Color Transformations for Printer Color Correction

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Abstract

Printer color correction involves the implementation of a transformation from a device independent color space to device dependent coordinates. This transformation is often implemented as a lookup table (LUT). In this paper, we investigate the effect of the choice of the input device independent color space on the accuracy of a color correction LUT. We examine the use of both standard color spaces, and a color space that is derived with information about the gamut of a particular printer. Each color space is evaluated by 1) the accuracy with which the LUT in that space inverts a printer model; 2) the volume of the printer gamut in that space; 3) the percentage of nodes of the LUT within printer gamut. Results indicate that these three metrics correlate reasonably well, and that the colorimetric RGB spaces are generally superior to luminance-chrominance spaces.

Introduction

An essential step towards achieving device independent color is the accurate characterization of each input and output color device in terms of a standard or colorimetric specification. The characterization maps device dependent coordinates to colorimetric coordinates. Color correction then involves inverting the characterization and obtaining a transformation from colorimetric to device coordinates. In this paper, we are concerned with color correction for a printer. Due to the complex nonlinear nature of most printing devices, the transformation from colorimetric to device coordinates is not adequately captured in simple functional form, and is therefore often implemented as a 3-D lookup table (LUT), with interpolation among the table node values.

Three important issues in the color correction problem are 1) the choice of color space to build the calibration LUT; 2) the method used to fill in the LUT values; and 3) the method of interpolation among the known LUT values. Several authors have addressed the problems of table filling and interpolation.[1, 2] In this paper, we focus on the problem of choosing a color space for a calibration LUT. The fundamental colorimetric specification of a color stimulus is in terms of its CIE tristimulus values, XYZ. In addition, a variety of colorimetric spaces have emerged over the years. These include various RGB and luminance-chrominance standards employed in television; the so-called uniform color spaces such as CIE L*a*b*; and the Ycc space recently introduced as a PhotoCD standard. Many of these spaces were derived to suit specific applications. Kasson and Plouffe[3] provide a comparison of several of these color spaces for the purpose of data interchange. An important issue there is the truncation or roundoff error introduced by quantization of the color components. Here we examine a different but related problem of how well a given color space is suited for printer color correction. We examine the use of several standard color spaces; and in addition, we derive a color space that utilizes information about the gamut of a particular printer.

Description of the Color Spaces

Standard Color Spaces

We consider the following set of standard color spaces for building printer calibration LUT's: CIE XYZ; CIE L*a*b*; SMPTE linear RGB; SMPTE gamma-corrected RGB ($\gamma = 2.2$); YES; and Photo Ycc. All these color spaces are defined from unique transformations of CIE XYZ. Details of the transformations are given in Ref. 3. In addition, we also examine an RGB space that was derived so that all colorimetric values produced by typical printers fall within the range [0-1] in this space. (This condition is not met by spaces such as SMPTE linear and gamma corrected RGB spaces, where we have to provide appropriate scale and offset factors so that all the printer data falls in the [0-1] range.) This coordinate system, which we shall call expanded RGB, is obtained from a linear transformation of CIE XYZ:

$$\begin{bmatrix} R_e \\ G_e \\ B_e \end{bmatrix} = \begin{bmatrix} 1.65 & -0.41 & -0.22 \\ -0.85 & 1.75 & 0.09 \\ 0.05 & -0.01 & 1.17 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}, \qquad (1)$$

where R_e, G_e, B_e refer to the expanded coordinates.

A Printer Dependent Color Space

We now examine a transformation that is derived from the calibration data for a particular printer. This transformation is from the colorimetric coordinates [R_e, G_e, B_e] to a new set of coordinates denoted by [R_p, G_p, B_p], and is of the form:

$$\begin{bmatrix} R_g \\ G_g \\ B_g \end{bmatrix} = \begin{bmatrix} R_e^{\gamma_1} \\ G_e^{\gamma_2} \\ B_e^{\gamma_3} \end{bmatrix}; \quad \begin{bmatrix} R_t \\ G_t \\ B_t \end{bmatrix} = A \begin{bmatrix} R_g \\ G_g \\ B_g \\ 1 \end{bmatrix} \quad ; \begin{bmatrix} R_p \\ G_p \\ B_p \end{bmatrix} = \begin{bmatrix} R_t^{\gamma_4} \\ G_t^{\gamma_5} \\ B_t^{\gamma_6} \end{bmatrix} \quad (2)$$

Here, all RGB values are assumed to be in the range [0, 1]; $[R_g, G_g, B_g]$ and $[R_t, G_t, B_t]$ refer to intermediate sets of coordinates; and **A** is a 3×4 matrix. As can be seen in (2), the overall transformation comprises an affine transformation preceded and followed by nonlinear componentwise functions. This form of transformation was motivated by masking methods in color correction[4], where a linear 3×3 mixing model was implemented in density space. In that case, the nonlinear componentwise functions were logarithmic transformations between reflectance and density. In our work, we choose the nonlinear functions to be power-law functions.

