A LOGICAL WAY TO SPECIFY COLOR STRENGTH, HUE ERROR, AND GRAYNESS

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ABSTRACT

The hue error of a printed color ink is currently characterized by its percentage deviation from the subtractive color corresponding to the high density reading of a densitometer, and by the direction of hue error that shifts toward the color of filter in the densitometer corresponding to the low density reading. This specification of hue error is clear for subtractive primary colors but ambiguous for overprint colors. It may give a wrong impression to those who are not familiar with the GATF Color Circle. It may mislead a press operator when regulating the ink keys to achieve the desired strength and hue of an overprint color. The calculated hue errors of printed inks differ slightly from those determined by the GATF Color Hexagon. The discrepancy is attributed to the equation that is not accurate enough.

The grayness of a printed color ink is determined by the ratio of the low to the high densitometer readings. It is a measure of the purity of a printed color ink. A "pure" subtractive color has zero percent grayness and an achromatic color has one hundred percent grayness. The purity of a printed color ink is obviously affected by the other two impure color components in the ink. A gray color is generally achieved in process printing by overprinting three subtractive primary colors. These considerations indicate that the grayness of a printed color should be determined by all three color components rather than by two of them.

A vector analysis method is proposed in this paper. It

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determines the ink hue, grayness, and strength of printed colors in a more consistent and rigorous way. The GATF Color Circle is slightly modified. This makes plotting press results in the Color Circle diagram unambiguous. Examples of press results using the GATF Newspaper Test Form will be presented. The direction of hue error of an overprint color may change from one newspaper column to another and from one sample sheet to another. It should be easier for the press operator to adjust press conditions to achieve the correct hue and strength of overprints by using this proposed method.

BACKGROUND

The increasing demand for color in newspapers has created a need for accurate and efficient methods which can be used to characterize the process of color reproduction. The Graphic Arts Technical Foundation, in a cooperative project with Rockwell International, developed the GATF Newspaper Test Form Kit in response to this need. The User's Guide supplied with the kit states "The GATF Newspaper Test Form Kit allows newspapers and other printers using nonheatset offset lithography to: diagnose their entire reproduction system; to define color and black-and-white reproduction characteristics (tone reproduction, gray balance, color correction, dot gain, print contrast, ink trapping); and to refine color scanner and halftone camera settings to produce high quality films suited to the reproduction process."

The authors made extensive use of the Test Form during recent color printing trials of the Goss keyless offset system at the St. Petersburg Times and Chou concurrently developed a software package for use in analyzing the Test Form data. In the course of this work confusion developed in regard to correct interpretations of color strength, hue error, and grayness measurements. The steps taken to eliminate this confusion are the subject of this paper.

CONVENTIONAL DENSITOMETRY TO CHARACTERIZE PRINTED COLORS

The literature which describes the nature of printed color is extensive. The works of Cox (1969), Bruno (1986), and Pobboravsky (1987) provide detailed discussions of the physics and perception of color and describe the tools that have been developed to analyze printed colors. The GATF Color Hexagon and Color Circle were used in the analysis reported herein to convert densitometer readings into the basic color parameters; strength, hue, and grayness. In this three-dimensional color space, the Color Circle addresses two dimensions, hue and grayness, and the Color Hexagon also addresses two dimensions, hue and strength.

According to Cox's report (1969), the strength, hue error, and grayness of a printed color are given by the following formulas.

$$\text{Strength} = H \quad (1)$$

$$\%\ \text{Hue Error} = 100 * (M-L) / (H-L) \quad (2)$$

$$\%\ \text{Grayness} = 100 * L / H \quad (3)$$

where H, M, and L are the high, medium, and low densitometer readings when the solid printed color of interest is measured with each of the three usual densitometric filters. As Bruno (1986) points out, the direction of hue error corresponds to the color of the filter for the low densitometer reading.

Interpretation of Color Strength

Table I lists the densitometric data measured with an X-Rite 328 densitometer from the single, two-color, and three-color solid ink patches of the GATF Color Reproduction Guide in the Test Form. These data are the average values of twenty consecutive copies in a test run at the St. Petersburg Times. The printing sequence was cyan, magenta, yellow. According to Equation 1, the strength of the magenta ink is 0.72, which is the density of its magenta component. In other words, the strength of a printed ink is equal to the density of the color component that is wanted. Because two color components are wanted in two-color overprints and three color components are wanted in the three-color overprint, it is inadequate to specify the strength of an overprint color by the density of only one color component. A more logical way to specify the strength of a printed color is essential.

Interpretation of Ink Hue

The grayness, hue error and direction of hue error for printed colors in Table I are summarized in Table II. The concept of ink hue may be easily visualized by considering, for example, the magenta ink patch as if it were an

TABLE I. DENSITOMETRIC DATA OF SEVEN SOLID INK PATCHES OBTAINED FROM GATF COLOR REPRODUCTION GUIDE.

