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The ABC of Input

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Abstract: Scanners, digital cameras, and other input devices always have been designed to separate an image into its RGB components. This tradition is rooted in the need to display the image with little or no processing. With the advent of inexpensive and fast computing, filters can be optimized to eliminate metamerism and to maximize the signal to noise. This paper introduces the concept of the ABC filter. In addition, a new method of calibration is presented that does not use either a single affine transform or colorimetric mapping over a gamut volume.

Introduction

Both television and graphic arts have a history of separating images with RGB filters. The filter choices, particularly in graphic arts, have been constrained by equipment, economic considerations, and standards. Because of these restrictions, the current RGB input devices are not delivering colorimetrically correct data to the systems that follow in the image chain.

The advent of television and subsequent developments led to the definition of a compatible transmission standard. The NTSC color TV transmission standard is founded on the use of a defined set of color primaries for CRTs. At that time color control was based on a RGB filtering of the camera's response. The RGB signals were processed for video display by using a simple 3X3-correction matrix and a signal shaping circuit. This NTSC standard works well for TV, but, not for high quality color applications.

Graphic arts scanners employ RGB filtering. Unlike television, the filters are chosen to match the absorption peaks of the CMY dyes in color film. The

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scanners are set up to measure density. The measured image densities are converted to CMY halftone dot areas. The color consistency is a problem. File sharing and distributed printing is difficult because RGB is not defined.

All of these input systems treat the RGB filters as though they were primaries. The systems use a linear correction of the input signals followed by an affine transform (Rao and Mintzer 1998). The transformed signals are sent directly to the output device. An alternative is to employ an array of color patches to measure the distortion of the input device and to build a 3-D lookup table eliminating this distortion. Both of these approaches artificially limit the input gamut.

The ABC of scanning refers to new sets of colorimetrically correct filters. These filters are transforms of the CIE 1931 color-matching functions. The new filters are designed to maximize the accuracy of the captured and corrected signals. This new method is able to reduce the residual errors resulting from variations in filter production.

The ABC Filters

Colorimeters are designed to have a spectral response that reproduces the CIE 1931 color-matching functions shown on Figure 1. The response

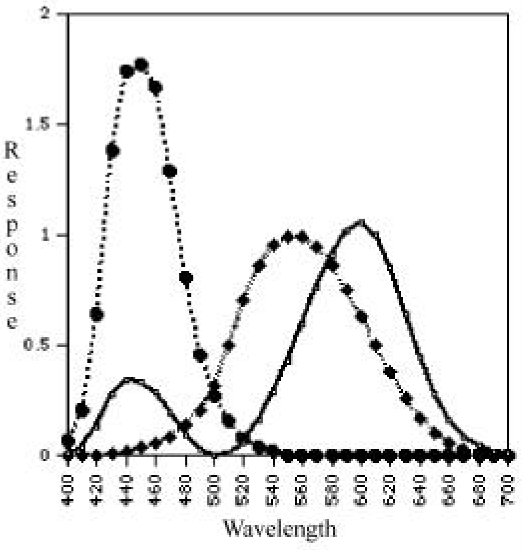

Figure 1. CIE 1931 Standard Observer

function, $\bar{x}(l)$, is difficult to reproduce using a single filter. Two filter channels are used to reproduce $\bar{x}(l)$. Therefore, four individually filtered sensors are required to build a colorimetrically correct scanner. The ABC filter set alleviate this problem by transforming the standard color-matching functions to three physically realizable filters.

The cone responses of human vision are a realizable three-channel filter system. A number of transformations (Wyszecki and Stiles 1982) have been made between the CIE 1931 color-matching functions and the RGB cone-like response functions. Figure 2. shows the abc filters resulting from a 3X3 transformation that is constrained to produce all positive filter values.

