An Intelligent Color Quality Control Method for Digital Printing

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Abstract

It is well known that color toner is “notoriously unstable”. Challenges designers and printers face are the difficulties in achieving accurate and consistent color print-outs using toner-based color copiers and laser printers due to inherent instabilities such as humidity changes, temperature fluctuations, variation and deterioration of toners and machine drift. This paper addresses these challenges by presenting a practical methodology enhancing the concept of color management for digital printing. Based on the methodology, an enabling technology, Focoltone Intelligent Color Calibration System (ICCS), has been developed. This technology is developed based on Artificial Intelligence (AI), it provides a novel method for comparing the printed colors against reference colors to generate color characteristics. The generated color characteristics represented using fuzzy logic and stored in a knowledge base, which can be presented to users in an understandable way, are useful for detecting color inconsistency in an automatic and intelligent manner. They can be used as a feedback to compensate colors by modifying an existing ICC profile to generate a better one in order to control the quality of the outputs of digital printing.

Introduction

With the advances in technology for digital printing, the use of color in imaging continues to grow at an ever-increasing pace. With the increased use of color images, demand for high quality color printing has also increased considerably. Print engines such as color copiers, printers and professional press systems create color images by combining a small number of colorants such as pigments or dyes in response to image data. For example, conventional color systems produce an image by combining cyan, magenta, yellow and black (CMYK) colorants. The same CMYK image data printed using different digital print systems (or called print engines) can produce images which have different color characteristics. This difference is due to different absorption spectra of the colorants, different amount (densities) of the colorants, and different mixing characteristics (trapping) of the colorants. The factors that may affect the color characteristics include temperature, humidity, paper type, type of toner/ink, and application. Up to now it is still difficult to establish whether the color output of a color reproduction system necessarily achieves the desired or correct color effect. It is often said that there is no printer that can reproduce color perfectly. With the emergence of open publishing systems based on a standard computing platform, color communication between different input/ output devices is getting more complex. The International Color Consortium (ICC) was established in 1993, to develop common standards independent of the type of color devices. A standard proposed by the ICC is the device-independent color profile specification[6] based on CIE LAB or CIE XYZ color space for transforming between different color models used by different input/output devices to ensure reliable color reproduction.

CIE LAB model is able to identify the difference of two colors by means of a color match in a well-defined color space. However, the accuracy of the color match depends on the complexity of the color transformation/masking equations. Higher the order of the polynomial for the color transformation, the more accurate the color match. Thus, since the algorithms are complex, there is usually a need to make a compromise between the number of test colors and the cost of computation.

ICC also recommended a guideline for creating an ICC profile for printing systems. However, the difficulty is in frequently generating a device dependent color characteristic data required for such a profile to meet the increasing demand for high quality color printing.

To overcome the above problems, numerous color management methods for calibrating digital color printing devices have been proposed, such as the patent documents described below:

McCauley disclosed a method for adaptive color characterizing and calibrating color document scanners, color display units and color printers using channel independent linear transfer function or calibration curves.[1] A calibration target including a plurality of color patches is used in the method which focuses on the transformation between CIE L*A*B* (or L*U*V*) and RGB spaces. However, since the transformation is based on CIE L*A*B* and RGB which are based on "additive colors", it is complicated to apply this method to color printers due to the inherent non-additive response of printing devices.

Another method for calibrating a subject printer using a subject scanner for determining the state of the subject printer and using an object scanner and an object printer as reference is introduced.[2] The same type of object scanner and printer are calibrated and their outputs saved as digital data to be supplied to users as references to compare with outputs of subject scanners and printers. The differences are used to calibrate the subject printers. In the case of calibrating a subject printer, a digital standard target is input to the subject printer. Output from the subject printer is then provided to a subject scanner, which has been calibrated prior to receiving the output. The output from the subject scanner is compared with the reference digital data provided to users and printer calibration curves are derived which are used to calibrate the subject printer. However, this method is limited to the specific type of object scanner and printer as the pre-determined reference digital data are not applicable to other types of scanners and printers. Furthermore, the accuracy of the color output after calibration using this method relies on consistency of color between subject and object scanners (and printers) and this is difficult to achieve.

