

SPECTRAL PROOFING

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Abstract: The revolution of “Device Independent Color” (Changing from density matching to colorimetric matching) has completely changed the workflow (from analog to digital) of color reproduction and has made a tremendous impact on the Graphic Arts industry. Now, another color revolution is about to come. This will be the change from colorimetric matching to spectral matching. Colorimetric Matching matches color only for the “average viewer” when viewed under standard viewing conditions. Spectral Matching will match color under any viewing condition for any viewer. Therefore, this revolution will not just change the workflow but redefine the entire Printing and Publishing industry. In this paper, color proofing application using spectral matching technology will be discussed.

Introduction

Color proofing is a process that predicts color of a color reproduction. Conceptually, both color reproduction and color proofing are processes of color matching although their matching targets and matching criteria are quite different. For color proofing, accuracy of color matching is more critical, but for color reproduction, pleasing color is the goal.

Every visible color has its own spectrum. Colors that have the same spectrum match each other. However, graphic art reproduction would not be possible if one could not use a small set of colorants to reproduce color. It was found that many color stimuli could be completely matched in color by the additive mixtures of three fixed primary stimuli (Trichromatic principle). And it was also found that under given viewing conditions, colors with different spectra could have the same appearance (Metamerism). Based on these color science principles graphic art reproduction became reality.

Metamerism (colors with different spectra (“shapes”) could have the same appearance (“area”)) suggests mathematical integration of weighted spectrum over all visible wavelengths. Therefore, color can be specified by integrating with different weighting functions. The color is based on densitometry when the weighting functions are a set of filtering response functions (for a scanner) or photo sensitivity functions (for a camera), and it is based on colorimetry when the weighting functions are a set of color matching functions derived from visual color matching experiments.

Traditional graphic art reproduction does not take advantage of colorimetry because photography is non-colorimetric, and the printed color image is controlled by color-separated films through optical process, which are operated basically in the “density domain”. The same is true for conventional color proofing (analog proofing). Because the weighting functions in densitometry does not relate to the human visual response, color matching quality relies heavily on the color property of the colorant and media.

The advancement of digital technology has revolutionized color reproduction in the last ten to fifteen years (Schreiber, 1985)(Liang, 1992). The digital camera can now capture colorimetric signals. Digital color signals are now used to directly control the plate making (computer to plate technology) and printing process (digital printer/proofers). With proper color management utilizing a digital computer, color can be matched colorimetrically under various printing conditions.

However, the shortcoming of current colorimetric matches is that colors match only under standard viewing conditions to an “average” observer. Since no one is the “average” observer, same colorimetric values could have different appearance to different observer (observer metamerism)(Alfvin, 1996). Therefore matching quality is judged differently from person to person. Furthermore, a match will become a mismatch when it is viewed under different lighting conditions (illuminant metamerism)(Berns, 1986). This issue is critical for catalog printing where people expect the color of a product to be the same as it is advertised in the catalog. It is also very important for packaging industry where customers would like to see that, under normal room lighting, the color image on the “box” represents the color of the contents in the “box” and that all specialty colors (such as Coca Cola Red) remain matched. Therefore the ultimate goal of color reproduction and color proofing is to achieve a color match that is independent of the observer and lighting condition. Spectral matching (matching spectrum) is the only way to reach this goal.

In recent years, the development of multi-spectral technology has brought spectral matching much closer to reality. High-resolution multi-spectral image capturing technology has been developed to enable input devices such as scanners or cameras to record the color spectrum of the image (Imai, 1998)(Burns, 1996). Spectral based multi-ink printing technology (Tzeng, 1998) (Iino, 1997) will enable output devices such as printers or proofers to utilize spectral match in the print reproduction.

The Spectral Model

If a spectrophotometer measures color spectrum in a 10 nm interval over the range of 400 nm to 700 nm, 31 “ideal” primary inks (with sharp spectrum in a

10 nm bandwidth) would be good enough to match spectrum. However, such ideal inks do not exist.

If ink reflective spectrum were additive, under certain conditions (a comparable color gamut), a color spectrum could be achieved by using a linear model of color mixing from a small set of non-ideal inks. But as we all know, reflective spectrum for printing ink is non-additive.