PRINTED INK	INK DENSITY OF COLOR COMPONENT MAGENTA (GREEN)*	YELLOW (BLUE)	CYAN (RED)
MAGENTA	0.72	0.47	0.14
YELLOW	0.08	0.55	0.06
CYAN	0.27	0.11	0.70
GREEN	0.31	0.58	0.72
BLUE	0.77	0.48	0.80
RED	0.70	0.69	0.14
3-COLOR	0.81	0.71	0.84

* The color of the filter is given in the parenthesis.

TABLE II. GRAYNESS, HUE ERROR AND DIRECTION OF HUE ERROR FOR COLOR INK PATCHES IN TABLE I.

PRINTED INK	% GRAYNESS	% HUE ERROR	DIRECTION
MAGENTA	19	57	RED
YELLOW	11	4	RED
CYAN	16	27	BLUE
GREEN	43	66	GREEN
BLUE	60	91	BLUE
RED	20	98	RED
3-COLOR	85	77	BLUE

overprint of three ideally-pure color components; magenta, yellow, and cyan. Because the magenta and yellow components, which dominate over the cyan component, produce red, the magenta ink has a red shade. Thus, the direction of hue error is useful in communicating the shade of a printed color. The other subtractive primary colors can be visualized and communicated similarly.

Table II shows that the hue error of the red overprint is 98%. A first impression of this result is that everything in the copy that is supposed to look red will look terrible, yet it does not. This is explained as follows. In the GATF Color Circle diagram, 0% hue error is assigned to the axes representing subtractive primary colors, and 100% hue error is assigned to the axes representing two-color overprints; green, blue, and red. Only with this in mind does it become clear that the red overprint has the most correct hue rather than the least correct as inferred by the 98% hue error notation. Moreover, the hue error of the three-color overprint is indeterminate according to Equation 2, if the densities of all three color components are equal.

Table II also indicates that the green overprint has a green shade, the blue overprint has a blue shade, and the red overprint has a red shade. These results seemed informationally awkward to us. A more explicit method is needed.

Communication of Ink Hue Data

Placing hue error data of primary colors on the Color Circle diagram is straightforward. The magenta is reddish and the point is located on the right side of the magenta axis toward the red axis, as shown in Figure 1. Confusion arises in attempting to place the data of overprint colors on the Color Circle. The red is reddish but where should the data point be located. The decision requires looking back at the optical density data in Table I. The density of the magenta component is highest in the red overprint and therefore the location of the red point is on the left side of the red axis toward the magenta axis. A similar situation applies to the other two-color overprints and to the three-color overprint. The current specification of hue error is not sufficient without more information.

The density data of blue overprints listed in Table III and the corresponding hue error data listed in Table IV were obtained by measuring the cross-press color control bars of the same print samples as in Table I. The hue error results in Table IV provide insufficient information for locating these data on the Color Circle diagram, with two exceptions. The hue errors of the blue ink patches at columns #1 and #5 are 100%, so their data points locate on the blue axis. By again referring to the ink density data, Table III, the data points for the blue ink targets at columns #3 and #4 should be located toward the magenta axis. And, the data points are to be placed toward the cyan axis for the printed targets at other columns. These results restate that this standard way of communicating hue error is ambiguous and awkward for overprint colors.

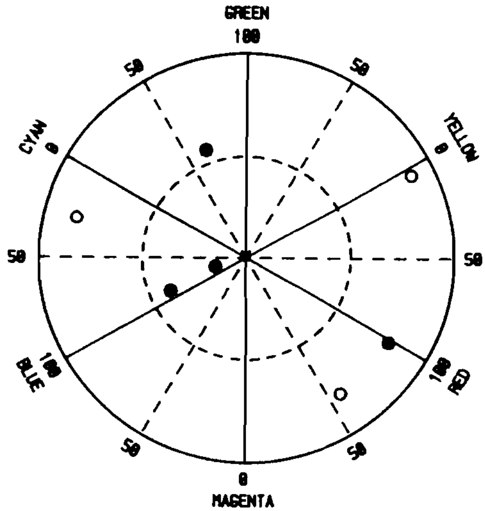

Figure 1. Plot of printed colors in Table I on Color Circle. Hue error and grayness were calculated using Equations 2 and 3. Open circles represent primary colors and solid circles represent overprints.

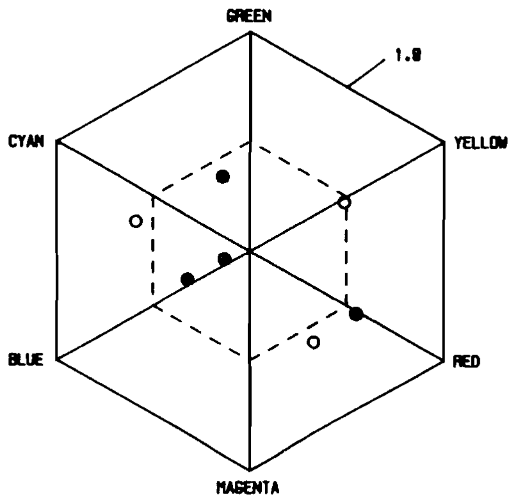

Figure 2. Plot of printed colors in Table I on Color Hexagon. Open circles represent primary colors and solid circles represent overprints.

