

sRGB Color Calibration of Standard Color Displays

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Abstract

A comprehensive and practical method is presented for ensuring that standard color displays deliver optimal perceptual color matching capability within sRGB standards. Display specific data is measured on the assembly line and stored in EDID data space within each unit. When the display is connected to a computer, a software utility retrieves the data and designs an optimizing filter to correct R, G, B and white points at all intensity levels for best perceptual match to sRGB standards. The basic philosophy and method is presented, empirical data is analyzed and feasibility is evaluated.

1. Introduction

In computer systems, the digital representation of color is in terms of variable mixes of three primary additive colors: Red, Green and Blue (R, G, B). The human visual system predictably perceives the close juxtaposition of the three basic colors as one resultant color. This illusion is the basis for color image processing. Using a-priori knowledge of the human visual system, it is possible to manipulate the intensity mix of the three basic colors to cause various desired color shades to be perceived [1]. In fact, a wide range of colors may be perceived in this manner.

For a high fidelity color system, it is of fundamental importance that the actual shade of color produced by any mix of the three primary colors be predictable. For this to occur, it is necessary to have precise proportional control of the intermediate intensities of each component primary color. It is also necessary to know, with reasonable accuracy, the actual shade of the basic colors. Currently in computer systems, this fidelity is lacking due to imprecise proportional brightness control of basic colors as well as no control/knowledge of the actual shading of the primary colors.

This paper addresses the second issue viz. variations and deviations in the color coordinates of the primary monitor colors. The primary color coordinates can vary from one monitor to the next from the same manufacturer. This variation may also be expected from one manufacturer to

the next. We measured the primary color coordinates of seven monitors of different manufacturers in our lab. The results are shown in Figure 1. Visually, there were some perceivable differences between these monitors. These differences become much more startling when comparing between display technologies such as LCD (Liquid Crystal Display) vs CRT (Cathode Ray Tube) monitors. Figure 2 shows the difference between a Compaq Flat Panel Monitor and a Compaq CRT monitor.

Computer Graphics Systems render image bitmaps to the monitor screen. These bitmaps consist of RGB triplets that directly relate to specific colors. This is because the image bitmap is generated under the assumption that the display device will conform to the standard sRGB color space [2]. Since we have evidence that all monitors do not conform exactly to the sRGB specification, we are interested in a method for processing the original bitmap given valid data regarding the actual primary color coordinates of the specific monitor that we are working with. A method is developed below to generate a filter that will correct for the deviations from the sRGB specification and essentially calibrate the monitor to display the best approximation of the color that an sRGB monitor would display, given the original unfiltered bitmap.

2. Altering the Gamut of a display bitmap

The x,y CIE (Commission International d'Eclairage) chromaticity coordinates of the primary colors of a display represent the apices of a triangle that bounds the range of colors that may be rendered by the display [3]. Any particular color rendered corresponds to one and only one ordered triplet of primary color intensity values (R,G,B). Images consisting of an array of these ordered triplets (image bitmaps) are developed based upon the assumption that the primary monitor R,G,B colors have certain CIE color coordinates. This assumption is (or should be) related to a standard color space. The sRGB standard, among other things, specifies the coordinates for the primary colors of the monitor [2]. If the monitor rendering the image bitmap does not conform to the sRGB standard for these colors,

then any and all colors rendered will likely be perceived incorrectly.

The goal here is to develop a method of "filtering" the image bitmap such that the output of the filter is a new image bitmap with modified (R,G,B) triplets that take into consideration the actual color coordinates of the particular monitor in comparison with the color coordinates assumed in the creation of the image bitmap. In this particular treatment, we shall assume that the original color coordinates used in the creation of the original image bitmap lie within the color gamut of the monitor. Below, we will discuss how the issue may be optimally resolved if the original color coordinates extend beyond the color gamut of the monitor.