A solution for this is to find a transformation by which the reflective spectrum in the transformed space is additive. Kubelka-Munk theory (Kubelka and Munk, 1931) has been successfully applied to spectrally match automotive paint. The K-M transformation of the reflective spectrum for opaque automotive paint on metallic material is relatively additive. However, in printing and proofing, most inks used are either transparent or translucent. The K-M transformation for printing ink on paper is, in general, not additive (Wyszecki, 1982). Furthermore, printing or proofing requires one ink set to match all colors in a color image.

Current research in RIT found that, using Principle Component Analysis (PCA)(Tzeng, 1998), colors in artwork painting could be spectrally matched by using no more than six inks in the press. Research in DuPont confirmed this finding for printing inks that colors printed on the press can be spectrally matched by using no more than six inks in a proofer.

Although the K-M model could not directly be used to derive ink concentrations (or the digital values of the six colors) for a spectral match, the overall modeling could be done in two stages:

1. Ink selection stage: use PCA to optimize a transformation with which an ink set that cover the given color gamut in the spectrum domain could be defined.
2. Color matching stage: use a separate printer model and proper color management system (Liang, 1998) (Iino, 1997) (Kang, 1997) to derive the ink concentrations (digital values) for selected ink set.

In the ink selection stage, color gamut and sampling sensitivity are two important issues while in the color matching stage, property of optimum and measure of metamerism are critical. Each of these four areas is discussed below.

Color Gamut in the Spectral Domain

It is always true for both colorimetric matching and spectral matching that one can only match color that is inside the color gamut of the printer/proofer although the color gamut in colorimetric space is quite different from the color gamut in the spectral domain or its transformed space. The analysis of color

gamut in spectral domain is more complex than in colorimetric domain. However, the gamut mapping in the spectral domain might have an advantage over that in the colorimetric domain. In practical situation, PCA is not sufficient for a complete gamut analysis because “holes” exist in the color gamut due to digitization in the input space and the improper internal mapping of the device. On the other hand, the “uncovered colors” in the reduced dimension from a PCA, although it constitutes only a small percentage, might be the important colors. The gamut analysis in spectral domain and the gamut mapping using spectral technology are separated issues that will not be discussed in this paper.

Sampling Sensitivity

PCA is sensitive to the sample distribution. If the color samples are not a true representation of the image color, the spectral matching could fail. In proofing, the task of sampling is relatively easy because all colors are printed with known primary inks and the sampling process is similar to device characterization. The critical question is that if the sampling scheme (the number of samples and the distribution of samples) changes, how would that affect the selection of ink?

The following experiments have been conducted to investigate the sampling sensitivity. Eight sampling schemes were chosen:

1. 3x3x3 grid samples uniformly distributed over the entire color gamut;
2. 4x4x4 grid samples uniformly distributed over the entire color gamut;
3. 6x6x6 grid samples uniformly distributed over the entire color gamut;
4. 11x11x11 grid samples uniformly distributed over the entire color gamut;
5. 27 random samples;
6. 64 random samples;
7. 216 random samples;
8. 1331 random samples;
9. 3 primary + 3 secondary + black and white all in 100% density.

Two sets of initial ink vectors were chosen for the experiment.

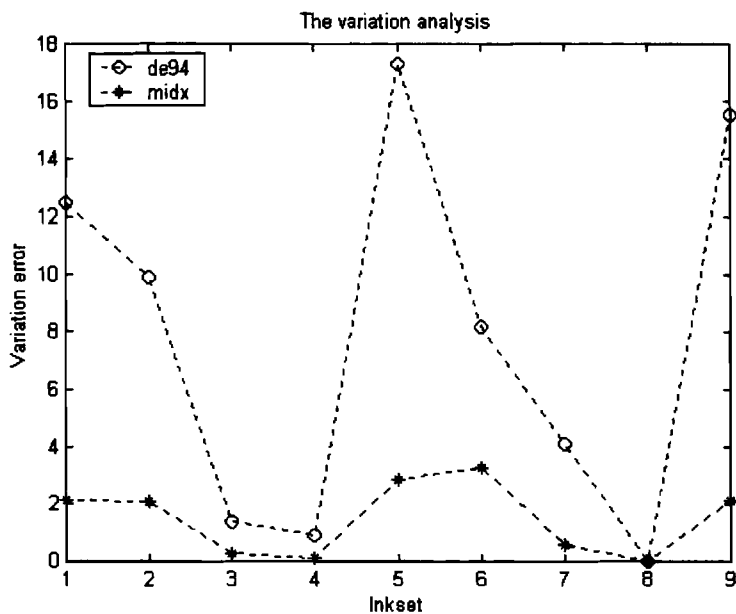


Figure 1.