TABLE III. DENSITOMETRIC DATA OF SOLID BLUE INK PATCHES OBTAINED FROM COLOR CONTROL BARS ON TOP OF THE GATF NEWSPAPER TEST FORM.

COLUMN NUMBER	INK DENSITY OF COLOR COMPONENT MAGENTA	YELLOW	CYAN
1	0.78	0.48	0.78
2	0.69	0.42	0.72
3	0.72	0.44	0.70
4	0.74	0.46	0.73
5	0.71	0.43	0.71
6	0.69	0.42	0.71
7	0.69	0.41	0.71
8	0.77	0.48	0.80

TABLE IV. HUE ERROR AND DIRECTION OF HUE ERROR OF BLUE INK PATCHES IN TABLE III.

COLUMN NUMBER	% HUE ERROR	DIRECTION
1	100	BLUE
2	90	BLUE
3	93	BLUE
4	96	BLUE
5	100	BLUE
6	93	BLUE
7	93	BLUE
8	91	BLUE

Inconsistency Between Color Circle and Hexagon Diagrams

In the Color Hexagon diagram approach, the densitometer readings are plotted directly onto the diagram, as shown in Figure 2 for the data in Table I. It is difficult to directly compare the ink hue results of the two diagrams, because different coordinate systems are used. This difficulty is resolved if we express the hue error of a printed color as the angle between the corresponding color axis and a line connecting the data point with the center of the diagram, because the angular displacement of the color axes are the same in both diagrams. Table V indicates that the ink hues in the Color Hexagon differ

TABLE V. HUE ERROR EXPRESSED BY THE DEGREE OF ANGLE DEVIATING FROM THE CORRESPONDING COLOR AXIS FOR PRINTED COLORS IN TABLE I.

PRINTED INKS	COLOR CIRCLE	COLOR HEXAGON
MAGENTA	34.1	34.6
YELLOW	2.4	2.1
CYAN	16.3	15.2
GREEN	20.5	19.6
BLUE	5.6	4.9
RED	1.1	0.9
3-COLOR	13.8	12.7

slightly from those in the Color Circle. This discrepancy results from the fact that Equation 2 is only a good approximation of hue error. It is not exact.

Interpretation of Grayness

The physical significance of grayness is not clearly described in the literature mentioned previously. The work of Cox (1969) indicates that grayness is a measure of the purity of a color ink. If so, both medium and low densitometer readings should be taken into consideration, not just the low reading, because both represent impure color components. The low densitometer reading has been referred to as the gray component of a printed color by Bruno (1986). It is inferred by Equation 3 that grayness is a measure of the strength of gray component. Contradictory results can arise. If the densities of three color components are increased by the same amount, both the grayness and the strength of gray component increase. This implies that grayness is indicative of the gray strength of the printed color. If the densities of all three color components are doubled, the gray strength of the color is obviously doubled, but the grayness according to Equation 3 remains the same. This indicates that grayness is not uniquely related to the gray strength of the color ink. Further investigation is very important to resolve these inconsistencies and to reveal the physical significance of grayness.

VECTOR ANALYSIS OF COLOR CHARACTERISTICS

Relation of Color Hexagon Diagram to Color Vectors

The procedure for plotting densitometric data of a printed color on the Color Hexagon has been outlined by Cox (1969). The low density reading or the gray component of a color ink is subtracted from the high and medium density readings. The resultant (H-L) and (M-L) values are used to locate the color point in the Color Hexagon. The (H-L) term is called the strength component and the (M-L) term is the hue error component. These give rise to the formulas of Equations 2 and 3 for calculating hue error and grayness. The densitometric data of the magenta ink in Table I are used as an example for positioning the data in the Hexagon diagram. The strength and hue error components are (0.72-0.14) or 0.58 and (0.47-0.14) or 0.33, respectively. The strength component is located first by stepping off 0.58 units from the center of the Hexagon along the magenta axis. The hue error component is then added by moving 0.33 units away from the magenta axis parallel to the yellow axis. The end point is the location of the magenta ink in the Color Hexagon diagram. The same procedure is used for all the colors plotted, and the results are shown in Figure 2.

