

MATCHING DIGITAL PRINTERS TO ANALOG PROOFERS

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Key Words

Color, Proofing, Printer, Match, Model.

ABSTRACT

Color proofing is an important element of the color reproduction process. It is used to predict the appearance of the final reproduction and to monitor and control the many steps of the reproduction process. The conventional analog proofing process is expensive, complex and slow. With the advanced digital printing technologies such as thermal dye transfer and ink jet technology, one is able to produce color image inexpensively, more easily and more quickly. However, because the mechanism of these technologies are very different from press, matching color of digital printers to analog proofers is the key to digital proofing. In this paper, a method of doing device-independent high quality color matching is described. Color matching issues on different types of digital printing technologies will also be addressed.

BASIC CONCEPTS

Matching a digital printer to an analog proofer, like all other color matching problems in color reproduction, requires:

1. a matching strategy;
2. a matching target which can be specified (be measurable);

3. a system model of the matching problem;
4. a strategy that handles not "matchable" (out of gamut) colors.

Definitions of Color matching

First of all, one has to define what "match". There are basically three types of match:

- *global scale match* : The average color informations (the number of bits) represented in the two color gamuts are the same.

- *colorimetric match* : under standard viewing conditions, the tristimulus values of every corresponding color level in the two color gamuts are the same.

- *appearance match* : the two corresponding colors look the same.

In the application of color proofing, colors are compared with the same image under standard viewing conditions. Therefore, for color inside the common color gamut, a colorimetric match strategy is appropriate. For color outside the common color gamut, the balance between global scale match and appearance match will be adjusted based on the application.

Secondly, one has to determine how a system match is measured. To match every color in the outputs of the two devices is impractical because extremely large number of color samples are involved. In practice, there are mainly two approaches:

1. *primary-decomposition* : all colors are decomposed into a linear combination of a set of N "primaries" (which can be a non-orthogonal set). If samples from these "primaries" are matched, the linear combinations of them are considered matched.

2. *color space sampling* : if all colors from a sufficiently large set of samples over the entire

color space are matched, the colors between samples are considered matched.

Our experience showed that matching in primaries (e.g. CMYK) is not good enough. Therefore a color space sampling approach is used.

Color space for matching

Color can be represented in many different ways. However, since color matching is performed between two different types of devices, for high quality color matching a device-independent color space has to be used. Although different device-independent color spaces are related, their effects on the quality of color matching are not the same. Because the matching process is driven by matching errors, a perceptually uniform color space, in which errors have the same visual scale, is most appropriate. CIE $L^*a^*b^*$, among all other CIE standard color spaces, from our experience, is considered one of the best approximations to a visually uniform color space. Therefore, it was chosen as the color space for our color matching process.

System model of matching

Matching the output color O of a given device to a targeted color T can be considered as a problem of finding a transformation T which transfers the input I to a new input I' , such that the output O' for the input I' matches the target T (Figure 1).

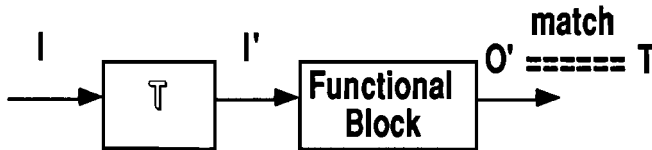


Figure 1.

The matching problem can further be reduced to a problem of finding a corresponding input I' for a given output T .

There are two approaches to this problem.