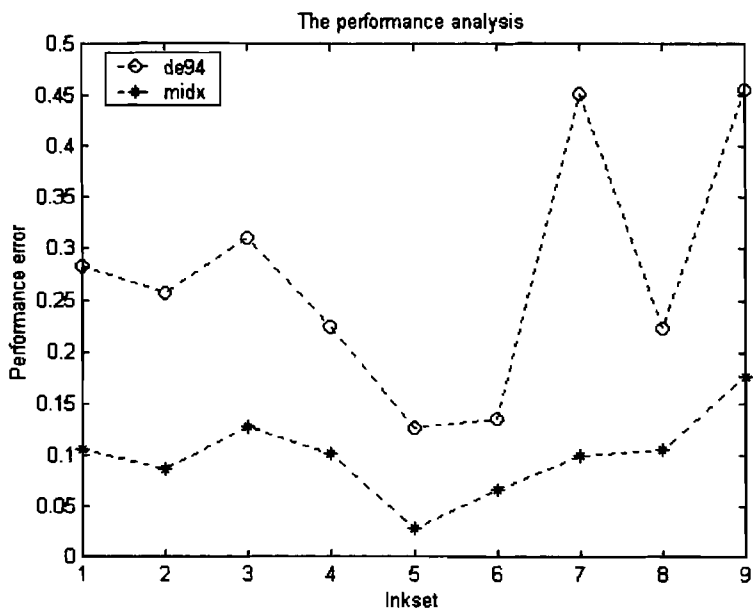


Figure 2.

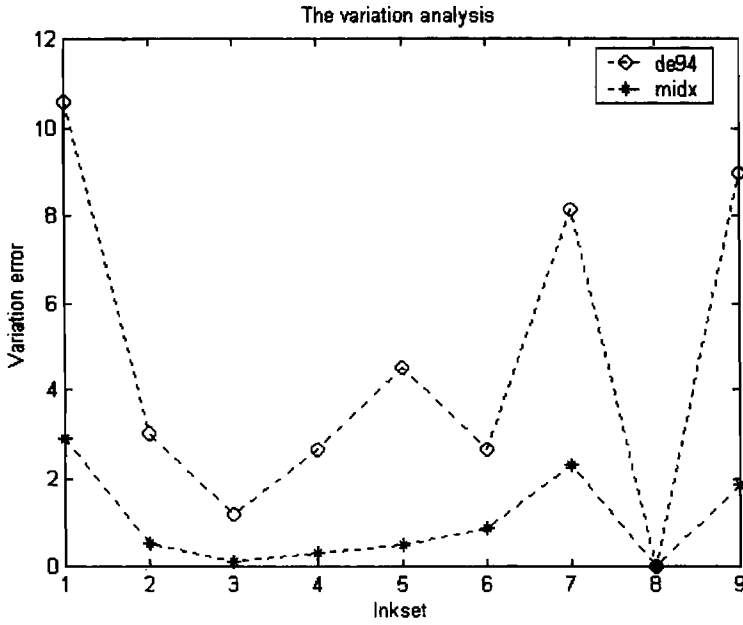


Figure 3.