The color points in Figure 2 can also be determined directly from the densities of all three color components. The magenta is chosen again for illustration, first moving 0.72 units away from the center along the magenta axis, followed by moving 0.47 units away from the magenta axis parallel to the yellow axis, and finally moving 0.14 units away from that position parallel to the cyan axis. If a vector is made by drawing a line from the center of the diagram to this magenta point, it then becomes the sum of three vectors corresponding to three measured color components. This illustrates that printed colors can be represented in the Color Hexagon space by the vector method. However, as mentioned in the previous section, printed colors should be described in three-dimensional space. The procedure of positioning color points in the two-dimensional Color Hexagon space using three linearly independent variables seems incorrect from the vector analysis perspective. An explicit, mathematically strict representation of printed colors by vectors is necessary.

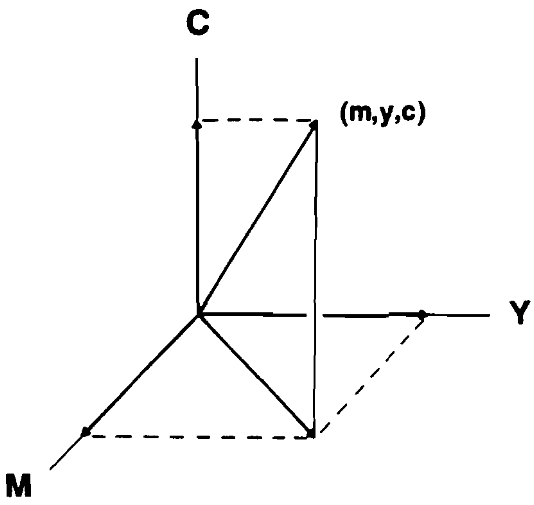

Figure 3. Vector representation of a printed color in the three-dimensional MYC coordinate system. The components of the color vector correspond to three densitometer readings.

MYC Coordinates for Primary Colors

Figure 3 illustrates schematically that a color vector can be expressed by a proper combination of three unit vectors in a three-dimensional Cartesian coordinate system as follows.

$$V = mM + yY + cC \quad (4)$$

where V is the color vector. The capital letters of M, Y, and C represent respectively the unit vectors corresponding to magenta, yellow, and cyan. The lower case letters of m, y, and c are the appropriate scalars, which correspond to the densitometer readings for the magenta, yellow, and cyan components. For convenience, coordinates in this system will be called the MYC coordinates. Thus, a printed color can be uniquely specified by a data set (m, y, c) in the MYC coordinates.

Because the densities of three color components are equal for achromatic colors, vectors representing gray and black colors lie along the diagonal of the coordinate

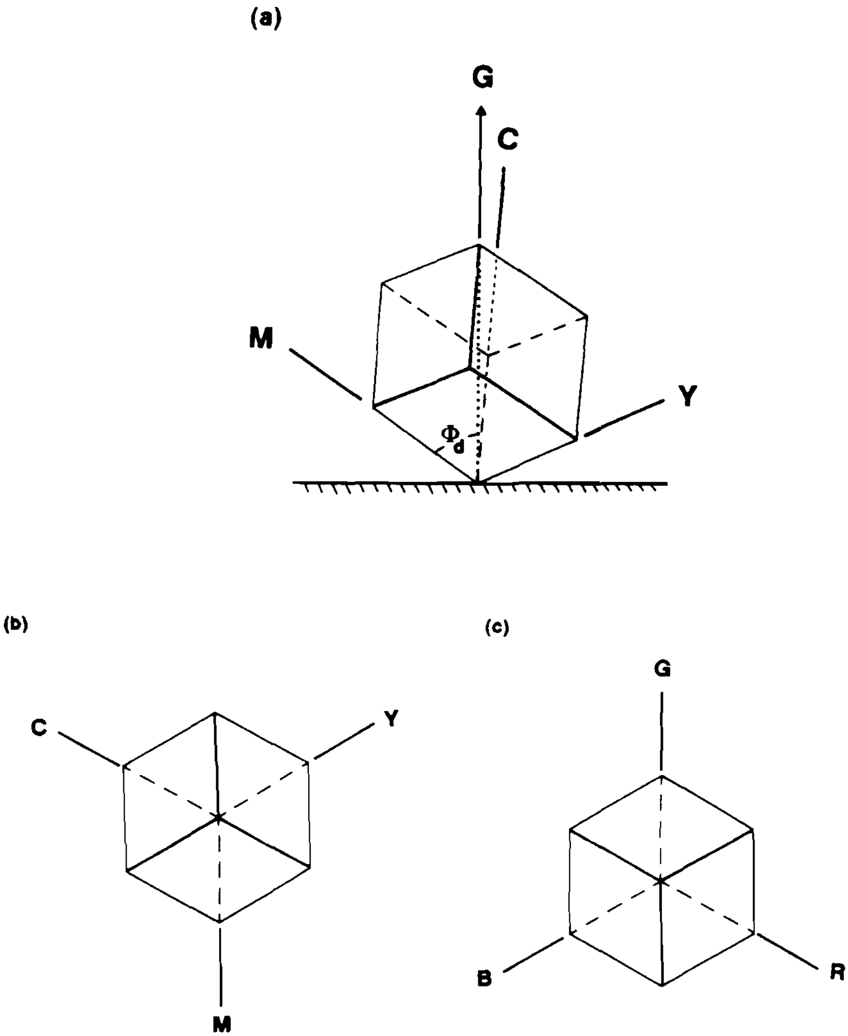

Figure 4. Schematic diagram showing the transformation of the MYC or GBR coordinates into the CHG coordinates. (a) side view; (b) top view for the MYC coordinates; and (c) top view for the GBR coordinates.