Richard disclosed a method for calibrating colorants of a color copying and printing system using a scanner as a densitometer.[3] To set up the scanner for this purpose, a scanner profile is obtained by scanning a standard gray scale test strip comprising a plurality of gray scale patches, each with known reference density values. The density values of the scanned test strip are compared with the known reference density values to obtain the scanner profile. Once the scanner profile is obtained, the scanner is ready to calibrate a printer. A calibration target used in the method comprises a plurality of single-color-component color patches printed using the printer to be calibrated. The calibration target is next scanned (which can be scanned simultaneously with the standard gray test strip above) and converted to an absolute density scale using the scanner profile. After conversion to absolute densities, the scanned calibration scale is compared to the originating test data to determine the printer profile which is used to calibrate the printer. Based on the color patches printed after a color calibration has been performed as above, it is still difficult to tell whether the desired colors are being printed or the printer is indeed calibrated since there is no direct comparison between the patches and the test strip as the latter is used to generate a mapping from RBG to absolute CMYK density. Moreover, there is a need to obtain the scanner profile in order to perform the calibration of the printing system.

David presented a method and system for measuring color difference.[4] This method is used for objective color comparison by means of automatically and quantitatively measuring color difference between a color distribution of an object and a reference color image using "color distance" in a color system. The color distance is preferably based on Euclidean distance which is given by:

$$Distance = \sqrt{(iRef - iS)^2 + (hRef - hS)^2 + (sRef - sS)^2}$$

Here, *iRef* is the intensity of the reference pixel, and *iS* is the intensity of the sample pixel, the *h* and *s* components are the hue and saturation quantities, respectively. However, the method is limited to machine vision system for color recognition, color filtering, and color–based image segmentation and thus the method proposed therein is only concerned with determining whether there is a color difference.

This paper presents an intelligent method for digital printing which alleviates at least one of the above disadvantages. This method is based on Negative Color Comparison and fuzzy inference.

In the following sections, we present the overview of the methodology followed by detailed discussion of the negative color comparison algorithm and fuzzy color knowledge processing which are the key technologies for the methodology. The last section is the discussion and conclusion.

Overview of the Proposed Methodology

This paper presents a method of calibrating a print engine based on a calibration chart[5] having a first plurality of reference colors. the method comprises the following steps:

i) printing a test sheet[5] from the print engine; the test sheet having a second plurality of test colors thereon, each test color corresponding to a reference color;
ii) digitizing the reference and test colors;
iii) calculating a color difference between corresponding pairs of digitized reference and test colors using fuzzy functions;
iv) adjusting the print engine in accordance with the difference to reduce the color difference between each color pair by means of ICC profile; and
v) verifying the color.

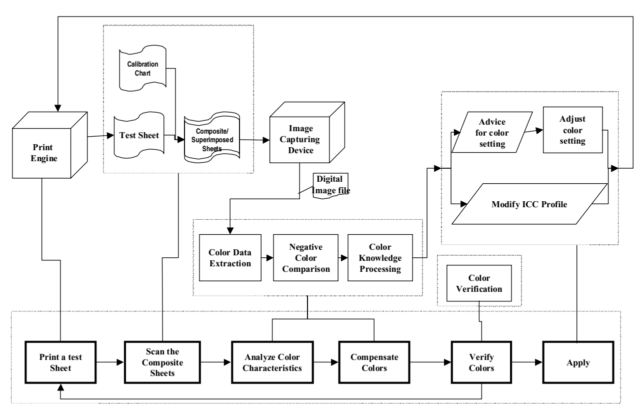

Figure 1. Diagram for the proposed methodology

Figure 1 shows the various steps of performing color print standardization. To begin the calibration process, the user selects a print engine to calibrate which can be a local printer or a network printer and also the ICC profile (if any) for that printer. At the first step, a test sheet is printed on a sheet of paper by the printer to be calibrated. In this paper, a network print engine such as a Canon CLC 1150 copier, is used as an example. The image capturing device is a scanner integral to the Canon brand CLC 1150 copier. The output of this step is a printed test sheet. The test sheet and the calibration chart are then overlaid with the chart being placed on top of the test sheet to form the composite.

At the second step, the composite sheet is next scanned by the scanner described above. The output from the scanner is a digital image file in a CMYK color model, preferably in TIFF format.

