A DIGITAL COLOR SEPARATING SYSTEM BASED ON PRINCIPLES OF COLORIMETRY

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Abstract: A color separating scanning system has been developed that is based on principles of colorimetry. The system consists of three major elements; an input scanner, an electronic previewing console, and a laser film writer. These three components share a common data base that describes the color at each position within the picture. This data base has its roots in the 1960 CIE Uniform Chromaticity Scale (UCS) or u,v,L system of color specification, not the c,m,y,k ink space specification that is more traditional in the graphic arts industry.

This paper describes the system from the point of view of the color scientist, reviews the reasons for choosing the 1960 CIE UCS, and discusses some of the difficulties encountered providing a user interface to the c,m,y,k oriented operator.

Introduction

Any color reproduction system can be divided by function into analysis and synthesis stages. The analysis stage is a sampling process whereby the original color is divided into its (usually three) component parts. The synthesis stage is the process whereby three or more colorants are combined to produce an approximation of the

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original color. To be useful, a color separating scanner must additionally contain a color modification stage to alter the color at any given point in the image. This is done for two reasons: (1) the colorants used in the synthesis stage may not be the same as those in the original and some modification may be needed to correctly reproduce the color and (2) exact or colorimetric color reproduction (Hunt, 1975) may not be the desired aim; that is colors may need to be changed for editorial or aesthetic reasons or to make up for errors in other stages of the reproduction process.

This paper describes the DESIGNMASTER^R 8000 color separating system which has been developed by EIKONIX Corporation. In the DESIGNMASTER^R system two types of color adjustments are handled quite separately. Modifications that are required due to imperfections in the physical processes that reproduce the colors are handled automatically by a series of colorimetric models and associated calibrations. Modifications that are necessitated by editorial or aesthetic considerations are implemented by the operator through the previewing console using various color altering functions. The operator views these changes on an electronic previewing monitor at the workstation where a highly calibrated facsimile of the final printed output is displayed.

Background

Two basic approaches to the design of color separating scanners emerged in the 1930's and 1940's. The Hardy and Wurzburg scanner was developed first at the Interchemical Corporation and later at RCA. This unit depended on photographic means to create the initial three color separations and used an electronic solution of the Neugebauer equations to perform necessary color corrections. The Murray and Morse Scanner was developed at Eastman Kodak and later at Time-Life. This was a direct separating system that used an electronic solution of the masking equations to perform the color corrections. The Murray and Morse Scanner was later known as the Time-Springdale Colour Scanner and then the Printing Developments Incorporated (PDI) Scanner. The Interchemical approach has been described by Hardy and Wurzburg (1937, 1948), Hardy and Dench (1948), Rydz and Marquart (1954), and Rose (1955). The Kodak approach has been described by Murray and Morse (1937) and Bishop (1951). Yule (1967) and Hunt (1975) have reviewed the history of these developments and discussed some of the advantages and disadvantages of each.

The Interchemical Scanner was based on matching of tristimulus values of each point in the copy with those of the corresponding point in the reproduction. The Eastman Kodak Scanner was designed to emulate traditional photographic color correction techniques. A system based on tristimulus matching is theoretically capable of producing a colorimetrically exact reproduction of the original for all colors that fall within the gamut of the reproduction system. Systems based on solutions of the masking equations are capable of exact color matching for only four colors (Pearson) unless the colorants used to produce the original are the same as those used to produce the reproduction (Yule, 1967). This is rare in graphic arts applications though it may be the case in photographic copying of photographic originals (such as slide duplicating).

From a colorimetric point of view the DESIGNMASTER^R has more in common with the Hardy and Wurzburg approach than that of Murray and Morse. The input scanner measures the tristimulus values directly from the copy to be reproduced. The system uses a standard colorimetric space for internal representation of the color at each point in the picture. Color corrections are affected in this standard color space. The conversion from color to ink space is made by solving a set of modified Neugebauer equations. Using a standard color representation for the color picture data base allows the three system calibrations (input, preview, and output) to be performed independently. This is possible because each system element needs to be related only to the standard representation, not directly to the others. The standard color data base also will permit the system to be easily interfaced to other sources of color data (broadcast video or satellite communication system for example) or output devices (ink jet plotters, electrostatic printers, etc.) providing that appropriate colorimetric models and calibrations can be implemented.

