Method for Optimizing CIELAB

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Abstract

One of the goals of color appearance models is perceptual uniformity. In a perceptually uniform space, 1 ΔE difference between two colors would have similar magnitude visually regardless of the hue, chroma, or lightness of the colors being compared. In reality, there can be significant differences in perceived magnitude, resulting in modified ΔE metrics such as ΔE_{94} *and* ΔE_{2000}*. This paper proposes a method for improving existing expressions for CIELAB by modifying the matrix converting LMS->XYZ and the coefficients in CIELAB.*

Introduction

The intent of the development of CIELAB was to create a color space that was more perceptually uniform than that of CIEXYZ. In theory, this would mean that equal Euclidean distances in this space between two colors would indicate equivalent magnitude of perceived difference regardless of direction or region of color. In reality, CIELAB has been far from achieving this goal when such Euclidean distance (known as ΔE) is used, requiring the development of non-Euclidean distance metrics such as ΔE_{94} and ΔE_{2000}. Note that for chromas of magnitude 100, the correction to ΔE_{94} in the direction of chroma is a reduction by a factor of 5!

Color order systems such as Munsell were used to optimize and validate CIELAB and is still used to validate more recent CAMs. Since the degree of agreement between CIELAB and Munsell appears closer than between CIELAB and these more recent non-Euclidean metrics, we shall consider whether the assumptions for using Munsell to confirm or optimize CAMs is correct.

This paper is an interim report to:

1) Propose a new interpretation and optimization of XYZ in relation to the cone responses LMS
2) Combine this approach with modified coefficients in CIELAB to achieve the original goal of CIELAB, which was to create a simple, uniform perceptual color space where differences of 1 ΔE have similar magnitude of visual impact

Background

We begin by constructing a model for the human observer analogous to the construction of a digital camera. We assume that the eye and brain comprise of RGB detectors (the cones) with linear response functions which are subsequently processed by circuitry and signal processing:

We will now propose a physical interpretation to XYZ, namely the *sensation* of red, gray, and blue in the brain. This corresponds well to the historical definition of CIELAB as well as other color opponent models, i.e. L*(Y) based on gray only, a*(X,Y) which is calculated from red vs. gray, and b*(Y,Z) which is calculated from gray vs. blue.

We note that the inverse of matrices for converting XYZ->LMS, such as Hunt-Pointer-Estevez, can be used to convert LMS->XYZ. Since LMS (the cone response of the eye) is the basis for color matching, we may regard the conversion of LMS->XYZ as an LMS "mixing" or "cross-contaminating" transformation, which results in XYZ, the actual final sensation of color in the eye+brain system.

We will postulate that inter-channel mixing of LMS to XYZ is directly related to color differentiation, we will endeavor to optimize the conversion of LMS to XYZ based on empirical data extracted from order systems such as Munsell.

Optimization of LMS->XYZ via Equalization of Perceptual Differences

The conversion of LMS->XYZ is essentially a problem with 6 variables (i.e. the amount of mixing of 2 channels with each of the primary channels). The conversion matrix is constrained by the requirement that the values of XYZ are equal for an equal energy spectrum:

$$\begin{pmatrix}1\\1\\1\end{pmatrix} = M'_{LMS->XYZ}\begin{pmatrix}1\\1\\1\end{pmatrix} = \begin{pmatrix}m_{11} & m_{12} & m_{13}\\ m_{21} & m_{22} & m_{23}\\ m_{31} & m_{32} & m_{33}\end{pmatrix}\begin{pmatrix}1\\1\\1\end{pmatrix} \tag{1}$$

$$\begin{aligned} m_{11} &= 1 - m_{12} - m_{13}\\ m_{22} &= 1 - m_{21} - m_{23}\\ m_{33} &= 1 - m_{31} - m_{32} \end{aligned}$$

$$M'_{LMS->XYZ} = \begin{pmatrix}1 - m_{XM} - m_{XS} & m_{XM} & m_{XS}\\ m_{YL} & 1 - m_{YL} - m_{YS} & m_{YS}\\ m_{ZL} & m_{ZM} & 1 - m_{ZL} - m_{ZM}\end{pmatrix}$$

The subscripts i=1,2,3 denote X,Y,Z while j=1,2,3 denotes L,M,S. The m_{ij} coefficients therefore indicate the mixing of L,M, and S into channels X,Y, and Z. For example, $m_{12}=m_{XM}$ indicates the mixing of medium wavelength sensitivity cone M into the X "red" sensation in the brain. If no mixing occurs, i.e. if $m_{ij}=0$ for

$i \neq j$, then L,M, and S would map directly to X,Y, and Z, which of course is not the case

The improved determination of the amount of positive/negative inter-channel mixing can be accomplished by defining a variable function converting LMS->XYZ->CIELAB via an adjustable LMS->XYZ matrix. This adjustable version of CIELAB can be used to calculate the ΔE differences between adjacent colors defined in the Munsell color ordering system as well as any other ordered color systems (COS).