The free parameters in this transformation are the coefficients of the matrix **A**, and the six power values $\gamma_1,..., \gamma_6$. The parameters are chosen to get the best fit in the least squares sense between the estimated printer values $[R_p, G_p, B_p]$ and the true printer values $[R_d, G_d, B_d]$ (where R_d = 1-Cyan, G_d = 1-Magenta, B_d = 1-Yellow). Hence, the transformation (2) is an attempt to approximate, in a simple functional form, the relationship between colorimetric data $[R_e, G_e, B_e]$, and device data $[R_d, G_d, B_d]$. Finally, the 3-D color correction LUT is built in the $[R_p, G_p, B_p]$ color space, and corrects for the residual error between $[R_p, G_p, B_p]$ and $[R_d, G_d, B_d]$.

The matrix coefficients and power values are optimized as follows. A training set S of device data $[R_d, G_d. B_d]$ is printed, and measured to yield colorimetric data $[R_e, G_e, B_e]$. An iteration is carried out over the γ_i's, $1 \le i \le 6$, where each γ_i is assumed to take on one of the values 1/3, 1/2, 1, 2, 3. For each combination of $\gamma_1,..., \gamma_6$, the matrix **A** is derived that results in an affine least squares fit between $[R_t, G_t, B_t]$ and $[R_d^{1/\gamma_4}, G_d^{1/\gamma_5}, B_d^{1/\gamma_6}]$. Finally, the set of $\gamma_1,..., \gamma_6$, and corresponding **A** are chosen that result in the minimum approximation error between $[R_p, G_p, B_p]$ and $[R_d, G_d, B_d]$.

If we adopt the ordinary least squares (pseudo-inverse) solution, we minimize the average squared error in the range space of **A**, namely $[R_t, G_t, B_t]$. However, we would prefer to minimize squared error in a color space that is more visually meaningful, or alternatively, to modify the squared error in $[R_t, G_t, B_t]$ with a weighting function that reflects the visual importance of that error, and then solve the weighted least squares problem. Adopting the latter approach, we use a weighting function $W(R_g, G_g, B_g)$ that reflects the effect in CIELAB space of a unit perturbation in the space $[R_g, G_g, B_g]$ (the domain space of **A**). Such an effect may be approximated through local linear differential analysis:

$$\begin{bmatrix} \Delta L & \Delta a & \Delta b \end{bmatrix}^t = \mathbf{J} * \begin{bmatrix} \Delta R_g & \Delta G_g & \Delta B_g \end{bmatrix}^t, \quad (3)$$

and

$$W(R_g, G_g, B_g) = \Delta E = [\Delta L^2 + \Delta a^2 + \Delta b^2]^{1/2}.$$

Here, **J** is the 3×3 Jacobian of the transformation from $[R_g, G_g, B_g]$ to L*a*b*, and the operator * denotes matrix multiplication. We may assume for simplicity a unit perturbation, $\Delta R_g = \Delta G_g = \Delta B_g = 1$ in (3), and perform a normalization to ensure that the sum of the weights W over all the data points is unity. Finally, each of the data points $[R_g, G_g, B_g]$ and $[R_d^{1/\gamma_4}, G_d^{1/\gamma_5}, B_d^{1/\gamma_6}]$ are multiplied with the pointwise weighting function W, and the matrix **A** is derived through the least squares solution with the weighted data.

Evaluation of Color Spaces for Printer Calibration

In our work, we assume that the expanded coordinate system $[R_e, G_e, B_e]$ is the starting point for color correction. We then transform $[R_e, G_e, B_e]$ to each of the proposed color spaces, and build a color correction LUT that maps that space to device coordinates $[R_d, G_d, B_d]$.

Inversion of a Printer Model

One way to test the efficacy of a color correction system is to examine how well it inverts the colorimetric characterization of the device. In our work, we simulate the characterization with a printer model. The use of a model allows us to rapidly process large amounts of data without making additional measurements, and eliminates the introduction of system noise. The printer model we use is a spectral Neugebauer model with Yule-Nielsen correction,[5] derived for a Xerox 5775 four color xerographic printer.

The procedure is summarized in Figure 1. A test set of printer data $[R_d, G_d, B_d]$ is printed and measured to obtain colorimetric data $[R_e, G_e, B_e]$. The latter are passed through the desired color correction transformation **T** and 3-D LUT to obtain estimates of printer values $[R_d', G_d', B_d']$. Since the printer is a 4 colorant device, a predetermined undercolor removal strategy is used to convert the printer RGB values to the CMYK primaries. The printer model then computes the colorimetric L*a*b* response to these printer primaries. Finally, the ΔE error between the true LAB values and estimated LAB values indicates the accuracy with which the proposed color correction scheme inverts the printer model.