Color Space Chosen

As a digital scanner, colors within the system are represented by numbers, not by photographic densities or electronic voltages. The system chosen to represent the color data in the DESIGNMASTER^R is the 1960 CIE uvL representation. This colorimetric system was chosen for several reasons. It is:

1. based on color matching theory. Colors that match under given viewing conditions have the same uvL representation even if they are metamers.

2. a projective transformation of a set of tristimulus values. This leaves luminance (L) unaltered and separate from chrominance (hue and saturation).

3. a reasonably uniform color space. Equal distances in the (u,v) plane are fairly equal in appearance -- regardless of the position of the two points in the plane.

4. a standard and internationally accepted method for specification of color.

The uvL color space is defined (CIE, 1959), (MacAdam, 1937) in terms of color matching. Any color can be matched with a combination of amounts U, V, and W of each of the three primaries in the uvL system. The values of U, V, and W are the color's tristimulus values (TSV's) and they uniquely specify that color. The chromaticity coordinates, (u,v) of the color are simply the projection of the point in the U, V, W color solid onto the (u,v) plane. Algebraically, the projection is performed by dividing the U and V tristimulus values by the sum of all three TSV's. This is shown in Equation 1.

$$u = U/(U+V+W) \quad 1.a$$
$$v = V/(U+V+W) \quad 1.b$$
$$w = W/(U+V+W) \quad 1.c$$

Since $u+v+w = 1$ it is customary to compute only u and v. The second primary is chosen so that its color matching function (cmf) is the photoptic visibility function. The luminance, L, is equal to the V tristimulus value.

A diagram of the (u,v) plane is shown in Figure 1. The familiar horseshoe shaped curve is known as the spectral locus and represents the chromaticity coordinates of all of the spectral colors in this space. The point labeled N is neutral or white. This point on the gray axis corresponds to the color of the standard D_{5000} viewing source. The distance from white is a measure of the saturation of any given color (similar to chroma in the Munsell System). The angular position of any point in the (u,v) diagram (relative to a line parallel to the u axis and with a vertex at the white point) represents the hue of the corresponding color. The third dimension, luminance is closely related to brightness, (Bartleson and Breneman, 1967) or value in the Munsell System. The chromaticity coordinates of typical cyan, magenta, and yellow ink solids, as well as their two color overprints, are shown in Figure 1 for reference.

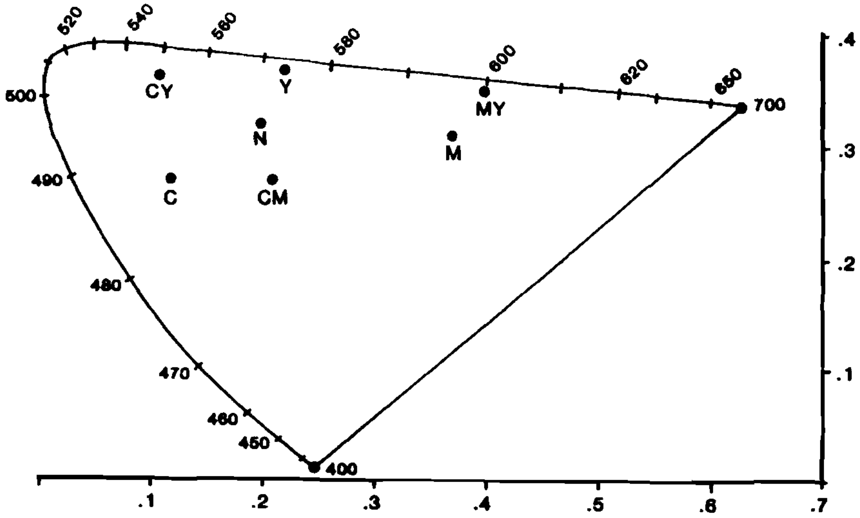

Figure 1 (u,v) Chromaticity Diagram

Description of the System

The system consists of four major components:

I. The 8701 Input Scanner

II. The 8101 Electronic Picture Preview and Editing Station

III. The Associated Electronics

IV. The 8601 Laser Film Writer

The 8701 Input Scanner separates the original into its component tristimulus values on a point by point basis. These values are then converted into numeric representations that can be processed and stored by the digital computers. The 8701 consists of a tungsten halogen illumination system, a set of color separating filters, imaging optics, a precision object stage, a 2048 element self-scanned photodiode array, and the necessary A/D converters and electronic control circuits.

The 8101 Electronic Picture Preview and Editing Station (EPPES) consists of a black and white control monitor, a light pen, a high resolution color previewing monitor, and a keyboard. This station is the operator's control console. All operator interaction with the system is accomplished with the light pen. The operator uses this device to select among various choices from menus displayed on the black and white control monitor. The operator views the color corrections on the color previewing monitor in real time.

The Associated Electronics subsystem contains a general purpose digital computer that controls the system, a special purpose Input Color Computer (ICC), a special purpose Color Correcting and Scaling Computer (CCSC), a special purpose Image Preview Processer (IPP), and 480 Megabytes of mass storage for picture data. This subsystem performs all data manipulations necessary for the system to operate and provides storage for picture data.

The 8601 Laser Film Writer is a drum-based unit capable of writing either halftone or continuous-tone color separation positives or negatives. It is equipped with a blue laser and contains an electronic screener.

In the DESIGNMASTER^R system all color changes are performed on the uvL data. These are converted to other units only for purposes of interfacing with the physical systems that reproduce the colors. The three special purpose processors (the ICC, the IPP, and the CCSC) can be thought of as color interfaces that convert data from one form of color specification to another. The ICC converts the scanner red, green, and blue tristimulus inputs to uvL for their subsequent storage in, and processing by, other elements of the system. The IPP converts uvL values in the picture data base to the required red, green, and blue voltages necessary to reproduce colors on the previewing monitor. The CCSC converts uvL color data to the necessary combinations of cyan, magenta, yellow, and black ink (c,m,y,k) required to reproduce colors on the hard proof or press sheet.

A block diagram of the system is shown in Figure 2.

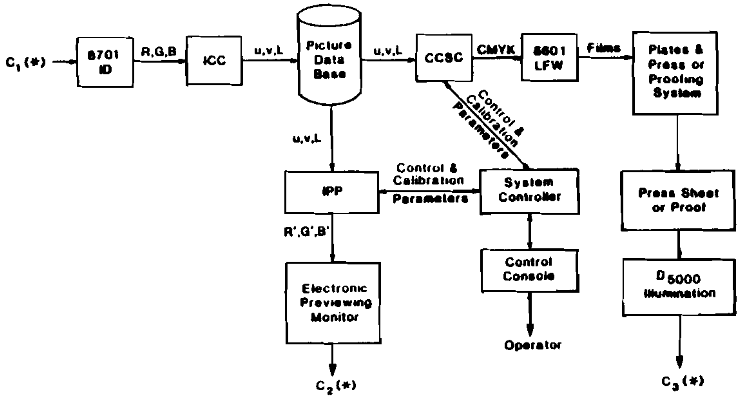

Figure 2 System Block Diagram

The input to the system is a reflection or transmission color patch. The output is displayed color or film used to prepare a hard copy proof or press sheet. To simplify the discussion, it will be assumed that the input sample is a transmitting one with spectral transmittance $C_1(*)$. However, the sample could be a reflection print in which case $C_1(*)$ would be its spectral reflectance. The outputs of the system also have spectral power distributions. The distribution of the patch as displayed on the preview monitor is $C_2(*)$. The distribution of the proof is $C_3(*) = P_{5000} \times R_3(*)$; where P_{5000} is the spectral power distribution of the standard D_{5000} viewing source (ANSI,1972), $R_3(*)$ is the effective spectral reflectance of the proof, and (*) is the wavelength.