After the image of the composite sheet is obtained, at the third step, the color characteristic of the image is analyzed next. There are three different stages for this step, which are described in details in the following sections.

The output of the color knowledge processing is next applied to the printer. As illustrated in Fig. 1, there are two methods for adjusting the color output of the print engine: with ICC profiles or without ICC profiles. If the printing system supports ICC profile, the color adjustment can be performed by modifying the ICC profile which is simpler. Otherwise, the adjustment can also be done by changing the color settings with the inputs being provided by the color knowledge processing.

Although the color measurement and adjustment can be performed automatically without human intervention, it also provides for a verification step before the adjustment data or settings are applied to the print engine. Since we are concerned with the comparison of two colors, if the two colors appear satisfactory visually on the display, it should also be acceptable to the naked eye when the color settings are applied to the print engine for printing on paper.

After applying the settings, the user can simply print another test page to compare the result with the calibration chart to see the improvement in the color effects or alternatively, he can print a color picture to see the results.

Negative Color Comparison

Instead of measuring the color itself, the Negative Color Comparison measures the difference in colors and in paper "subjective" and "objective" comparisons are used.

Subjective color comparison mainly relies on the human eye to visually compare one color with another color being used as a reference. It is a fact that the human eye cannot measure color accurately but can only compare them. To elaborate: two individuals looking at a single color will see the color differently, these two individuals looking at two different colors will still see each of them differently, but they will see the difference between the two colors with the same accuracy. Thus, in color comparison, the nature of the color is not important but what is important is the difference between the two colors which appears consistent between two persons. Based on this, subjective color comparison is typically used in visual color calibration.

Objective color comparison, on the other hand, requires the use of a measuring device to measure the colorants or intensity of a color and compare with another reference color. Devices for measuring the color for objective comparison include the spectrophotometer, colorimeter, densitometer and scanner.

Once the color data is extracted, the next step is to compare the data obtained between the standard color patches and the test patches on the composite sheet. Fig. 2 illustrates detailed steps of performing "negative" color comparison to capture the color characteristics of the color patches.

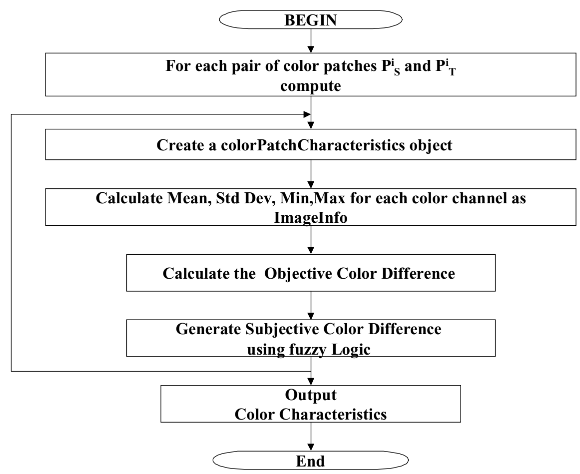

Figure 2. Calculate color characteristics

The color data extraction step outputs the color data of each pair of color patches P_i^S and P_i^T (i.e. a standard and a test color patch) to the negative comparison step. This step is shown in detail in Fig. 1. To begin the color comparison, a new object of type of ColorPatchCharacteristics (see Fig. 3) is created for each pair of color patches P_i^S and P_i^T which is associated with three other objects, namely CImageInfo, CobjectiveColorDifference and CsubjectiveColorDifference. This is illustrated in Fig. 3 which is a UML (United Modeling Language) class diagram representing the color characteristics.

For each color patch, the intensity distribution of each colorant C,M,Y,K forming a pixel is calculated in terms of mean, standard deviation, minimum colorant and maximum colorant. The values of these parameters are stored in the object CImageInfo representing information for the pixel data of the color patches extracted from the scanned image file.