In order to develop a color correcting filter, it is necessary to have a deterministic method of mapping from R,G,B bitmap data directly to the perceived color coordinates. An experiment was conducted to determine if it is possible to directly compute the perceived color coordinates resulting from any mix of known primaries. The coordinates of each primary were measured. Then 25%, 50% and 75% of each of the other primaries were added to the first primary, together and separately, and the coordinates measured each time. The idea was to determine if the coordinates of the colors resulting from the mixed primaries would align graphically so as to suggest a simple deterministic method of color prediction. See Figure 3 and Figure 4 for the results. It was found that it is not possible to work linearly within the CIE 1931 x,y chromaticity color space. That is to say that, given

$$[Y, x, y]R; [Y, x, y]G; [Y, x, y]B \quad (1)$$

it is not possible to predict by linear combination the

$$[Y, x, y]R + G + B \quad (2)$$

that results from adding the three given intensities of colors together.

It was determined that mapping $[Y, x, y]$ to $[Y, u, v]$ using the mapping [4]

$$u = \frac{4x}{-2x + 12y + 1} \quad (3)$$

and

$$v = \frac{9y}{-2x + 12y + 1} \quad (4)$$

yields a color space that is linear in the sense that given

$$[Y, u, v]R; [Y, u, v]G; [Y, u, v]B \quad (5)$$

It is entirely possible to predict the resulting color coordinates

$$[Y, u, v]R + G + B \quad (6)$$

by computing the Y weighted average for u and v and by summing the Y values to get the resultant color. If $[Y, u, v]R$ is the intensity Y_r with coordinates u_r and v_r of the red component of the display and likewise $[Y, u, v]B$ and $[Y, u, v]G$ correspond to the blue and green components respectively, then mixing these three will yield an analytically predictable resultant color with intensity given by

$$Y = Y_r + Y_g + Y_b \quad (7)$$

and coordinates given by

$$u = \frac{Y_r u_r + Y_g u_g + Y_b u_b}{Y_r + Y_g + Y_b} \quad (8)$$

$$v = \frac{Y_r v_r + Y_g v_g + Y_b v_b}{Y_r + Y_g + Y_b} \quad (9)$$

So, to shift the display gamut from the triangle defined by

$$[Y, u, v]R; [Y, u, v]G; [Y, u, v]B \quad (10)$$

to the triangle defined by

$$[\tilde{Y}, \tilde{u}, \tilde{v}]R; [\tilde{Y}, \tilde{u}, \tilde{v}]G; [\tilde{Y}, \tilde{u}, \tilde{v}]B \quad (11)$$

(with the requirement that the $\tilde{}$ triangle is contained within the original triangle) we simply select an attenuation and mixing matrix A given by:

$$A = \begin{pmatrix} a_{rr} & a_{rg} & a_{rb} \\ a_{gr} & a_{gg} & a_{gb} \\ a_{br} & a_{bg} & a_{bb} \end{pmatrix} \quad (12)$$

such that the following holds true

$$\tilde{u}_r = \frac{Y_r a_{rr} u_r + Y_g a_{rg} u_g + Y_b a_{rb} u_b}{Y_r a_{rr} + Y_g a_{rg} + Y_b a_{rb}} \quad (13)$$

$$\tilde{u}_g = \frac{Y_r a_{gr} u_r + Y_g a_{gg} u_g + Y_b a_{gb} u_b}{Y_r a_{gr} + Y_g a_{gg} + Y_b a_{gb}} \quad (14)$$

$$\tilde{u}_b = \frac{Y_r a_{br} u_r + Y_g a_{bg} u_g + Y_b a_{bb} u_b}{Y_r a_{br} + Y_g a_{bg} + Y_b a_{bb}} \quad (15)$$

and similarly

$$\tilde{v}_r = \frac{Y_r a_{rr} v_r + Y_g a_{rg} v_g + Y_b a_{rb} v_b}{Y_r a_{rr} + Y_g a_{rg} + Y_b a_{rb}} \quad (16)$$

$$\tilde{v}_g = \frac{Y_r a_{gr} v_r + Y_g a_{gg} v_g + Y_b a_{gb} v_b}{Y_r a_{gr} + Y_g a_{gg} + Y_b a_{gb}} \quad (17)$$

$$\tilde{v}_b = \frac{Y_r a_{br} v_r + Y_g a_{bg} v_g + Y_b a_{bb} v_b}{Y_r a_{br} + Y_g a_{bg} + Y_b a_{bb}} \quad (18)$$

An iterative error minimizing computer program was used to determine the elements of the attenuation and mixing matrix A.