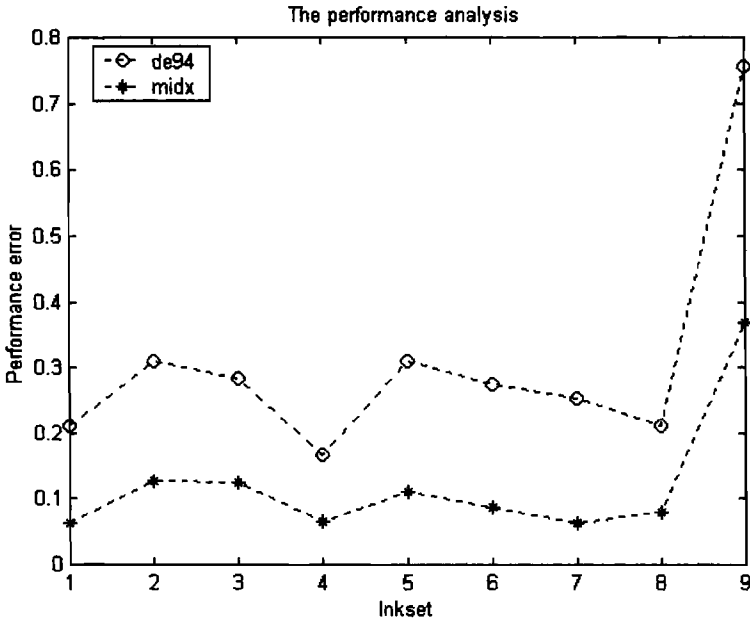


Figure 4.

Figure 1 (for the first set of initial ink vectors) and Figure 3 (for the second set of initial ink vectors) show the spectrum variation of the derived ink sets from the reference ink set (the set 8) in terms of mean CIE 94 delta E and mean metamerism index. Figure 2 (for the first set) and Figure 4 (the second set) show the color matching performance (match to 1331 uniform samples) of each set in terms of mean CIE 94 delta E and mean metamerism index.

From Figure 1, the ink set derived from 1331 grid samples (set 4) is very close to the ink set derived from 1331 random samples (set 8) and the spectrum variation decreases as the number of samples increases (set 1 to set 4 and set 5 to set 8). However, for different initial ink vectors, Figure 3 does not follow the same trend (see set 3 to set 4 and set 6 to set 7). Although different sampling schemes results in different ink sets (distinguishable from each other by as much as 2 to 18 mean delta E), the difference in color matching error is very small (around 0.3 mean delta E). This means that

1. there are many possible ink sets that have similar matching performance;
2. the ink selection model for proofing application is not sensitive to the sampling scheme;
3. a very small set of samples will be sufficient.

Multi-color System

In the color matching stage, a multiple-color system will be used. The multiple-color system allows color matching to use more than four non-processing color inks. It has been used to expand the color gamut for Hi-Fi printing. Our experience has shown that by using a selected ink set, colorimetric matching could sometimes produce exceptional spectral matching result. By using a colorimetric matching system to do spectral matching, we can work with a 3-D "profile connection space" (PCS) instead of a 31-D PCS. However, for a 6-color multi-color system, there are many possible transformations from the colorimetric PCS to a 6-color space. We have found that different color combinations have significantly different spectral matching performance. Furthermore, there are many possible spectra that have the same colorimetric value. Therefore, in order to use a colorimetric matching system to do spectral matching, having proper color management is very important. The color management technique for spectral matching using colorimetric matching system will not be discussed in this paper.

On the other hand, there is an advantage to working in a 31-D spectral PCS in that the transformation to the device color space (the six-color ink domain) is unique. In this case, the capability of correct mapping depends on the property

of optimum. In either case, the measure of metamerism is critical because the color matching algorithm is controlled by the error criterion.

Properties of Optimum

PCA has shown that one can find an ink set to match a color spectrally with no more than six inks. The actual ink set is derived by expanding the eigen vectors into the ink domain and finding an ink set that minimizes the matching error to the test samples. Therefore, the ink selection process is an optimization process. In terms of the shape of the optimum, there are sharp optimum and flat optimum. In terms of the number of optimum, there are single optimum and multiple optima. Sharp optimum ink set indicates high sensitivity to spectrum error but it also has high probability of being correctly selected. Multiple optima provide flexibility for spectral ink selection and spectral ink design but it has high probability of getting local minimum.

Figure 1 – 4 clearly indicates multiple optima – different ink sets were obtained when different sampling scheme or different initial ink vectors were used. Experiments were conducted to examine the sharpness of the optima and to investigate for local optimum. First, we selected two significantly different ink sets (about 12 mean delta E) for the first initial ink vectors (set 1 and set 9 in Figure 1). We then slowly varied the spectrum of set 1 toward set 9 (10 steps in the experiment). The matching error is plotted in Figure 5.