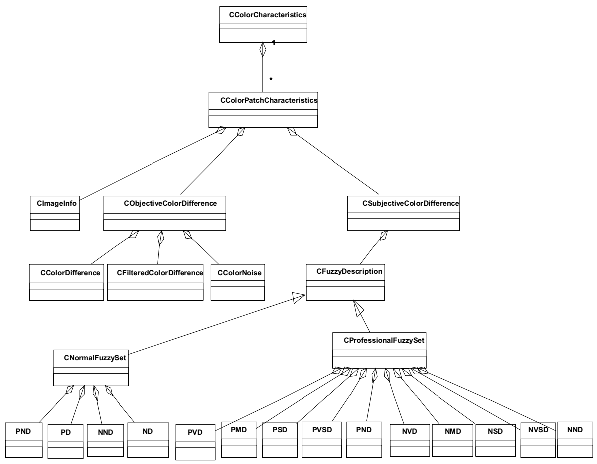

Figure 3. Color Characteristics Classes

Based on the distribution of the colorants forming each color patch, it is reasonable to use the mean values of the colorants to represent the overall intensity of each color patch. The objective color differences can be computed using the following formulas for each color channel C,M,Y and K:

$$d^C(P_i^S,P_i^T) = \omega\times(\overline{P_i^S(C)} - \overline{P_i^T(C)}) \quad (1)$$

$$d^M(P_i^S,P_i^T) = \omega\times(\overline{P_i^S(M)} - \overline{P_i^T(M)}) \quad (2)$$

$$d^Y(P_i^S,P_i^T) = \omega\times(\overline{P_i^S(Y)} - \overline{P_i^T(Y)}) \quad (3)$$

$$d^K(P_i^S,P_i^T) = \omega\times(\overline{P_i^S(K)} - \overline{P_i^T(K)}) \quad (4)$$

where $\overline{P_i^S(x)}$ and $\overline{P_i^T(x)}$ represent the mean of colorants of standard color patch P_i^S and test color patch P_i^T, respectively; ω is a constant related to the depth of color represented in a pixel, in this invention, ω = 100/255 as 32 bits is used for each pixel; and $x \in \{C,M,Y,K\}$.

At this stage, the difference in intensity, if any, for each colorant C,M,Y,K for each pair of test and standard color patches is known but the color difference does not consider whether there is noise which may affect the measurement.

To take the noise factor into consideration, it is important to know whether a color patch is actually without one or more of the base colorants. For example, if a color patch is supposed to represent color FCS1001[1] and there is a certain amount of black color detected based on the objective measurement, the color of the test patch should appear grayish which is incorrect since FCS 1001 should not have any composition of black color. In order to represent this characteristic, a filtered color channel for the color patch is defined. For any color channel x, it is a filtered channel for the color patch if its colorant is not zero in the color represented by the color patch. The filtered color difference is defined as follows:

$$fd^C(P_i^S,P_i^T) = \begin{cases} d^C(P_i^S,P_i^T) & \text{if } C \text{ is a filtered color channel;} \\ 0 & \text{else} \end{cases} \quad (5)$$

$$fd^M(P_i^S,P_i^T) = \begin{cases} d^M(P_i^S,P_i^T) & \text{if } M \text{ is a filtered color channel;} \\ 0 & \text{else} \end{cases} \quad (6)$$

$$fd^Y(P_i^S,P_i^T) = \begin{cases} d^Y(P_i^S,P_i^T) & \text{if } Y \text{ is a filtered color channel;} \\ 0 & \text{else} \end{cases} \quad (7)$$

$$fd^K(P_i^S,P_i^T) = \begin{cases} d^K(P_i^S,P_i^T) & \text{if } K \text{ is a filtered color channel;} \\ 0 & \text{else} \end{cases} \quad (8)$$

As mentioned earlier, since the ideal percentage density of each colorant is known with black colorant supposed to be 0% for FCS 1001, it is possible to determine whether there is noise present by comparing the filtered color difference and the color difference obtained earlier.