system, and the zero vector, that is the origin of the coordinate system, represents white. This condition allows resolving any color vector into one achromatic and two chromatic components by applying the mathematical principle of coordinate transformation. The two chromatic components result in the so-called color plane which characterizes the strength and hue of the color. The achromatic component lies along the diagonal line that is perpendicular to the color plane and represents the gray axis.

The coordinates in the new system, the CHG coordinates, will be discussed in detail later. The coordinate transformation can be easily visualized by placing a cube on a piece of flat paper in such a way that only one corner of the cube, which represents the origin of the MYC coordinates, touches the paper and the diagonal of the cube or the gray axis is perpendicular to the paper, as is shown in Figure 4a. When viewed from the top corner of the cube (Figure 4b), the projection of the three principal axes (MYC) of the cube onto the paper results in three axes corresponding to the primary colors in the color plane. Each axis in the color plane is separated from the other two by 120 degrees. These projected axes constitute the familiar primary color axes in the Color Hexagon diagram.

GBR Coordinates for Two-color Overprints

Any two-color overprint measured with a densitometer is traditionally specified by the densities of its magenta, yellow, and cyan components. These values are inadequate to specifying the strength of overprint colors using Equation 1. However, with the vector method the densities of magenta, yellow, and cyan components of an overprint can be converted into the densities of more useful color components. The transformation is carried out by rotating the MYC coordinate system around the gray axis by 60 degrees. The resulting system has three principal axes corresponding to the green, blue, and red, so its coordinates are called the GBR coordinates. The equation for this rotational transformation is given by

$$\begin{bmatrix} g \\ b \\ r \end{bmatrix} = (1/3) \begin{bmatrix} -1 & 2 & 2 \\ 2 & -1 & 2 \\ 2 & 2 & -1 \end{bmatrix} \begin{bmatrix} m \\ y \\ c \end{bmatrix} \qquad (5)$$

where g, b, and r are respectively the transformed

TABLE VI. TRANSFORMED DENSITOMETRIC DATA OF OVERPRINT COLORS IN TABLE I.

PRINTED INK	INK DENSITY OF COLOR COMPONENT GREEN	BLUE	RED
GREEN	0.76	0.49	0.35
BLUE	0.60	0.89	0.57
RED	0.32	0.33	0.88
3-COLOR	0.76	0.86	0.73

densities of green, blue, and red components of an overprint color. m, y, and c are the densitometer readings for magenta, yellow, and cyan components, respectively. Table VI lists the density data of overprint colors transformed from the data in Table I. Here, the density of the green component is, as logically expected, highest in the green overprint. Similarly, the densities of the blue and red components are highest in the blue and red overprints, respectively. This creates a new set of high, medium, and low density data for two-color overprints and tends to make Equation 1 applicable to specifying the color strength of two-color overprints. Yet, Equation 1 is still not appropriate for the three-color overprint, because three color components are wanted and it is not possible to mathematically resolve them into a single, wanted component. As will be discussed later, the high density value does not correctly characterize the color strength from the vector analysis perspective.

The GBR coordinates can be in turn transformed into the CHG coordinates by the same procedure. Figure 4c shows the top view of this transformation. The projected axes on the color plane form the two-color overprint axes in the Color Hexagon diagram. The Color Hexagon diagram shown in Figure 2 is obviously constructed by overlapping these two projected coordinate systems. It becomes clear that the vectors used to position color points in the Color Hexagon diagram are in fact the projections of the magenta, yellow, and cyan components in the MYC coordinates onto the color plane of the CHG coordinates. This resolves the confusion and hesitancy we had about placing three linearly independent vectors in a two-dimensional space. For convenience, densitometer readings can be used directly to locate color points in the Color Hexagon diagram without taking into account this projection factor.