Applying the matrix transpose of matrix A, A^t to an R,G,B triplet from the bitmap input as follows

$$[\tilde{R}\tilde{G}\tilde{B}] = [RGB]A^t \quad (19)$$

then gives us our desired filtered output that achieves our gamut modifying goal.

3. Parametric Gamut Reduction

The above technique gives us the ability to alter the gamut of our display device with the benefit of reshaping the triangular bounds of the resultant gamut and the color mapping of each point within. This is handy if the desired gamut is contained within the bounds of the monitor gamut. For those instances when this is not the case, we introduce the concept of parametrically reduced gamuts.

The concept of parametric gamut reduction refers to the idea of taking 100% of each basic color and adding $t\%$ of each of the other two basic colors to it. The resulting set of three colors define a gamut that is $t\%$ reduced from the original. Rendering an image bitmap in the parametrically reduced gamut results in an image that is perceptibly of the same color with lowered overall saturation. In the extreme cases when $t = 0$, the gamut is unchanged and when $t = 100$, only one color (white) is contained within the gamut. This is one solution to the problem. Other solutions may exist but for the purpose of this discussion, this solution is adequate in the sense that it is linear and offers a perceptually pleasing solution.

So if desired gamut is bounded by a triangle with apices at $(u_r, v_r), (u_g, v_g), (u_b, v_b)$ with intensities (Y_r, Y_g, Y_b) , then a $t\%$ reduction of this gamut would be bounded by apices at $(\tilde{u}_r, \tilde{v}_r), (\tilde{u}_g, \tilde{v}_g), (\tilde{u}_b, \tilde{v}_b)$. The new apices are computed as

$$\tilde{u}_r = \frac{Y_r u_r + Y_g T u_g + Y_b T u_b}{Y_r + Y_g T + Y_b T} \quad (20)$$

$$\tilde{u}_g = \frac{Y_r T u_r + Y_g u_g + Y_b T u_b}{Y_r T + Y_g + Y_b T} \quad (21)$$

$$\tilde{u}_b = \frac{Y_r T u_r + Y_g T u_g + Y_b u_b}{Y_r T + Y_g T + Y_b} \quad (22)$$

and similarly

$$\tilde{v}_r = \frac{Y_r v_r + Y_g T v_g + Y_b T v_b}{Y_r + Y_g T + Y_b T} \quad (23)$$

$$\tilde{v}_g = \frac{Y_r T v_r + Y_g v_g + Y_b T v_b}{Y_r T + Y_g + Y_b T} \quad (24)$$

$$\tilde{v}_b = \frac{Y_r T v_r + Y_g T v_g + Y_b v_b}{Y_r T + Y_g T + Y_b} \quad (25)$$

The intensity of each modified apex is

$$\tilde{Y}_r = Y_r + T Y_g + T Y_b \quad (26)$$

$$\tilde{Y}_g = T Y_r + Y_g + T Y_b \quad (27)$$

$$\tilde{Y}_b = T Y_r + T Y_g + Y_b \quad (28)$$

where $T = \frac{t}{100}$.

Refer to Figure 5 for a graphical example of parametrically reduced gamuts. Note that the white point stays the same and the lines joining the apices of the gamut intersect at the white point and represent the loci of apices of all parametrically reduced gamuts.

The parameter t is selected easily by iteratively increasing the parameter t and testing to ensure that the $t\%$ reduced gamut is bounded by the monitors actual gamut.

