Computer-Controlled CRT Colorimetry: A View from CIE

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Abstract

Color displays are ubiquitous with computing. As our color accuracy needs increase, so do our needs to define accurately the color appearance of CRT imagery. The first step in this process involves defining the colorimetric properties of the display. The CIE has addressed this need through technical committee.[2-26] A technical report is undergoing divisional balloting. It is titled, "The Relationship Between Digital And Colorimetric Data For Computer-Controlled CRT Displays." Chapters include: metrology (spectral instrumentation, wideband instrumentation, sampling rates, optimization methods), model relationship (digital to spectral conversion, internal and ambient flare, assumptions), and a worked example to predict spectral radiance or tristimulus values of the entire color gamut from a minimal number of measurements. This paper summarizes this CIE technical report.

Introduction

Cathode ray tubes are used extensively in both broadcast television and computer-controlled visual display. Understanding the relationship between digital data and resulting radiant output is critical when these devices are used as stimulus generators for visual experiments, or to define a digital representation of an image in color reproduction. The CIE, through Division Two's technical committee,[2-26] Measurement of Color Self-Luminous Displays, has produced a technical report[1] to establish the relationship between digital data and measured spectral radiance and CIE tristimulus values for computer-controlled CRT displays. The purpose of the report is to summarize the state-of-the art of CRT device characterization and provide guidance for other standardizing organizations and users.

Title and Membership

This technical report has a provisional number and title: The Relationship Between Digital And Colorimetric Data For Computer-Controlled CRT Displays, CIE 122-1996. The committee is composed of the following members: Roy S. Berns (U.S., Chairman), V.A. Gavin (Russia), F. Le Goff (France), Mark Gorzynski (U.S.), Andrew Hanson (England), Brian Powell (Australia), Danny C. Rich (U.S.), and Frank Rochow (Germany). These members span academia, standardizing laboratories, instrument manufacturers, and broadcast television.

Metrology

The first salient chapter describes design criteria for measurement instrumentation. Both spectral and wide-band devices are considered. Key issues for spectroradiometers include photometric linearity, wavelength accuracy, and methods of calibration verification. Key issues for colorimeters and photometers include photometric linearity and filter-fit accuracy. Accuracy requirements are given when known. For example, when displaying pictorial images, wavelength accuracy should be within ±0.5 nm for spectroradiometers. Sampling rates are also considered due to the pulsed nature of CRT displays.

A section is presented that provides a theoretical framework for the practice of using single- and three-channel devices with poor filter fit to achieve acceptable device characterizations by premeasuring the class of displays requiring characterization with an accurate spectroradiometer or colorimeter.

Relationship between Digital and Spectral or Colorimetric Data

The focal chapter defines the mathematical relationship between digital and spectral or colorimetric data for computer-controlled CRT displays. The model has a historical basis from both vacuum-tube physics[2,3] and broadcast television[4] and is based in large part on research by Motta.[5] Recent enhancements have included internal flare.[6,7] The spectral model is shown in the following equations, where d represents digital data; N counts the number of bits in the digital to analog converter, k_g and k_o are system gain and system offset parameters; γ is an exponent accounting for the nonlinearity between amplified video voltages and beam currents; R, G, and B are monitor tristimulus values, and L_λ is spectral radiance. The matrix equations can also be shown as CIE tristimulus coordinates as shown in Equation 3.