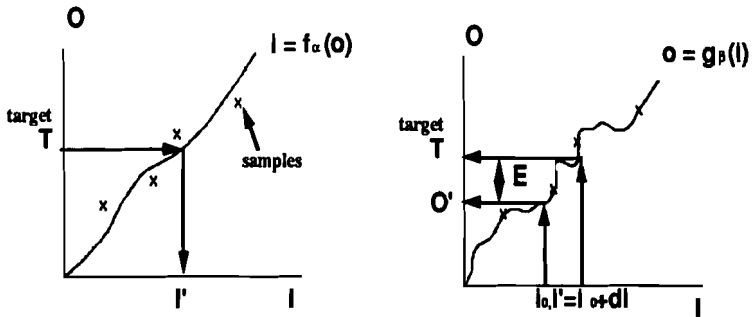


Figure 2. backward modeling vs. forward modeling with backward searching

1. *Backward-modeling*: Backward modeling of the device (left side of figure 2) is a straight forward approach to the problem. However, reversing a forward device model is not trivial. Many physical models, such as Neugebauer, are very difficult to reverse. Most interpolation techniques used for mathematic modeling are designed for regularly spaced data samples. They cannot be used for backward modeling because the distribution of sample points in the interpolating space, which is the output color space of the device (such as CIElab), is irregular. Techniques of interpolation from scattered data are less mature and more complex, and their performance depends on the distribution of samples in the device's output color space which, in many cases, are very difficult to control. Similarly, the performance of various regression techniques (line fitting techniques) used for mathematical modeling are limited by the controllability of sample distribution in the output color space. Neural network technologies have not been very successful for modeling in the color matching problem because it is practically difficult to achieve high accuracy of mapping for a large set of training samples, and conceptually uncontrollable of its interpolation performance on non-training samples.

2. *forward-model-with-backward-searching*: In the forward-model-with-backward-searching approach (right side of Figure 2), an initial output color value is predicted by the forward model and compared with the target. An adjustment in the input of the model is then calculated by an optimization procedure which minimizes the matching error (the difference between the predicted value and the target). A new output value is predicted again through the forward model for the new input value which is the initial input value plus the adjustment found. The process is repeated until a zero error (for an in-gamut color) or a minimum error (for an out-of-gamut color) is reached. Because the sample distribution in the input space is controllable, the use of forward models provides much more freedom in the design of sampling schemes than backward models. With a sufficiently large set of samples, the difference between models will become insignificant when a proper distribution of samples is chosen. This means that one can use the fastest and simplest model (e.g. a piecewise linear model) for the device without significantly affecting the accuracy of the model. Therefore, the key element of the design for this type of techniques is the searching algorithm rather than the model. The two most critical factors in the design of searching algorithm are the speed of convergence and the capability of overcoming the so called "local minimum problem".

Our system model uses the "forward-model-with-backward-searching" approach. A multi-dimensional piecewise linear model is used and an optimization procedure called *Modified Vector Shading* (MVS) technique was developed. MVS has a high convergence rate and is capable of eliminating completely the "local minimum" problem.

Gamut Mapping Strategy

Because different printers have different color gamuts, some colors in the output of the proofer may not be producible by the printer. In order to preserve the information in the color image, one has to represent the non-reproducible colors within the printer's color gamut. Techniques

of this sort are often referred to as gamut mapping.

There are basically two approaches to the gamut mapping problem:

1. *Input-space-mapping*: the mapping is done inherently in the input space by first normalizing the CIE RGB value to 8 bits, then converting CIE RGB to printer's CMY by using the complementary relationship between additive color and subtractive color, and finally determining K by utilizing the gray-equivalence property, which associates the black ink with the three primary inks, by using or Gray Component Replacement (GCR). The advantage of such mapping is that no knowledge of output color gamut is needed, and no color artifacts will be produced. However, its overall color accuracy is relatively low because both the complementary relationship and the gray-equivalence property are not truly valid.

2. *Output-space-mapping*: the mapping is done by either truncating the out-of-gamut colors or re-scaling (compressing) the color values in the proofer's output space according to a given criterion. The criterion is either attribute restricted (e.g. constant hue, constant lightness or constant saturation) or error-restricted (e.g. minimum delta E), or geometric-restricted (e.g. compression toward center). None of the attribute-restricted compression performs well in all regions of the color gamut. For example, the constant-lightness compression performs poorly in the region above the upper surface of the color gamut especially around the yellow region. Either the error-restricted compression or the attribute-restricted compression may produce color artifacts due to the crossover of compression paths. All output space mapping technique require complete (three dimension) knowledge of the output color gamut, and the compression processes are usually time consuming.

A gamut mapping technique which takes the advantage of both input-space-mapping and output-space-mapping approaches, was developed for our color matching system.

TECHNICAL DESCRIPTION

The system developed for matching a digital printer to an analog proofer is, in fact, a subsystem of GIMS (the Generic Image Matching System) developed by DuPont. The basic technical functions of all GIMS' subsystems are similar. The details can be found in the reference (Liang 1992). The details on the new gamut mapping technique will not be presented at this time and may be presented in a later paper. The followings are outlines of the description from the reference (Liang 1992).