4. Feasibility

The utility of the premise of this discussion rests upon knowledge of the actual CIE coordinates of the specific monitor that we are working with. For this to be practical, the desired information should reside within the monitor. Currently, in normal PC monitors, this information is actually already stored in EDID (Extended Display Interface Data) data file. Presently, this information is generic in nature and does not represent the precise characteristics of each individual monitor. However, this data can be made more accurate and pertinent to the specific monitor by simply making accurate measurements of the primary color coordinates for each specific monitor at the time of manufacture. This data can then be immediately written into the non-volatile EDID data RAM of that specific monitor. In this way, a simple manufacturing step can facilitate the availability of the required information. Given this information, a filter can be designed for each specific monitor by using software that retrieves this information at startup. It may be noted that the implementation of the filter described above requires nine multiplies and nine adds per pixel. This could be accomplished using software. If better dynamics are required, it could be easily accomplished using dedicated hardware.

5. Summary

For color fidelity it is necessary to have predictable brightness control over basic display colors. It is necessary to know the exact gamut of the display. It is also necessary to use the above information to filter the image bitmap being

	RED			GREEN			BLUE		
	Y	x	y	Y	x	y	Y	x	y
Tritron CRT Sony CPD-210G	13.2	0.615	0.353	35.3	0.278	0.624	5.14	0.15	0.062
Toshiba CRT Compaq MV400	7.51	0.608	0.357	28.2	0.275	0.624	2.77	0.15	0.058
Samsung CRT Daewoo 15"	11.3	0.615	0.349	49	0.288	0.614	5.86	0.152	0.067
Orion LAF gun Compaq MV520	13.1	0.607	0.352	46.1	0.274	0.618	5.28	0.151	0.059
Samsung CRT Compaq MV520	6.76	0.591	0.345	29.9	0.288	0.603	3.78	0.153	0.07
Samsung CRT Compaq MV520	7.66	0.602	0.347	32.3	0.289	0.605	4.41	0.152	0.067
Chungwa CRT Compaq MV520	7.5	0.6	0.354	27.2	0.279	0.616	3.43	0.152	0.062

Figure 1. Color Coordinates of seven manufacturers' CRT monitors

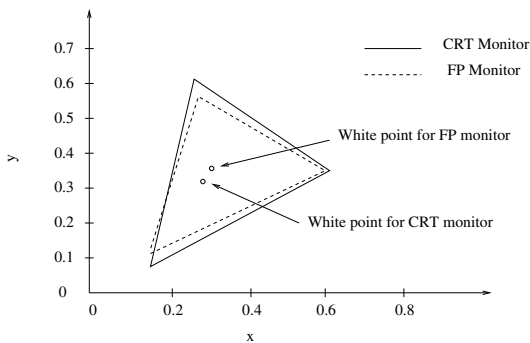


Figure 2. Color Gamut of a Compaq LCD vs. CRT monitor.

rendered such that the resulting image is perceived as originally intended. Currently the problem is that there is no accommodation for variations in the basic color shade. Our proposed solution measures and records the basic color coordinates within each monitor. Software program reads the recorded data and designs an optimizing filter at startup. No user intervention is required for this operation.

References

[1] H. Grassmann, "On the theory of compound colors," *The London, Edinburgh and Dublin Philosophical Mag. and J. Sci.*, vol. 4, pp. 254-264, 1854.

[2] M. Stokes, M. Anderson, M. Chandrasekar, and R. Motta, *A Standard Default Color Space for the Internet*, <http://www.w3.org/Graphics/Color/sRGB.html>, 1996.

[3] F.W. Billmeyer and M. Saltzman, "Principles of color technology," *John Wiley and Sons*, vol. 5, pp. 104-105, 1966.