Because of the glass faceplate on all CRT displays, inter-reflection flare can occur between neighboring pixels; this can cause a discrepancy between the measured and emitted flux at a given pixel location. The amount of inter-reflection flare depends on the faceplate properties such as its thickness, refractive index, surface coatings, and the radiant exitance of nearby pixels. Furthermore, the electron beam generated by the cathode may scatter upon interaction with the phosphor screen leading to secondary emissions. Optical radiation due to internal scattering and internal reflection results in internal flare. When a display is situated in an environment with ambient illumination, the flux reflecting from the faceplate to the observer also must be taken into account. Optical radiation due to ambient lighting is defined as ambient flare.

$$R = \begin{cases} \left(k_{g,r}\left(\dfrac{d_r}{2^N-1}\right)+k_{o,r}\right)^{\gamma_r} & ; \quad \left(k_{g,r}\left(\dfrac{d_r}{2^N-1}\right)+k_{o,r}\right) \geq 0 \\ 0 & ; \quad \left(k_{g,r}\left(\dfrac{d_r}{2^N-1}\right)+k_{o,r}\right) < 0 \end{cases}$$

$$G = \begin{cases} \left(k_{g,g}\left(\dfrac{d_g}{2^N-1}\right)+k_{o,g}\right)^{\gamma_g} & ; \quad \left(k_{g,g}\left(\dfrac{d_g}{2^N-1}\right)+k_{o,g}\right) \geq 0 \\ 0 & ; \quad \left(k_{g,g}\left(\dfrac{d_g}{2^N-1}\right)+k_{o,g}\right) < 0 \end{cases}$$

$$B = \begin{cases} \left(k_{g,b}\left(\dfrac{d_b}{2^N-1}\right)+k_{o,b}\right)^{\gamma_b} & ; \quad \left(k_{g,b}\left(\dfrac{d_b}{2^N-1}\right)+k_{o,b}\right) \geq 0 \\ 0 & ; \quad \left(k_{g,b}\left(\dfrac{d_b}{2^N-1}\right)+k_{o,b}\right) < 0 \end{cases} \qquad (1)$$

$$\begin{bmatrix} L_{\lambda=1} \\ \cdot \\ \cdot \\ \cdot \\ L_{\lambda=n} \end{bmatrix}_{\text{measured}} = \begin{bmatrix} L_{\lambda=1} \\ \cdot \\ \cdot \\ \cdot \\ L_{\lambda=n} \end{bmatrix}_{\substack{\text{ambient}\\\text{flare}}} + \begin{bmatrix} L_{\lambda=1} \\ \cdot \\ \cdot \\ \cdot \\ L_{\lambda=n} \end{bmatrix}_{\substack{\text{inter-}\\\text{reflection}\\\text{flare}}}$$

$$+ \begin{bmatrix} L_{\lambda=1,r,\max} & L_{\lambda=1,g,\max} & L_{\lambda=1,b,\max} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ L_{\lambda=n,r,\max} & L_{\lambda=n,g,\max} & L_{\lambda=n,b,\max} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \qquad (2)$$

There are several key assumptions implicit in these equations. The first concerns the three video look-up tables contained in the graphics display controller. The model assumes these LUTs do not alter input values. The second assumption concerns the additivity assumptions of the linear transformation matrices. It is assumed that the channels do not interact and that they have constant chromaticities. The final assumption concerns spatial inhomogeneity. The model applies to a single area of the display. Methods that account for spatial inhomogeneity are referenced in the technical report.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{measured}} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\substack{\text{ambient}\\\text{flare}}} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\substack{\text{internal}\\\text{flare}}} \qquad (3)$$

$$+ \begin{bmatrix} X_{r,\max} & X_{g,\max} & X_{b,\max} \\ Y_{r,\max} & Y_{g,\max} & Y_{b,\max} \\ Z_{r,\max} & Z_{g,\max} & Z_{b,\max} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Example Calculations

The next chapter provides a worked example including measuring internal and ambient flare, checking channel and spatial independence, and estimating the various model parameters. The importance of accounting for internal flare is shown below. Before subtracting the contribution of internal flare from a set of measured data consisting of red, green, and blue primary ramps, the chromaticities of each primary were unstable. Following subtraction, the primaries stabilized in their measured chromaticities. This leads to reasonable results when relying on the primary transformation matrix to convert between monitor and CIE tristimulus values.