In order to calibrate the calculations for visual differences, we will assume that the simplest metric for the most simple range of colors is correct, i.e. L* for a series of white/gray/black colors. This has already been confirmed by comparing the series of Munsel grays with L*, as shown in figure 10-6 of Fairchild's *Color Appearance Models*.

Since the matrix defined above is invariant with regards to white, the values of L* for neutral colors will not change with optimization of the matrix. The L* of chromatic colors, on the other hand, will be strongly affected by selection of the m_{ij} mixing coefficients. If the current calculation for XYZ results in certain chromatic colors looking significantly lighter as they become more chromatic at constant luminosity Y or L*, this would indicate a value of m_{YL} or m_{YS} that was too small, resulting in a calculated value of Y that was too low for increasing L(red) or S(blue).

Hence, the interpretation of "1 ΔE" with regards to magnitude of visual difference in color will be the magnitude of visual difference in white/gray/black. Differences of 1 ΔE for all other pairs of colors will be compared to this reference. If a particular pair of colors differ by 1 ΔE, the perceived magnitude of difference should be similar to a 1 ΔE difference of white/gray/black.

We therefore define a cost function to be minimized, which is a summation of errors in predicting ΔE for a color-order system (COS) such as Munsell. We define ΔE, ΔL*, ΔC*, ΔH* between pairs of colors using the increments Δi, Δj, Δk for the values of value, chroma, and hue. We consider the differences between adjacent colors and the average difference between colors, for example in the case of chroma:

$$CostFunction = \sum_{i=1,j=1,k=1}^{i=N_{Value},\, j=N_{Chroma},\, k=N_{Hue}} [\Delta C^*_{ijk} - \overline{\Delta C^*_{ik}}]^2$$

$$\overline{\Delta C^*}_{ikChroma} = \frac{1}{N_{Chroma}} \sum_{j=1}^{j=N_{Chroma}} \Delta C^*_{ijk}\,(M'_{LMS->XYZ}) \qquad (2)$$

The above cost functions can be minimized by modifying the LMS->XYZ conversion. We proceed to optimize the LMS->XYZ conversion by converting XYZ to LMS with the standard matrix and then LMS to XYZ' by modifying the values of the conversion matrix:

$$\overrightarrow{XYZ'} = M'_{LMS->XYZ}\, M^{-1}_{LMS->XYZ} \overrightarrow{XYZ} \qquad (3)$$

We note that the above optimizations of LMS->XYZ (which are performed by minimizing the cost function) will be affected by the coefficients that currently exist in the equations for scaling L*a*b*. These coefficients (100,500, 200 respectively) were empirically determined based on Munsell, and would have been affected by choice of LMS->XYZ, if the current matrix conversion does not adequately reflect human sensation of color. Hence, these values along with the conversion matrix can be optimized together.

A least squares fit (LSF) was performed on the Munsell data set. In the fit, the values of m_{ij} from equation (1) above were automatically adjusted as well as the scaling coefficients used to calculate a* and b* (currently 500 and 200 respectively in the CIELAB equations). The error minimization was performed on the cost function using Powell's method, using the average change in chroma of CIELAB between increments of Munsell chroma for calculating the standard deviation in chroma increments for LAB_E. This latter choice was made to ensure that LAB_E would be as consistent as possible with historical metrics, and to avoid reducing the standard deviation of the chroma increments by accidentally reducing the overall chroma itself for all colors. Results were:

Calculated Parameters for XYZ_E

LMStoXYZMatrix	LMS_L	LMS_M	LMS_S
XYZ_X=	1.834	1.006	0.172
XYZ_Y=	0.282	0.733	-0.016
XYZ_Z=	0.050	0.162	0.887
a* Coefficient=	524.90		
b* Coefficient=	220.12		

The above values resulted in a 33% improvement in the consistency of ΔE with the Munsell data. Research is now underway to further optimize the above procedure in order to demonstrate significant improvements to the practical use of ΔE for purposes of specifications and gamut mapping.

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References

[1] Mark D. Fairchild, Color Appearance Models, (Addison-Wesley, Reading Massachusetts, 1998)
[2] Gunter Wyszecki and W.S. Stiles, Color Science: Concepts and Methods, Quantitative Data and Formulae, 2nd Edition, (John Wiley&Sons, NY, 1982)
[3] Robert Hunt, The Reproduction of Colour, (Fountain Press, England, fifth edition, 1995).

Author Biography

Christopher Edge received his undergraduate degree and Ph.D. in physics from the University of Virginia in 1978 and 1988 respectively. He began his career with Kodak GCG (then 3M graphic prep systems) 1986 by helping to develop the optics and RIP for one of the first digital halftone proofing systems. During the 1990's he led the development of color technology for the highly successful Rainbow Desktop Proofer™, which became the basis for the Color Fidelity Module™ and Color Locking Software™ technologies. Beginning in 2000, he led the development of the core technologies for Kodak Matchprint Virtual™, which has inspired his recent efforts into the development of improved human observer functions.