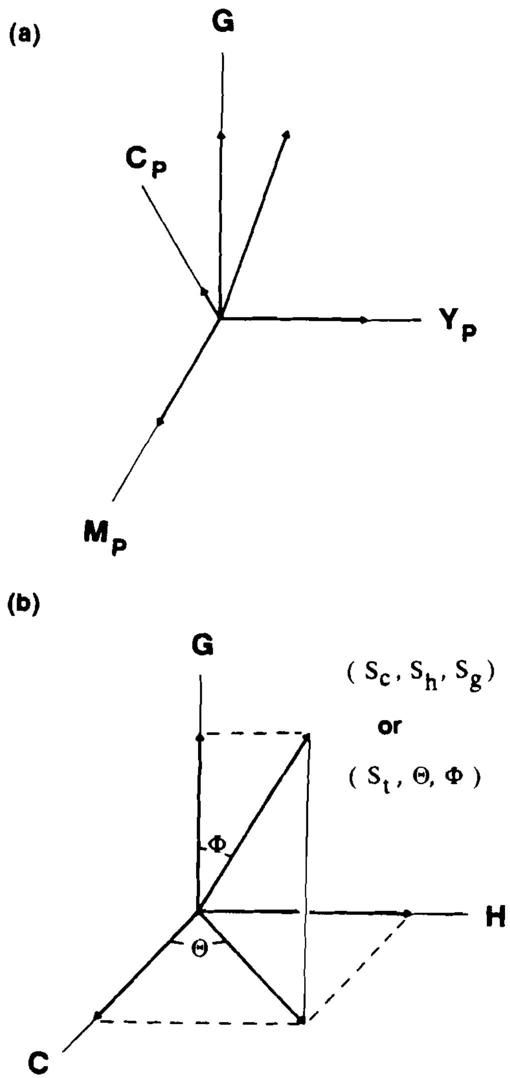

Figure 5. Schematic diagram showing (a) three vector components in the MYC coordinates being temporarily resolved into four components in the CHG coordinates and (b) three coplanar vectors being rearranged into the color strength and hue error components.

CHG Coordinates for All Printed Colors

It is shown in Figure 4a that the angle between the gray axis and any color axis in the MYC or GBR coordinate system is given by Φ_d, which is equal to $\arctan(\sqrt{2})$. Each color component in the MYC or GBR coordinate system can be resolved into two components in the CHG coordinates, one along the gray axis and the other along the projected color axis in the Color Hexagon space. The conversion factors are $\sqrt{1/3}$ or $\cos\Phi_d$ for the gray component and $\sqrt{2/3}$ or $\sin\Phi_d$ for the projected color component. Accordingly, a color vector in the MYC or GBR coordinate system can be temporarily resolved into four vectors in the CHG coordinate system, as shown in Figure 5a. The vertical vector determines the gray strength and the other three coplanar vectors characterize the chromatic appearance of the printed color. These three coplanar vectors can be rearranged into two independent vectors, a color strength vector along the color axis of interest, that is magenta, yellow, or cyan for a primary color or green, blue, or red for a two-color overprint, and a hue error vector perpendicular to the color axis (Figure 5b). This is the previously mentioned CHG coordinate system. C, H, and G stand for color, hue error, and gray, respectively.

Based on these transformations, any set of high, medium, and low (H, M, L) densitometer readings for primary colors or any set of transformed densities for overprint colors can be converted into the color strength, hue error, and gray components in the CHG coordinates by the following equations.

$$S_c = H \sin\Phi_d - (M+L) \cos(\pi/3) \sin\Phi_d = \sqrt{2/3}\, H - (M+L) / \sqrt{6} \qquad (6)$$

$$S_h = (M-L) \sin(\pi/3) \sin\Phi_d = (M-L) / \sqrt{2} \qquad (7)$$

$$S_g = (H+M+L) \cos\Phi_d = (H+M+L) / \sqrt{3} \qquad (8)$$

where S_c is the strength of color component.
S_h is the strength of hue error component.
S_g is the strength of gray component.

A major result of these manipulations is that both primary and overprint colors can be specified in the CHG coordinates by a single set of relatively simple equations that represent the more realistic set of data (S_c, S_h, S_g). When the densities of three color components of the three-color overprint are not equal, its color strength is not equal to zero according to Equation 6. In this case, both MYC and GBR coordinates can be used to specify its color strength and hue error, but the color axis used has to be identified. An example will be presented later. The second important result is that the strength of a printed color includes contributions from all three density values, as indicated by Equation 6, not just from the high density value, Equation 1.

Logical Definitions of Hue Error and Grayness

A color vector can also be expressed by the spherical coordinates, (S_t, θ, ϕ), as illustrated in Figure 5b. Doing so is advantageous in expressing the hue error and grayness of printed colors. The relationships between the spherical and CHG coordinates are as follows.

$$S_t = \sqrt{H^2 + M^2 + L^2} \quad (9)$$

$$S_c = S_t \sin\phi \cos\theta \quad (10)$$

$$S_h = S_t \sin\phi \sin\theta \quad (11)$$

$$S_g = S_t \cos\phi \quad (12)$$

where S_t is called the total strength to distinguish from the strength of color component.

θ is the angle between the projected vector on the Color Hexagon space and the color axis.

ϕ is the angle between the color vector and the gray axis.