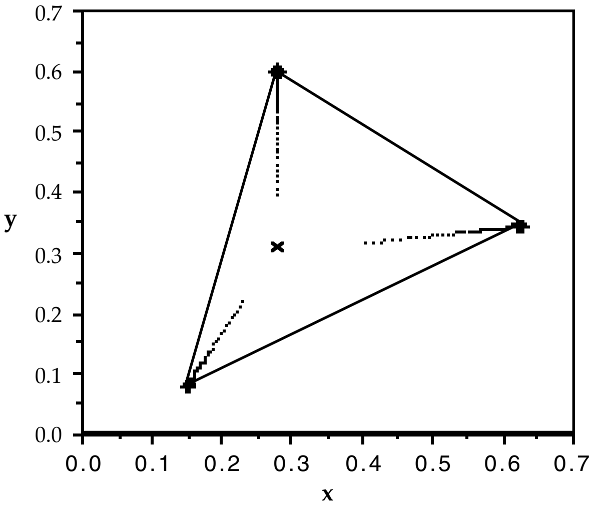

Figure 1. Chromaticities of red, green, and blue primary ramps both before (.) and after (+) subtracting internal flare. Background chromaticity is also shown (x).

Technical Report Conclusions

The report concludes with the following recommended procedures when characterizing computer-controlled CRT displays:

1. Instrument calibration and verification;
2. Measure the ambient and internal flare;

3. Spatial independence check;
4. Measure the tristimulus values of two or more neutrals uniformly sampling monitor tristimulus space between white and the darkest gray that can be measured with high precision;
5. Measure the tristimulus values of full red, green, and blue;
6. Determine linear transformation matrix;
7. Check for channel independence by determining whether the calculated white (R + G + B) is the same as the measured white;
8. Invert the linear transformation matrix;
9. For the neutral measurements, convert the CIE tristimulus values to monitor tristimulus values using the inverse transformation;
10. Normalize the monitor tristimulus values by dividing by their maximum value;
11. Determine k_o, k_g, and γ for each channel ($k_{o,r}$, $k_{g,r}$, ..., $k_{g,b}$, γ_b) or build three one-dimensional look-up tables;
12. Use the k_o, k_g, and γ parameters or look-up tables for each channel to derive an inverse equation or build three look-up tables that accomplish tone reproduction (so-called “gamma” correction); and
13. Test performance comparing measured and predicted colors sampling the display color gamut.

Caveats

It is important to note that the transfer function shown in Eq. (1) differs from that commonly used in broadcast television:[8]

$$\left(\frac{L}{L_{max}}\right)=\left(\frac{V}{V_{max}}\right)^{\gamma} \tag{4}$$

where L is measured luminance and V is video voltage. In television, it is assumed that following monitor set up, the amplified black video level and the video amplifier offset cancel each other. This corresponds to a system gain of unity and an system offset of zero. Thus, the transfer characteristics assumed to exist in broadcast television are a special case of that defined in Eq. (1). (The luminance ratio of Eq. (4) is equivalent to a monitor tristimulus value.)

Because internal flare is sometimes difficult to measure or ignored, the following equation has been suggested instead of Eq. (1):

$$R = k_f + \left(k_{g,r}\left(\frac{d_r}{2^N-1}\right)+k_{o,r}\right)^{\gamma_r} \tag{5}$$

where k_f accounts for internal flare. Note that this is equivalent to Eq. (1) and the addition of the ambient flare vector shown in Eq. (2) or (3). Depending on the dynamic range of one’s measurement equipment, it may be easier to statistically estimate the internal flare using Eq. (5) as opposed to direct measurements.

Finally, although Eq. (1) is the most faithful mathematical description of a computer-controlled CRT’s transfer function, many different functional forms (polynomial equations, multiple gamma values, etc.) are used successfully as well as direct LUT mappings. The optimal method of device colorimetric characterization depends on measurement equipment, the number of measurements one is willing to perform, user expertise, and precision and accuracy requirements.

References

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