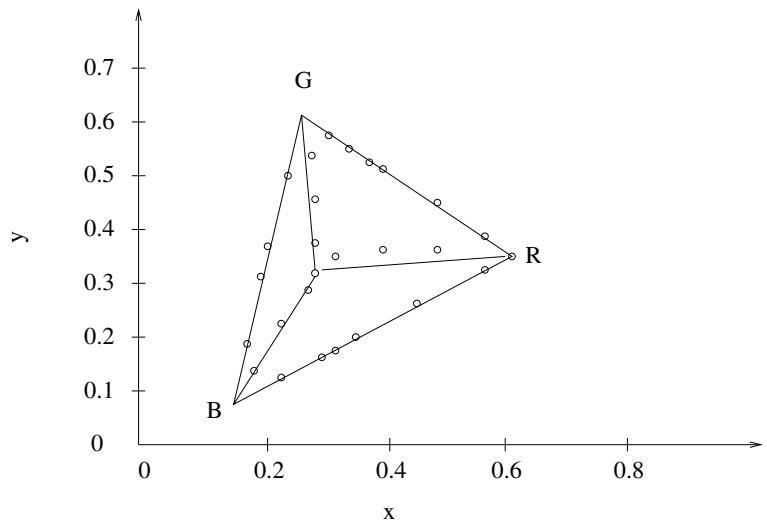


Figure 3. CIE 1931 x,y coordinates of various test color mixes.

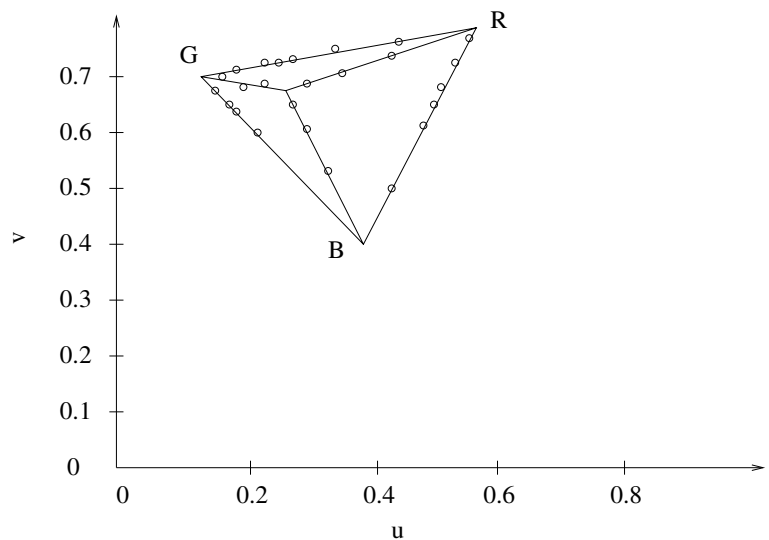


Figure 4. MacAdam mapped u,v coordinates of various test color mixes.

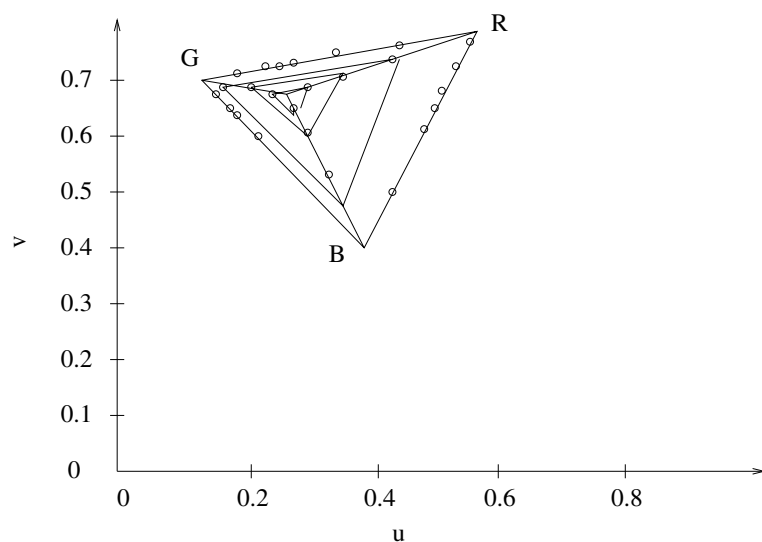


Figure 5. Parametrically reduced Gamuts.

- [4] D.L. MacAdam, "Projective transformations of the i.c.i color specifications," *Journal Optical Society of America*, vol. 27, pp. 294–299, 1937.