inconstancy of Predicted Reproduction Optimized for Maximizing Color Inconstancy Index by Different Ink Sets

	Mean CII	Maximum CII	Minimum CII	95% percentile CII	Number of samples out of gamut
Four-ink set optimized with maximum gamut	1.38	4.36	0.16	2.65	8 (2.8%)
Four-ink set optimized maximizing CII while limited to 5% gamut compromise	0.77	2.72	0.09	1.43	12 (4.2%)
Five-ink set optimized with maximum gamut	6.63	31.71	0.42	17.44	2 (0.7%)
Five-ink set optimized maximizing CII while limited to 5% gamut compromise	2.12	8.63	0.15	4.70	3 (1.1%)

Conclusions

In this research, the possibility of improving color constancy of prints by ink design was explored. The results show that the color inconstancy of prints can be limited to a relatively lower range by optimizing the ink set for minimizing the color inconstancy of all ink combinations. Later the color constancy of prints can be improved further by optimizing the color lookup table. Therefore, in order to improve the color stability of prints, the color constancy properties should be taken into consideration in both stages, ink design and the creation of the color lookup table. The color constancy of a specific ink set can be improved as a whole from the proper ink design. Moreover, the ink combinations with high color constancy can be selected based on the optimized color separation algorithm. In further research, the model of ink spectral curve will be improved so that the green ink curve can be simulated.

References:

1. R.S. Berns, Billmeyer and Saltzman's Principles of Color Technology, 3rd Ed., John Wiley & Sons (2000)
2. F.R. Clapper, Color reproduction, in T.H. James, editor, The Theory of the Photographic Process, 4th Ed., Macmillan, New York, 561-577 (1977).
3. N. Ohta, Stability of Selective Grey Obtainable by Use of Subtractive Color Dyes, Journal of Photographic Science, 20:149-153 (1972).
4. V. Ostromoukhov, Chromaticity gamut enhancement by heptatone multi-color printing, Proc. SPIE 1909, 139-151 (1993)
5. Y. Chen, R.S. Berns and L.A. Taplin, Extending Printing Color Gamut by Optimizing the Spectral Reflectance of Inks, Proc. IS&T/SID 12th Color Imaging Conference, 163-169 (2004)
6. J.A.S Viggiano, W.J. Hoagland, Colorant selection for six-color lithographic printing, Proc. IS&T/SID sixth Color Imaging Conference, 112-115 (1998).
7. R.S. Berns and F.W. Billmeyer, Proposed indices of metamerism with constant chromatic adaptation, Color Res. Appl. 8, 186-189 (1983)
8. M.R. Luo and R.W.G Hunt, A chromatic adaptation transform and a colour inconstancy index, Color Res Appl 23, 154-158 (1998)
9. N. Maroney, M.D. Fairchild, R.W.G Hunt, C. Li, M.R. Luo, T. Newman, The CIECAM02 color appearance model, Proc. IS&T/SID 10th Color Imaging Conference, 23-27 (2002)
10. N. OHTA, Introduction to Color Reproduction Technology, Corona Publishing Co., Ltd., 240 (1997).
11. O. Takayuki, Optimization of Subtractive Three Color Dyes for Dye-Based Color Ink Jet Printer, J Imag Sci Tech, 502-510. (2004)
12. P. Kubelka, and F. Munk, Ein Beitrag zur Optik der Farbanstriche, Z. Tech. Phys. 12:593 (1931).
13. J.A.C Yule and W.J. Nielsen, The penetration of light into paper and its effect on halftone reproductions, Proc. TAGA, 3:65, (1951).
14. Y. Chen, R.S. Berns, and L.A. Taplin, Six color printer characterization using an optimized cellular Yule-Nielsen spectral Neugebauer model, J Imag Sci Tech, 519-528, (2004).
15. C.B. Barber, D.P. Dobkin, and H.T. Huhdanpaa, The Quickhull Algorithm for Convex Hulls, ACM Transactions on Mathematical Software, Vol. 22, No. 4, Dec. 469-483 (1996).
16. Y. Chen, R.S. Berns and L.A. Taplin, A Multi-Ink Color-Separation Algorithm Maximizing Color Constancy, IS&T/SID 11th Color Imaging Conference, 277-281 (2003).

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 has published five papers in the related fields and owns a patent pending in the area of multi-ink printing. He is expected to accomplish his Ph.D dissertation recently.