The color difference for the color patches P_i^S and P_i^T in equations (1) to (4) and the filtered channels in equations (10) to (13) can be summarized as follows:

$$d_i = d(P_i^S,P_i^T) = \frac{1}{4}\times\sum_{x=C,M,Y,K} d^x(P_i^S,P_i^T) \quad (9)$$

$$fd_i = fd(P_i^S,P_i^T) = \frac{1}{m}\times\sum_{x\in\{C,M,Y,K\}} fd^x(P_i^S,P_i^T) \quad (10)$$

where m is the number of filtered color channels. The noise can be defined as fuzzy variable ε_i defined as:

$$\varepsilon_i = \varepsilon(P_i^S,P_i^T) = d(P_i^S,P_i^T) - fd(P_i^S,P_i^T) \quad (11)$$

The calculated values of the color difference is then stored in the CobjectiveColorDifference as a subset object called CColorDifference and the color differences from the filtered channels are stored in another subset object called CfilteredColorDifference. Specifically, Object CColor-Difference includes $d^C(P_i^S,P_i^T)$, $d^M(P_i^S,P_i^T)$, $d^Y(P_i^S,P_i^T)$, $d^K(P_i^S,P_i^T)$ and $d(P_i^S,P_i^T)$ whereas Object Cfiltered-ColorDifference includes $fd^C(P_i^S,P_i^T)$, $fd^M(P_i^S,P_i^T)$, $fd^Y(P_i^S,P_i^T)$, $fd^K(P_i^S,P_i^T)$ and $fd(P_i^S,P_i^T)$.

The noise obtained based on equation (11) is stored in object CColorNoise which is another subset of CobjectivecolorDifference.

The formula (1) ~ (11) for determining color difference is independent of the color model of the print engine or the image capturing device since the formula can be applied to the CMYK model as well as any other color models such as RGB, CIE XYZ, CIE Lab, etc. In general, let k be the number of color channels, the formula (9) ~ (11) can be generalized as follows:

$$d_i = d(P_i^S, P_i^T) = \frac{1}{k} \times \sum_{x=1}^{k} d^x(P_i^S, P_i^T) \quad (12)$$

$$fd_i = fd(P_i^S, P_i^T) = \frac{1}{m} \times \sum_{x \text{ is a filtered channel}} fd^x(P_i^S, P_i^T) \quad (13)$$

where m is the number of filtered color channels. The noise can be defined as:

$$\varepsilon_i = \varepsilon(P_i^S, P_i^T) = d(P_i^S, P_i^T) - fd(P_i^S, P_i^T) \quad (14)$$

Color Knowledge Representation

Having obtained the color difference based on objective measurements, the difference in the color measurements are "measured subjectively" using fuzzy rules. A fuzzy set for normal user level is defined by the following fuzzy values:

Table 1. Fuzzy Set for Normal Users

Fuzzy Value	Meaning
PND	Positive No Different
PD	Positive Different
NND	Negative No Different
ND	Negative Different

The image file is supposed to be saved as CMYK color mode and 8 bits per channel. Therefore, the captured color measurement for each channel is in the range from 0 to 255. The measurement is then divided by 255 and converted into a value of form of percentage so that the range of difference of color ΔD is ranged from –100% to +100%. These fuzzy membership functions can be also described using mathematical formulas as follows:

$$PND(\Delta D) = \begin{cases} 0 & \Delta D < 0\% \\ 1 & 0 <= \Delta D <= 1\% \\ (4\% - \Delta D) \times \frac{1}{4\% - 1\%} & 1\% < \Delta D < 4\% \\ 0 & \Delta D >= 4\% \end{cases} \quad (15)$$

$$PD(\Delta D) = \begin{cases} 0 & \Delta D < 1\% \\ (\Delta D - 1\%) \times \frac{1}{4\% - 1\%} & 1\% <= \Delta D <= 4\% \\ 1 & \Delta D > 4\% \end{cases} \quad (16)$$

$$NND(\Delta D) = \begin{cases} 0 & \Delta D > 0\% \\ 1 & -1\% <= \Delta D <= 0\% \\ (-4\% - \Delta D) \times \frac{1}{-4\% + 1\%} & -4\% < \Delta D < -1\% \\ 0 & \Delta D < -4\% \end{cases} \quad (17)$$

$$ND(\Delta D) = \begin{cases} 0 & \Delta D > -1\% \\ (\Delta D + 1\%) \times \frac{1}{-4\% + 1\%} & -4\% <= \Delta D <= -1\% \\ 1 & \Delta D < -4\% \end{cases} \quad (18)$$

Based on the above fuzzy membership functions, the subjective color difference can be generated in terms of the maximum of their values. For example, if the measurement of color difference value is +3%, the outputs of fuzzy membership functions for PND, PD, NND, and ND are 0.33, 0.67, 0, and 0, respectively. Therefore, PD whose measurement value is highest is assigned to the object CFuzzyDescription and fuzzy inference is used to adjust the colorants accordingly as further elaborated below.