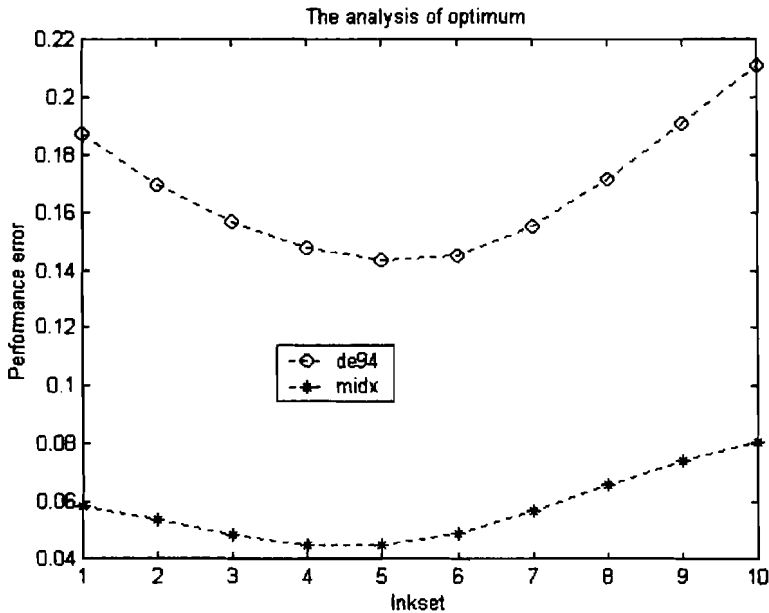


Figure 5.

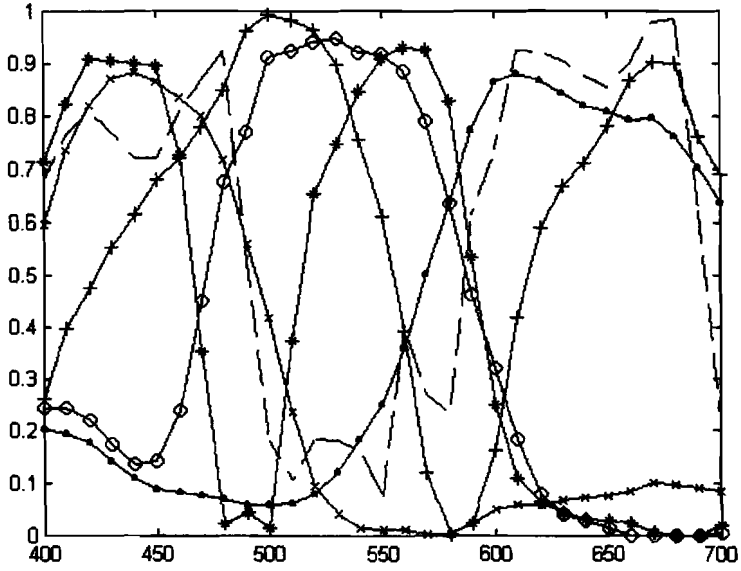


Figure 6

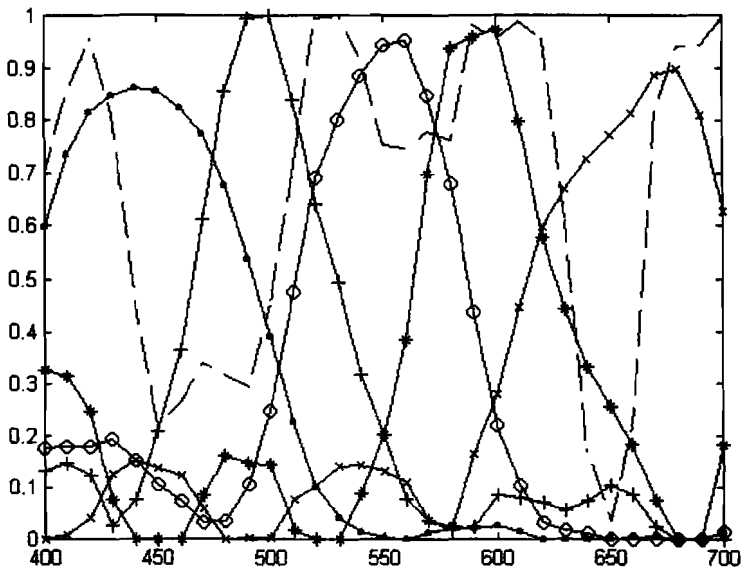


Figure 7.