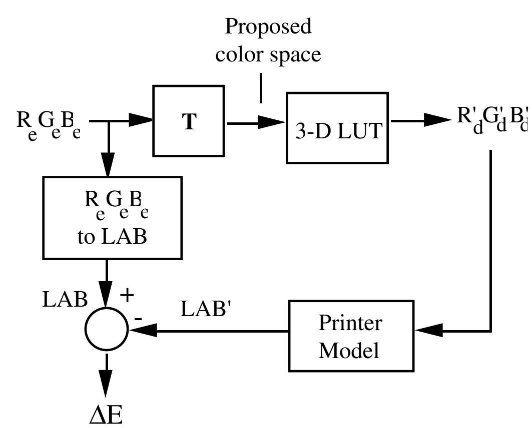

Figure 1. Block diagram summarizing process used to test inversion of printer model.

Comparison of the various color spaces in terms of (i) average ΔE from inverting printer model with 3-D LUT; (ii) normalized gamut volume; and (iii) percentage of LUT nodes in gamut

Color Space	Avg CIELAB ΔE from inverting a printer model			Gamut Volume	% LUT Nodes in Gamut
	4×4×4 nodes	8×8×8 nodes	16×16×16 nodes		
Printer optimized RGB	3.59	1.90	0.92	0.77	67
SMPTE linear RGB	6.00	2.10	1.03	0.42	26
SMPTE γ corrected RGB	6.90	2.38	1.29	0.23	20
Expanded RGB	6.54	2.33	1.19	0.29	12
CIE L*a*b*	14.0	5.00	2.05	0.07	12
YES	15.7	4.66	2.00	0.10	12
PhotoYcc	17.8	7.54	2.62	0.06	8
CIE XYZ	17.5	7.50	2.54	0.06	5

Volume of Printer Gamut

The gamut of a typical printer takes on different shapes and volumes in different color spaces. When building a 3-D LUT in a particular color space, we effectively span that space with a rectangular grid. If the gamut occupies only a small portion of that rectangular volume, then a large percentage of LUT nodes would lie outside the gamut. This makes the table interpolation more coarse, and hence less accurate, within the gamut. Conversely, if the gamut occupies a large volume in the color cube, then more of the LUT nodes would lie in the gamut, hence presumably achieving greater interpolation accuracy within gamut. Hence the second criterion we use to evaluate a color space is the volume of a printer gamut in that color space. The gamut volume is normalized by that of the cube represented by the LUT. As a related criterion, we also examine the percentage of LUT nodes that fall within the printer gamut.

Results

The various color spaces were compared using the aforementioned criteria. LUT's with 4×4×4, 8×8×8, and 16×16×16 nodes were examined. The LUT node locations were placed nonlinearly along each of the 3 coordinate axes to obtain greater interpolation accuracy in visually sensitive regions of color space (*e.g.* low luminance regions). A standard diagonal tetrahedral interpolation scheme[1] was used to obtain a continuous transformation from colorimetric to device coordinates. The printer model was used to generate the calibration data needed for building the LUT's. In order to test the accuracy of the LUT's for printer model inversion, a set of test data was used that was different from the calibration data.

The table summarizes the comparative study. We note, first of all, that in terms of all three criteria, the RGB space optimized for the particular printer is superior to all the standard color spaces, since the latter attempts to capture the color correction transformation in functional form prior to mapping with a LUT. Secondly, we observe that in general, the RGB spaces are more suitable for building calibration LUT's than are the luminance-chrominance spaces. This is probably because device RGB primaries are more closely aligned with colorimetric RGB coordinates, hence making the geometry of the printer gamut in an RGB space more amenable to the rectangular partitioning brought about by the LUT. It is not surprising that the XYZ space is one of the least desirable spaces to build a LUT, as it was designed to encompasses the entire visual gamut, which is much larger than typical printer gamuts. The PhotoYcc space is also undesirable for this problem because a large portion of that color space is devoted to specular highlights, and is outside the colorimetric realm of typical printers.

We remark that the differences in color correction accuracy among the various color spaces are a function of the size of the calibration LUT. As the LUT size becomes larger, the choice of color space becomes less critical. Finally, we note that there is considerable correlation among the criteria that we have used to evaluate the color spaces. Namely, the printer model inversion accuracy increases with the LUT interpolation accuracy, which is in turn dependent on the efficient use of nodes within the printer gamut.

Conclusions

In this paper, we have examined the choice of color space for the specific problem of printer color correction. For the chosen printer, the RGB spaces are more suited for constructing a color correction LUT than are luminance-chrominance spaces. In particular, an RGB space that exploits information about an individual printer will result in more efficient utilization of LUT nodes, and hence greater interpolation accuracy for that printer.

One important issue that we have not addressed here is that of mapping colors that are out of the gamut of the printer. All the standard color spaces discussed here allow for gamut mapping strategies to be incorporated into the 3-D LUT. The printer dependent transformation may also be expanded to allow for gamut mapping algorithms. This may be done by extrapolating the set of componentwise nonlinear functions that follow the linear transformation **A**. Finally, we mention that the proposed printer dependent transformation may be incorporated within the framework of PostScript Level 2 and the InterColor standards.

References

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