For the professional level, the fuzzy set is defined as follows:

Table 2. Fuzzy Set Definition

Fuzzy Value	Meaning
PND	Positive No Different
PVSD	Positive Very Slight Different
PSD	Positive Slight Different
PMD	Positive Moderate Different
PVD	Positive Very Different
NND	Negative No Different
NVSD	Negative Very Slight Different
NSD	Negative Slight Different
NMD	Negative Moderate Different
NVD	Negative Very Different

The above fuzzy sets are depicted in the class diagram of Fig. 3 which forms a subset object CFuzzyDescription under CSubjectiveColorDifference. As shown, the CFuzzy-Description object includes a Normal Fuzzy Set (for normal user level) and Professional Fuzzy Set (for professional level). As mentioned earlier, the Normal Fuzzy Set comprises fuzzy values: PND, PD, NND, and ND and the Professional Fuzzy Set includes PND, PVSD, PSD, PMD, PVD, NND, NVSD, NSD, NMD and NVD. The fuzzy value is used to specify rules, typically of an "if-then" structure and the inference engine enables the expert system to draw deductions from the rules in the knowledge base. An example of a fuzzy rule is: "If d^C is NSD then reduce C a little".

Discussion and Conclusion

This paper presented a method of calibrating a digital printer for color quality control based on the Focoltone Calibration Chart, Focoltone Test Sheet, the Negative Color Comparison and fuzzy logic. An advantage of the described method is that since the calibration chart can be pre-printed, a specific type of paper can thus be used and the quality and standard of the reference colors on the calibration chart can be assured and controlled. The test sheet, on the other hand, can be printed using paper used normally by the end user and thus the calibration would take into account effects of the normal printing paper. In addition, each test color corresponds to a reference color and thus a direct comparison can be made and each test color can be adjusted to match its corresponding reference color. For example, in a print engine based on the CMYK color model, selected combinations of colorants can be used to represent the entire gamut of the color model. Thus, once the print engine is calibrated against these selected combinations, there is a reasonable amount of confidence that the print engine can reproduce the colors in the entire gamut satisfactorily.

In addition, a further advantage is that there is no need to determine the absolute values of each color for comparison with their reference absolute values that are predetermined (for example, the hue or saturation), since the measurement is relative and thus it does not matter what is the actual value but what is important is the difference between the reference and test colors.

As color has physical and physiological characteristics, the only way to describe colors clearly is by means of comparison. No matter what kind of measurement technologies are used, the results should be consistent with visual assessment because the human eye is the final judge of color. In this perspective, The Negative Color Comparison algorithm and fuzzy color knowledge representation are more reasonable methods to represent characterizations of colors.

The Delta E is widely used for quantifying the color difference. The formula of Delta E has been refined several times in past 30 years in order to improve its accuracy. However, these formulae like CIELAB(1976), CIE 94 and CIE 2000 can only specify how much difference of two colors is, but can't point out how to reduce the difference. The Negative Color Comparison method presented in this paper can overcome this problem.

Based on the method presented in this paper, a calibration system, Focoltone Intelligent Calibration System, has been developed successfully. It can improve color consistency by compensating colors by means of ICC profiles.

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Biography

Dr. Zhang is Chief Scientist with KiKUZE Solutions Pte. Ltd. He is also a Research Scientist with Singapore Institute of Manufacturing Technology. His research interests include knowledge management, data mining, machine learning, artificial intelligence, computer security, software engineering, software development methodology and standard, intelligent control systems and enterprise information systems. His current research interest focuses on intelligent colour print quality control methodology and applications. He has over 20 years of experience in the research and development of software and has developed many enterprise-wide software solutions for many industries, notably, the financial, engineering, and printing sectors. He is currently leading several collaborative R&D projects with MIT, a local university and a local research institute on color quality control for digital printing. He is a corporate representative of ICC (International Color Consortium) and PODI (Print On Demand Initiative), and a member of IS&T, and ACM.