From Figure 5, one can observe a “real” optimum in step 5, which means that both ink sets derived from the ink selection model were local optima.

Next, we select another two ink sets (set 1 from Figure 1 and set 9 from Figure 3) that have much larger difference (about 60 mean delta E). Figure 6 and Figure 7 plot the spectrum for the two sets. We then repeat the above procedure and the result is plotted in Figure 8.

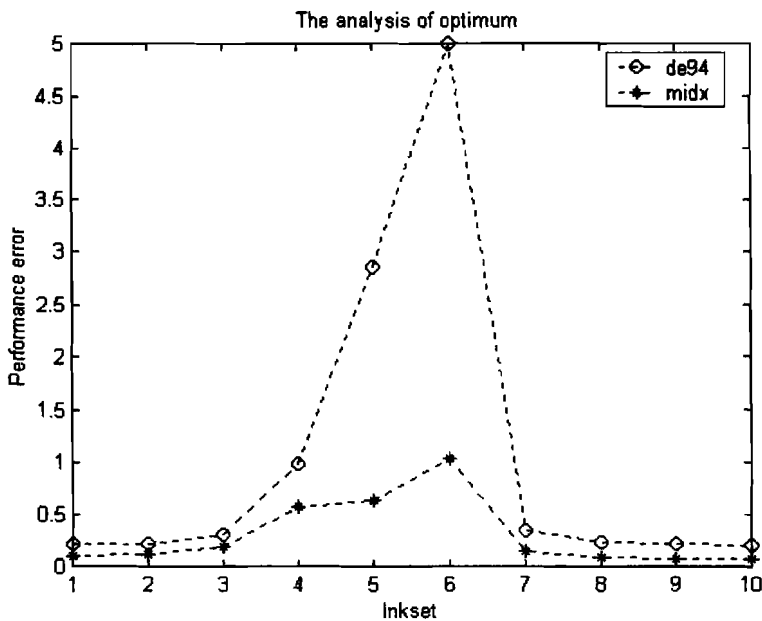


Figure 8

From Figure 8, one can see that both optima are flat. It will, therefore, have higher tolerance for ink selection error.

Multiple optima provide great flexibility in ink selection and ink design. By using the ink selection criterion or ink design criterion as control parameter, it is possible to obtain the designed ink set. How to control the optimization process to achieve desirable ink sets is out the scope of this paper.

Measurement of Metamerism

In spectral matching, accurate measurement of metamerism is very important. A general measure for metamerism is metamerism index. It is defined as

$$MI = \sqrt{(\Delta L_1 - \Delta L_2)^2 + (\Delta a_1 - \Delta a_2)^2 + (\Delta b_1 - \Delta b_2)^2} \quad (1)$$

It is the relative color difference between two illuminants (measure of illuminant metamerism) or between two observers (measure of observer metamerism).

An experiment is conducted to calculate both the observer metamerism index and illuminant metamerism index between samples taken from a press-run-test-sheet and a test sheet produced by a proofer. Eight colors (Cyan, Magenta, Yellow, Red, Green, Blue, three-color-gray and black) were chosen. Each color has ten levels in a 10% interval except for black (which has six levels). Illuminants used for measuring illuminant metamerism are D65 and illuminant A and observers used for calculating observer metamerism were CIE 1931 standard colorimetric observer and CIE 1964 supplementary standard colorimetric observer. Figure 9 and Figure 10 show the results.