It was mentioned previously that the hue error of a printed color can be specified by the angle between the projected color vector in the Color Hexagon space and the axis for the color of interest, that is, by the angle θ. Because the angle between the neighboring axes in both Color Circle and Color Hexagon diagrams is $\pi/3$, the percentage hue error can be calculated by the following formula.

$$\% \text{ Hue Error} = 100 * \theta / (\pi/3) \quad (13)$$

This equation provides an exact way of calculating the hue error of a printed color. Accordingly, when the densities of all three color components are equal, θ is equal to zero and hence the hue error is zero, as it should be, rather than indeterminate according to Equation 2.

Grayness is generally used to characterize the purity of a color. Consequently, the angle between the color vector in the CHG coordinate system and the gray axis is indicative of the grayness. Because ϕ is equal to ϕ_d (Figure 4a) for a pure chromatic color and is zero for an achromatic color, the grayness of a printed color is defined by the following equation.

$$\% \text{ Grayness} = 100 * (1 - \phi/\phi_d) \quad (14)$$

With the new grayness definition, Equation 14, the calculated grayness values for a pure chromatic color and for an achromatic color are correct, 0% and 100%, respectively.

When the densities of all three color components are increased by the same amount, the gray strength is increased by a quantity that is equal to the increment times $\sqrt{3}$ according to Equation 8. This equal increment of densities does not affect the color strength and hue error components according to Equations 6 and 7. The net result is a reduction in ϕ, so the grayness is increased. When the densities of all three color components are doubled, both gray and total strengths are doubled but the angle ϕ, and hence the grayness, does not change. These results indicate that grayness is indeed a measure of the purity of a color ink and the predictions made by the conventional and vector methods are qualitatively the same. However, the proposed method provides an explicit and quantitative correlation between the grayness and the gray strength of a printed color.

Relation of CHG Coordinates to Color Diagrams

Based on the discussion so far, a printed color can be equivalently specified by any of the following sets of data: (m, y, c), (g, b, r), (S_c, S_h, S_g), and (S_t, θ, ϕ). Each data set can be readily converted into any of the other sets of data. Historically, it is of more practical interest to specify a printed color by its color strength, hue error, and grayness. These parameters can be obtained from the data set (S_t, θ, ϕ) through Equations 10, 13, and 14. These equations indicate that color strength, hue error, and grayness are mutually independent variables and are, therefore, suitable for specifying characteristics of printed colors.

The interpretation of characteristics of printed colors using the GATF Color Hexagon and Color Circle diagrams becomes unambiguous with the implementation of the CHG coordinates. The Color Hexagon addresses the color strength and hue of a printed color. The strength of gray component is in the third dimension and, therefore, the center of the Color Hexagon diagram represents the white. Accordingly, gray and black colors locate above the center of the diagram and should not be plotted on the Color Hexagon diagram. However, for practical purpose, they can be placed at the center to indicate that their color strength and hue error are both zero.

If the densities of three color components of a printed ink are decreased by an equal amount, the resulting color vector in the MYC or GBR coordinate system changes in both direction and magnitude. In the CHG coordinate system, the gray strength or grayness is decreased accordingly, but the color strength and hue are not affected at all. This is the power of the Color Hexagon diagram for describing the color appearance of a printed ink. This also implies that the same color strength and hue of overprint colors can be achieved by reducing the constituting ink quantities equivalent to the low density component and by replacing that portion with a black ink, that is, the gray component replacement.

The Color Circle addresses the hue and grayness of a printed color. The color strength is in the third dimension. The center of the Color Circle corresponds to the gray axis, so it represents while, gray, and black colors, not just black as indicated by Cox (1969).

Practical Applications

The proposed method makes it possible to specify the color strength, hue error, and grayness for both primary and overprint colors in a more logical and explicit way. The specification of overprint colors by the densities of green, blue, and red components is also possible. The calculation of these parameters with the vector method is

TABLE VII. DENSITY OF MAJOR COMPONENT, COLOR STRENGTH, GRAYNESS, HUE ERROR AND DIRECTION OF HUE ERROR DETERMINED BY VECTOR METHOD FOR SOLID INK PATCHES IN TABLE I.

PRINTED INK	DENSITY	STRENGTH	% GRAYNESS	% HUE ERROR	DIRECTION
MAGENTA	0.72	0.34	49	58	RED
YELLOW	0.55	0.39	19	3	RED
CYAN	0.70	0.42	37	25	BLUE
GREEN	0.76	0.28	68	33	CYAN
BLUE	0.89	0.25	78	8	CYAN
RED	0.88	0.45	50	1	MAGENTA
3-COLOR (MYC)	0.84	0.07	93	79	BLUE (CYAN)
3-COLOR (GBR)	0.86	0.09	93	21	CYAN (BLUE)

more complicated than that outlined by Cox (1969). This is probably another reason why Equations 1 to 3 were widely used in the past. However, a densitometer can now readily be interfaced with a personal computer, so the specification of color characteristics by the vector method becomes a much easier task.