Basic procedures

1. Sampling (left side of Figure 3) Digital images of test patterns which represent grid-samples in the color space are printed by both the proofer and the printer. The $L^*a^*b^*$ value of each color patch is measured by a spectrophotometer for both the proofer and the printer.

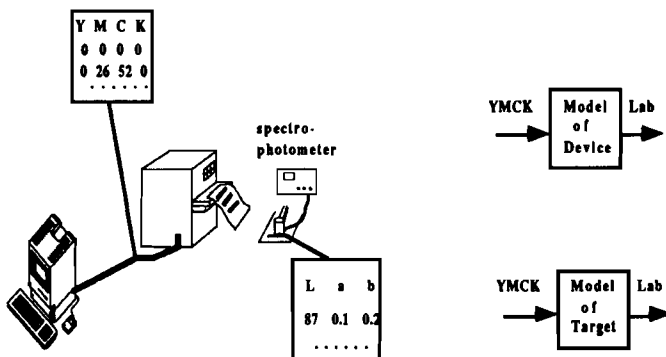


Figure 3 Sampling & Modeling

2. Modeling (right side of Figure 3) For both the proofer and the printer, the input/output relationship of the device is simulated in the forward direction using the measured data obtained from procedure 1.

3. Matching (left side of Figure 4) For every color value in the proofer's output, find a corresponding input color value of the printer

using an iterative optimization procedure which minimizes the matching error. Once the new input value is found, update the Look-Up-Table (LUT).

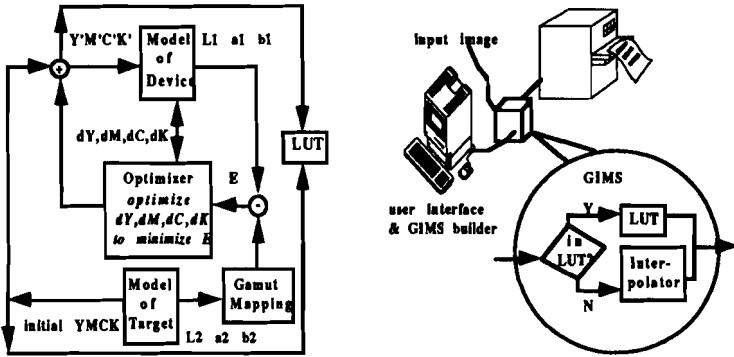


Figure 4. Matching & Implementing

4. Implementation (right side of Figure 4) Mapping between the old set of inputs and the new set of inputs of the printer is implemented by a LUT and an interpolator.

Key Element

The key element in the system is the Optimizer. It performs three functions simultaneously.

The minimum error searching algorithm: the searching procedure developed for our system is called the Modified Vector Shading (MVS) algorithm. It calculates the adjustments in the input space by solving a set of partial differential equations associated with the matching errors. One set of differential equations that is used by GIMS is given below (assuming input as CMYK and output represented by CIE $L^*a^*b^*$):

$$(\partial b / \partial y) da - (\partial a / \partial y) db = [(\partial b / \partial y) (\partial a / \partial m) - (\partial a / \partial y) (\partial b / \partial m)] dm + [(\partial b / \partial y) (\partial a / \partial c) - (\partial a / \partial y) (\partial b / \partial c)] dc$$

$$(\partial a / \partial y) dL - (\partial L / \partial y) da = [(\partial a / \partial y) (\partial L / \partial m) - (\partial L / \partial y) (\partial a / \partial m)] dm + [(\partial a / \partial y) (\partial L / \partial c) - (\partial L / \partial y) (\partial a / \partial c)] dc$$

$$dL = (\partial L/\partial y) dy + (\partial L/\partial m) dm + (\partial L/\partial c) dc$$

The K values are controlled by a preset criterion according to the printer's limitation or the user's need.

The error correction algorithm: the most common problem in optimization processes is the so called "local minimum problem". Without an effective algorithm to overcome this problem, the iterated searching algorithm can not work properly. An intelligent initiator was developed which eliminates the local minimum problem.