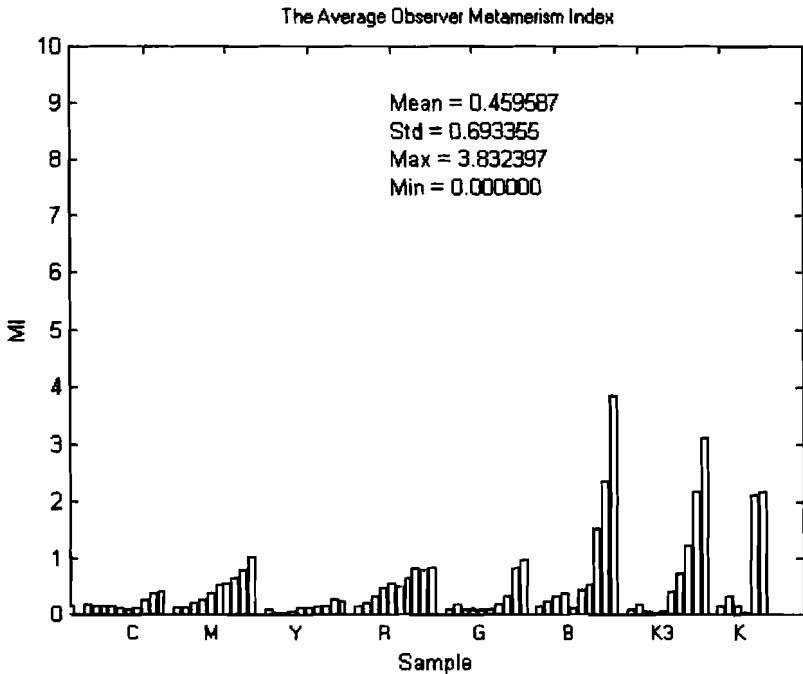


Figure 9.

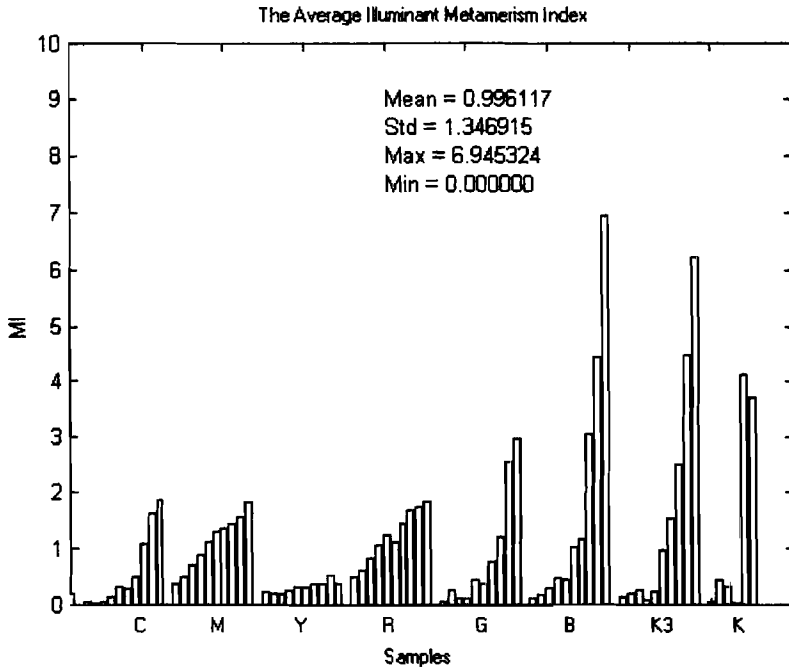


Figure 10.

From Figure 9, a match could have appeared to two different persons with up to 4 delta E color difference in blue and 3 delta E in three-color-gray. From Figure 10, up to 7 delta E color difference could have been observed when viewing under two different light sources.

However, we have found that the metamerism index will be small if the initial color difference is small. Therefore, the general formula for measuring metamerism is not perfect. Its accuracy also relies on the uniformity of the color space. DuPont has developed different metrics for measuring metamerism, which have been used in spectral matching of automotive paint. Its usage in spectral proofing is under study.

Summary

Proofing using spectral matching technology will match color under any lighting condition for any viewer and therefore produce truer proofs. It is found that no more than six inks in the proofer will be sufficient to spectrally match color of the press under various printing conditions. It is also found that a very small set of samples will be sufficient to derive the optimum ink set. For a given spectrum of printing primary, it is possible to obtain many different ink sets for the proofer that have similar spectral matching performance.

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