The color strength, hue error, and grayness calculated by the proposed method are listed in Table VII for the same printed colors as in Table I. The direction of hue error is specified by the color toward which the color point shifts. It becomes clear in this case that a pure green overprint, for example, can be achieved by decreasing the amount of cyan ink or by increasing the amount of yellow ink, depending on the desired strength of the green color. Similar situation applies to the other two-color overprints.

The color strength of the three-color overprint can be specified by the color strength of the major component in the MYC and GBR coordinates. The color axis corresponding to the major component is indicated by the color in the parenthesis of the hue error direction, as seen in Table VII. Both color strength and hue error values differ in these two systems. The greater strength value and the

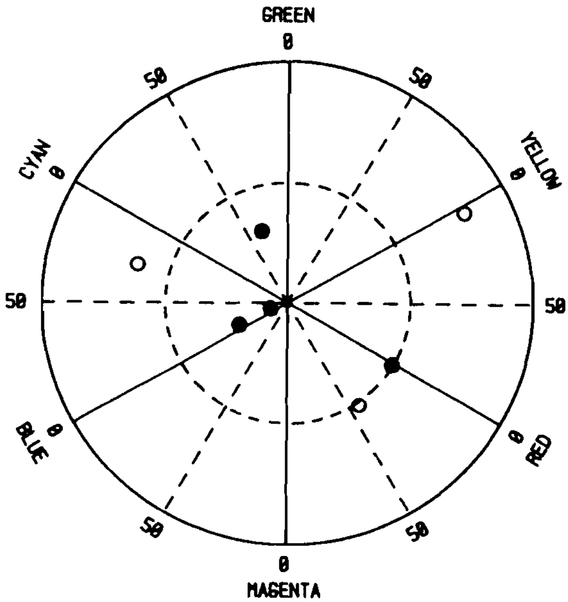

Figure 6. Plot of printed colors in Table I on revised Color Circle. Hue error and grayness are calculated using Equations 13 and 14. Open circles represent primary colors and solid circles represent overprints.

TABLE VIII. DENSITY OF BLUE COMPONENT, COLOR STRENGTH, GRAYNESS, HUE ERROR AND DIRECTION OF HUE ERROR DETERMINED BY VECTOR METHOD FOR BLUE INK PATCHES IN TABLE III.

COLUMN	DENSITY	STRENGTH	% GRAYNESS	% HUE ERROR	DIRECTION
1	0.88	0.24	79	0	
2	0.80	0.23	77	9	CYAN
3	0.80	0.22	79	6	MAGENTA
4	0.83	0.22	79	3	MAGENTA
5	0.80	0.23	78	0	
6	0.79	0.23	77	6	CYAN
7	0.80	0.24	77	6	CYAN
8	0.89	0.25	78	8	CYAN

smaller hue error value, when specified by the blue component, indicate that this three-color overprint has a stronger blue shade.

By using the proposed method, the Color Circle diagram now can be more easily constructed, without the necessity of referring to the ink density data. Figure 6 shows the Color Circle plot of this set of printed colors to be slightly different from Figure 1 in that zero percent hue error is assigned to all axes for both primary colors and two-color overprints. The locations of color points also differ significantly in both diagrams.

Table VIII lists the density of blue component, color strength, grayness, hue error and direction of hue error determined by the vector method for the same blue ink patches as in Table III. The density of blue component varies from 0.79 to 0.89, yet the variation in color strength is very small, ranging from 0.22 to 0.25. The absolute hue error value does not provide sufficient information about the ink hue without correct specification of hue error direction. The proposed method clearly specifies the direction of hue error. The shade of these blue ink patches varies from slightly red to slightly green. This will help the press operator adjust ink keys in the right direction to obtain the desired strength and hue of the overprint colors that are uniform across the web.

Pros and Cons of Proposed Method

The major advantage of the proposed vector method is in printing process control. It offers an explicit guide to the press operator in controlling press conditions for achieving desired characteristics of printed colors. A closed loop control for process printing is also possible when the desired characteristics of printed colors are programmed into the computer.

Some contradictory predictions arise when using the vector method in specifying color characteristics of printed inks. The gray strength of a pure color is generally perceived to be zero, as is inferred by the conventional densitometry method. The vector method predicts that the gray strength of a pure color ink is equal to the total strength times $\cos\phi_d$ or $\sqrt{1/3}$. The densities of an ideal red overprint is, for example, (1, 1, 0) in the MYC coordinates. The calculated grayness is 0% by the conventional method, yet it is 35.6% by the vector method. This indicates that the vector method does not apply to the Color Triangle diagram from which the mask factor for color separation is evaluated. We are now investigating the applicability of this method to the color separation.

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