The input sample is scanned three times by the Image Digitizer, once through each of the three filters, to produce three raster representations. A number is assigned at each point of each of the three images which is proportional to the transmittance as measured through the appropriate filter. The filters have been selected so that the three spectral response functions of the system very nearly form a set of Color Matching Functions (cmf's). This is a requirement if the instrument is to correctly reproduce colors regardless of the spectral transmittance of the original (Yule, 1967). No logarithmic amplifier is included in the circuits before the A/D converter.

The red, green, and blue (R,G,B) data values at each point form a set of TSV's relative to an arbitrary set of primaries. The ICC converts the R, G, and B tristimulus values (TSV's) to those of the standard U, V, and W system by premultiplying the column vector consisting of R, G, and B by a three by three conversion matrix, A. This is shown by Equation 2.

$$\begin{bmatrix} U \\ V \\ W \end{bmatrix} = A \begin{bmatrix} R \\ G \\ B \end{bmatrix} \qquad 2.$$

The standard tristimulus values are used to form the projection according to Equation 1 and the result is stored on the system's magnetic disks for later recall and processing.

After an original is scanned it can be previewed at the operator's control console. The operator selects the picture, the uvL data is read from the magnetic disks into the preview processor, and the IPP converts the uvL data to the R', G', and B' values necessary to display the color on the previewing monitor by passing the data through specially constructed look-up tables (LUT's). The calculations required to construct these tables are straightforward. Initially, the uvL specification of the color is projected out into the U, V, W tristimulus solid according to Equation 3.

$$w = 1-u-v \qquad 3.a$$

$$U+V+W = V \times L \qquad 3.b$$

$$U = u \times (U+V+W) \qquad 3.c$$

$$V = v \times (U+V+W) \qquad 3.d$$

$$W = w \times (U+V+W) \qquad 3.e$$

According to Equation 4, the U, V, W tristimulus values are then converted to R', G', and B' TSV's for the color monitor phosphor primaries.

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} \begin{matrix} = \\ = \\ = \end{matrix} \; D \begin{bmatrix} U \\ V \\ W \end{bmatrix} \qquad 4.$$

In Equation 4, D is a three by three conversion matrix. The calculation of D is shown in Equation 5.

$$D = \begin{bmatrix} U_rU_gU_b \\ V_rV_gV_b \\ W_rW_gW_b \end{bmatrix}^{-1} \qquad 5.$$

In Equation 5, U_r, V_r, and W_r are the tristimulus values of the monitor face when only the red phosphor is excited. U_g, V_g, W_g, and U_b, V_b, W_b are defined analogously for the green and blue phosphors respectively. The resulting spectral power distribution of the patch displayed on the monitor is given by Equation 6.

$$C_2(*) = R'C_r(*) + G'C_g(*) + B'C_b(*) \quad 6.$$

In Equation 6, $C_r(*)$ is the spectral power distribution of the red phosphor primary. $C_g(*)$ and $C_b(*)$ are defined analogously for the green and blue monitor primaries respectively.

When the image is displayed the operator is free to make any color changes necessary. The color correction functions do not affect the high resolution picture data itself; rather, they continuously update a series of data correction tables. While the monitor is being refreshed, these tables are applied to the data by LUT's in the preview processor. The corrections are saved so that the affected changes can be made automatically to the data when they are written onto film. No additional processing of the main data base is required to effect these changes. At any time the operator can save all of the changes made in what is called a "set-up" for later recall.

The final stage of the process is to write the four color separations using the Laser Film Writer. After the operator selects the picture to be written and specifies the required size and screen angles, the current state of the color correction tables are used to modify a set of ink look-up tables that are loaded into the CCSC. The association of inking with uvL value is not directly controllable by the operator. Any color manipulation requested is affected by remapping the uvL data and using the resulting modified color to address the ink look-up table. The purpose of the ink table is to convert the uvL representation of a color to the required inking (combination of c, m, y, and k) necessary to reproduce that color. The ink tables are not used to alter or correct the appearance of the picture.