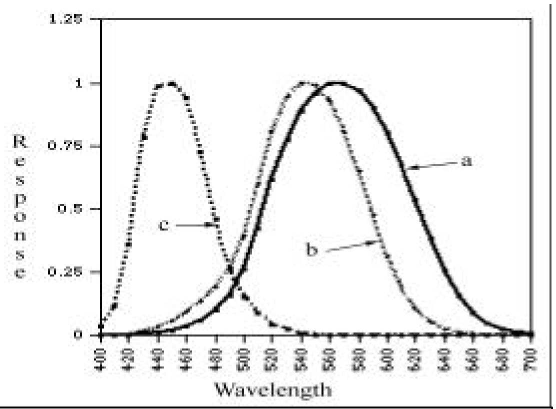

Figure 2. abc Cone-like Color-matching Functions

The abc color-matching functions are a linear combination of the xyz color-matching functions. Therefore, the CIE XYZ tristimulus values are also a linear combination of the ABC tristimulus values as follows,

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 1.8706 & -1.3704 & .3754 \\ .6352 & .3915 & 0 \\ 0 & 0 & 1.7721 \end{pmatrix} \bullet \begin{pmatrix} A \\ B \\ C \end{pmatrix} \qquad (1)$$

Juenger (1998) modified this approach by optimizing the matrix of equation (1) to minimize the noise and to maximize the sensitivity of a digital camera. His analysis assumed the use of CIE L*a*b* to encode the signals. The optimized abc color-matching functions are shown on Figure 3.

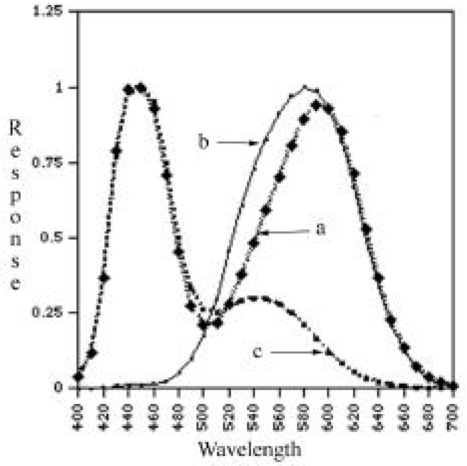

Figure 3. Optimized abc Color-matching Functions

Juenger produced a linear transform that considered the high degree of covariance existing among L*,a*, and b*. The matrix given by Equation 2. is only valid for this condition. The relation between ABC and XYZ is,

$$\begin{matrix} X \\ Y \\ Z \end{matrix} = \begin{bmatrix} -.08 & 1.91 & -.83 \\ 1.58 & -1.41 & .83 \\ -.91 & 1.08 & .83 \end{bmatrix} \bullet \begin{matrix} A \\ B \\ C \end{matrix} \qquad (2)$$

The matrix given by Equation 2. is not valid for other color spaces for which the covariance coefficients would be quite different.

An infinite number of abc color-matching functions exist. The choice of the function depends on the native color space and always-present manufacturing constraints. Because of the increased computational speed of computers, there is no reason abc filters should not replace RGB filters. As we will see in the next section, the abc filters remove the problems of metamerism and make calibration much easier. In the future, all input devices can deliver either XYZ tristimulus or a colorimetrically defined RGB.

Calibration

Detectors are linear and always respond proportionally to the number of photons absorbed. Therefore, any filter triad will react to light falling on the detector and produce a signal, RGB. If the number of photons is reduced by half the value of RGB will be half the starting value. The filtered detectors will produce a value, RGB, when stimulated by an illuminant whose tristimulus values are XYZ. Reduce the color, XYZ, by an amount, say, c. Then the detectors will produce RGB reduced by the same factor, c. Since detectors are linear, there is no need to examine more than a single color at a given chromaticity coordinate, (x, y). This follows from the definition of (x, y) given by Equation 3. below,

$$\begin{aligned} x &= \frac{X}{X+Y+Z} = \frac{c \bullet X}{c \bullet (X+Y+Z)} \\ y &= \frac{Y}{X+Y+Z} = \frac{c \bullet Y}{c \bullet (X+Y+Z)} \end{aligned} \qquad (3)$$

We recommend that the calibration target be comprised of colors that have the highest lightness and chroma possible. These colors will yield maximum signal to noise and produce the most accurate calibration. A target, like the one shown in Figure 4., is required for systems that do not use abc filters.