The gamut mapping procedure: our gamut mapping procedure is a part of the searching procedure rather than a separate procedure that performs gamut mapping to the targeted color prior to searching. Therefore, it is more efficient. Details on this subject will be presented in a separate paper.

Implementation

A multidimensional linear interpolator with a small LUT (a few kilobytes) was used to implement the system. The implementation can be in either software or hardware.

PRINTER ISSUES

Since the color matching system is operated in the device-independent color space, its performance should be, ideally, device-independent. However, this is only true if

1. the color appearance is spatially and temporally independent;
2. the tristimulus values measured are spatially independent;
3. the color surface is well behaved.

When these conditions are not met, the color matching performance will become device-dependent.

The removal of such dependency requires knowledge of the printer's characteristics.

Dependency of color appearance: It is well known that color appearance is spatially and temporally dependent, which means that changes in surrounding color and previously viewed colors affect the color appearance. However, in the color proofing situation, colors are compared with the same image under standard viewing conditions. Therefore, most adaptation effects are reduced to mainly a paper adaptation effect which has been compensated by the use of CIE Lab space.

Dependency of color values: The spatial dependency of color appearance refer to colors having the same color value but different appearance affected by the surrounding colors. The spatial dependency of color values refers to value changes in color affected by previous processed color. All printers are "band-limited" devices meaning that they require time to return to the initial state after every operation. When the period of operation is shorter than the reset time, the next operation is affected by the changes in the initial state. For thermal dye sublimation printers, such an effect is called the thermal history effect. Techniques which eliminate such effects have been developed. More discussion on this subject can be found in the reference (Liang 93).

Behavior of color surface: The color matching process involves sampling and interpolation. From the signal processing point of view, the linear interpolation process is equivalent to a low-pass filtering process to the digital samples which is governed by the Nyquist's sampling theory. When the color surface in the mapping space is ill-behaved, which means that the mapping of a smooth surface of one color space into another color space exhibits "high frequency" patterns, the regular sampling scheme might fail at that area.

The factor that affects the surface behavior is due to the introduction of a pseudo base vector K (black). K is not a real independent base vector. The color representations in CMYK space are non-

unique. Although the value of K is controlled by a procedure governed by a defined criterion (e.g. minimum amount of black ink) to make the new mapping space relatively smooth, it might still fail in some very ill-behaved regions. It was found that the procedure controlling K alone worked fine for a contone digital printer such as thermal dye sublimation printer, but was not good enough for a semi-halftone (pseudo-halftone) digital printer such as ink jet printer.e

Pure contone images have constant dot size with variable density. Pure halftone images have constant density with variable dot size. In both cases, the dot position is fixed in the center of the pixel. Semi-halftone technology, on the other hand, produces color gray levels with a mixture of different techniques (such as error diffusion plus multiple-drop techniques used in ink jet digital printers) of which dot size, dot density and dot position are all variable. The mapping color surface for a digital printer using semi-halftone technique was found ill-behaved in many areas, especially around the grey axis. A procedure that correlates color in the ill-behaved region was developed to eliminate the resulted artifacts from the region.

SUMMARY

Matching digital printer to analog proofer is very important to the success of digital proofing.

The technology of matching a digital printer to an analog proofer, described in this paper, is based on colorimetric measurements from a set of samples over the entire color space.

The color matching is performed and evaluated in a device-independent uniform color space, namely the CIEL*a*b* color space.

The matching problem is basically a backward modeling problem. The forward-model-with-backward-searching approach, with a sufficiently large set of samples and an intelligent sampling scheme, is believed to be more effective than the straight forward backward-modeling approach.

The central problem of such an approach is the backward-searching element rather than the forward model. The key element developed and described in this paper contains a fast converging search algorithm (the Modified Vector Shading (MVS) technique), an intelligent initiator that eliminates the "local minimum" problem, and a novel gamut mapping technique.

For contone digital printers such as thermal dye sublimation printers, the effect of spatial dependency of color values is sometimes non-negligible. In such cases, the color matching system will include an element that eliminates that effect.

For semi-half-tone (pseudo-half-tone) printers such as ink jet printers, the color surface is sometimes ill-behaved. When this happens, the color matching system will adjust its sampling scheme and make use of the color correlator to eliminate the resulted artifact.

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