Different sets of tables can be calculated for different press, paper, and ink conditions. Ink tables also control varying amounts of under color removal (UCR) and maximum ink coverage. The generation of ink look-up tables is an off-line operation that employs a search to find the inking that best reproduces each required color. Input transparencies have dynamic range and gamut in excess of that of the four color lithographic printing process (Hunt, 1975), (Korman and Yule, 1971). Therefore, there are colors that appear in the data but are unprintable. Printable colors are reproduced exactly in the colorimetric sense. For unprintable colors the proper trade off between desaturation and lightening is found. The offset lithographic printing process is simulated by a colorimetric model within the ink table generation programs. This model is based on an extension of the Neugebauer equations (Neugebauer, 1937), (Pobboravsky and Pearson) and satisfies some of the objections raised by Callahan (1952) and by Clapper and Yule (1953) involving multiple internal reflections within the paper base.

The Color Correction Functions

The basic color correction functions available to the operator consist of (1) gray balance, (2) tonal gradation, and (3) selective color. The system is also capable of performing rectilinear cropping and previewed unsharp masking.

The Gray Balance Function introduces a chrominance shift. Either the entire tonal range of the picture is affected or independently the shadows, three-quarter tones, midtones, quarter tones, or highlight regions may be modified. This function is useful for removing color casts in pictures caused by improper film processing or lighting. The amount of the chrominance shift and its direction are selected by moving a cursor about in the (u,v) chromaticity plane displayed on the control monitor. The direction of the line connecting the white point in the (u,v) diagram with the cursor position specifies the direction of the color shift and the length of the line indicates its magnitude. The color modifications are made by remapping the data in its uvL representation, not in R', G', B' or c, m, y, k, so that tone reproduction characteristics are unaffected by this function. Most operators have little experience with color represented in this manner. However, being a more simplified explanation of color, including graphic feed back, operators quickly master the skills necessary to operate the system. Lines connecting the white point with the chromaticity coordinates of the cyan, magenta, and yellow solids are graphically represented in the u,v diagram displayed on the control monitor. These lines are drawn only for reference, they have no special colorimetric significance.

The Tonal Gradation Function is used to adjust the tone reproduction characteristics of the output copy. In this function the operator is presented with a tone reproduction curve on the control monitor. The curve has a series of control points that can be adjusted to give the curve any desired shape. A plot of the output verses input density transfer function is displayed on the control monitor in real time as the picture is changed on the preview monitor. Only the luminance component of the data is affected by this function. No chrominance shifts are introduced when changes are made.

The selective color function allows the operator to shift any color in the picture independently in hue, saturation and/or luminance without affecting any other colors. When this function is active the operator is again presented with a diagram of the (u,v) chromaticity plane. The positions of the selected color before and after changes are made, are displayed in real time.

In addition, to aid the scanner operator, a percent dot read-out (PDR) function is provided. This function allows the operator to read the percent dot values assigned to any given color by placing a cursor at the appropriate location in the picture. When the operator leaves this function, the cursor remains locked onto the selected position so that the inking can be monitored as corrections are made.

Future additions to the system currently under development include scratch and blemish removal, electronic retouching, local area correction, and a page manager.

If a color is unprintable, the system does not display the measured color, but rather the desaturated and tonally compressed versions that will be printed. The nature of this distortion is available from calibrations that are required by the output stage of the system. The data are corrected for unprintability at all times so that, using the various color correction functions, the operator cannot push colors outside of the printable gamut. One non-physical calibration set is provided. If the operator selects the "Display" as a press calibration the system presents the image as if all colors displayable on the preview monitor were printable. This gives him a way to, in real time, "toggle" between a display of the original copy as scanned by the input station and a display of the picture as it will be printed.

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