Figure 4. Calibration Target

System with abc filters do not require such an extensive target. Figure 5. Shows a target that has six chromatic patches and a number of gray patches. The gray patches are used to check the linearity of the color channels.

Figure 5. abc Filter Reflection Calibration Target

RGB filtered systems require that the calibration target colorants be the same as those used in the image material. The abc system does not have this restriction if the abc filters are close to the desired functions.

The calibration procedure is identical for either target. A triple of near colors is used to determine a 3X3 conversion matrix from RGB to CIE XYZ. An example is the choice of white, yellow, and green from the abc reflection calibration target. The conversion of RGB to XYZ is shown by Equation 4.,

$$\begin{matrix} X \\ Y \\ Z \end{matrix} = \overline{M} \bullet \begin{matrix} R \\ G \\ B \end{matrix} \qquad (4)$$

$\overline{M}$ is a 3X3 matrix given by Equation 5.,

$$\overline{M} = \begin{matrix} Xw & Xg & Xy \\ Yw & Yg & Yy \\ Zw & Zg & Zy \end{matrix} \bullet \begin{matrix} Rw & Rg & Ry \\ Gw & Gg & Gy \\ Bw & Bg & By \end{matrix}^{-1} \qquad (5)$$

The matrices for each color triad are computed once and the XYZ values are stored in a two-dimensional array. The array is indexed by red-green chromaticity coordinates denoted, (r, g). The (r, g) coordinates are determined by Equation 6.,

$$r = \frac{R}{R+G+B}$$

(6)

$$g = \frac{G}{R+G+B}$$

The RGB values are those measured on the target. Intermediate RGB values within the triad of colors are interpolated from the values at the vertices of the triad. The values of XYZ calculated from the interpolated RGB and of the sum, R+G+B, are stored as a function of (r, g).

Given any arbitrary RGB,’ we can determine the calibrated value of XYZ’ with the following procedure,

1] The chromaticity coordinates (r’, g’) can be determined from RGB’ by using Equation (6).

2] The values XYZ and the RGB sum are retrieved from location (r’, g’).

3] The proportionality constant, c, is computed by Equation (7),

$$c = \frac{R'+G'+B'}{R+G+B} \tag{7}$$

4] The XYZ’ associated with RGB’ is given by Equation (8)

$$XYZ' = c \bullet XYZ \tag{8}$$

We are finished.

This simple four-step calculation is fast and accurate. The use of the scaling constant, c, yields a compact data structure that is computationally denser than three-dimensional interpolation. The two-dimensional lookup table replaces a complex three-dimensional search followed by an interpolation. This calibration method is the key to having an open image exchange format. Documents will no longer need input profiles attached to the image file.

Conclusion

The main theme of this paper is that all input devices can be either manufactured or calibrated to produce standard XYZ or RGB output. The output can be either CIE XYZ or some new standard RGB space. Two strategies are offered to calibrate input devices. The first is a new concept in filter design, the abc color-matching functions. These filters are related to the CIE standard observer's color-matching function. A 3X3 matrix is derived that transforms the CIE standard observer color-matching functions to a physically realizable filter set. This filter set uses three sensors as compared to the four sensors required to approximate the CIE color-matching functions.

A calibration method is presented that converts extant RGB input devices to calibrated colorimeters. The calibration is limited to the colorant of the image material. Therefore, the system has to have separate calibrations for print film and graphic arts materials. The calibration method is based on a new two-dimensional lookup data storage. The data storage is compact and has computational efficiency. The new lookup table should speed up separations by a factor of fifteen.

The combination of the abc filters and the new color separation method should not only improve work flow, but the computational efficiency should make better use of current assets. The largest benefit of the new system is that documents can be shared regardless of the source, and input profiles are unnecessary

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