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Improved Matrix Method for Tristimulus Colorimetry of Displays

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Abstract

A new calibration method has been developed to improve the accuracy of chromaticity coordinates obtained from a tristimulus colorimeter for color displays. Matrix methods such as the one recommended by ASTM are well known for this purpose, but they may fail to work as expected due to experimental noise and errors. As these matrix methods are based on tristimulus values, the accuracy of the luminance measurement affects the accuracy of the corrected chromaticity. This new method utilizes *x, y* values only, and is independent of *Y* values. Thus, in principle, it eliminates errors due to luminance measurement variations. A correction matrix is obtained from the *x, y* values of three primary colors and a white color of a display, measured by the target instrument and a reference instrument. A computer simulation was conducted to evaluate the effect of random noise in *Y*. Experiments were conducted using a commercial tristimulus colorimeter and a spectroradiometer, measuring 14 colors of a CRT display. The results show noticeable improvement in chromaticity accuracy over the current practice.

1. INTRODUCTION

Accurate chromaticity measurements of color displays such as cathode ray tubes (CRTs) and flat panel displays are increasingly important as their qualities improve and customers demand accurate color reproduction. Tristimulus colorimeters are commonly used to measure chromaticity of such displays. However, due to imperfect matching of the spectral responsivities of tristimulus colorimeters to the color matching functions, measurement errors are inevitable when the spectral power distribution of a display being tested is dissimilar to that of the calibration source. Tristimulus colorimeters and luminance meters are normally calibrated with CIE Illuminant A.

Matrix techniques are known to improve the accuracy of tristimulus colorimeters for color display measurements, utilizing the fact that the colored light produced by most displays is a linear superposition of the spectral power distributions of three primaries. ASTM (American Society for Testing and Materials) E1455 [1,2] recommends a method to derive a correction matrix (R' matrix) that transforms measured X_m, Y_m, Z_m values into better agreement with the reference values X, Y, Z. The matrix is made such that the root-mean-square difference between transformed X_m, Y_m, Z_m and X, Y, Z for several different colors of a display is minimized.

These matrix methods, however, may not work as expected due to experimental noise and errors. Because these conventional methods are based on tristimulus values, the errors in luminance affect the accuracy of the corrected results of chromaticity as well as luminance. The variation of luminance measurements can occur due to instability of the display, flicker effect on the detectors, interreflections between the display surface and the instrument, etc., while the measurement of (x, y) is normally more stable and reproducible since it is a relative measurement, and the error factors mentioned above tend to be canceled out if the three channels are sampled at the same time. This problem can be solved by our recent work [3], in which the correction matrix is determined by minimization only for (x, y) differences. This method, however, requires a numerical iterative solution, and it is difficult to apply for a portable instrument.

A new technique for the matrix method (Four-Color Method) has been developed, which is based on the (x, y) values only, and is independent of Y value. Thus, in principle, it eliminates errors arising due to luminance measurement variations. The correction matrix is obtained from the (x, y) values of the three primary colors plus white from the display measured by a target instrument and a reference instrument. A computer simulation was conducted to evaluate the effect of random errors in Y. An experiment was conducted using a commercial tristimulus colorimeter and a spectroradiometer, measuring 14 colors of a CRT display. The results are analyzed using the Four–Color Method as well as other conventional methods.

2. THEORY

The primary colors (red, green, and blue) and a white color of a display are measured by a target instrument (a colorimeter being optimized) and a reference instrument (a reference tristimulus colorimeter or spectroradiometer). From the chromaticity coordinates $(x_{\mathrm{m,R}}, y_{\mathrm{m,R}})$, $(x_{\mathrm{m,G}}, y_{\mathrm{m,G}})$, and $(x_{\mathrm{m,B}}, y_{\mathrm{m,B}})$ of red, green, and blue measured by the target instrument, the relative tristimulus values of the primary colors from the target instrument are defined by

$$\boldsymbol{M}_{\mathrm{RGB}} = \begin{bmatrix} X_{\mathrm{m,R}} & X_{\mathrm{m,G}} & X_{\mathrm{m,B}} \\ Y_{\mathrm{m,R}} & Y_{\mathrm{m,G}} & Y_{\mathrm{m,B}} \\ Z_{\mathrm{m,R}} & Z_{\mathrm{m,G}} & Z_{\mathrm{m,B}} \end{bmatrix} = \begin{bmatrix} x_{\mathrm{m,R}} & x_{\mathrm{m,G}} & x_{\mathrm{m,B}} \\ y_{\mathrm{m,R}} & y_{\mathrm{m,G}} & y_{\mathrm{m,B}} \\ z_{\mathrm{m,R}} & z_{\mathrm{m,G}} & z_{\mathrm{m,B}} \end{bmatrix} \begin{bmatrix} k_{\mathrm{m,R}} & 0 & 0 \\ 0 & k_{\mathrm{m,G}} & 0 \\ 0 & 0 & k_{\mathrm{m,B}} \end{bmatrix} \quad (1)$$

$$\text{where } k_{\mathrm{m,R}} + k_{\mathrm{m,G}} + k_{\mathrm{m,B}} = 1 .$$

$k_{\mathrm{m,R}}$, $k_{\mathrm{m,G}}$ and $k_{\mathrm{m,B}}$ are the relative factors for measured luminance of each display color, and are now unknown variables. z with any subscript s is obtained from x_s and y_s by

$$z_{\mathrm{s}} = 1 - x_{\mathrm{s}} - y_{\mathrm{s}} . \quad (2)$$

From the chromaticity coordinates $(x_{\mathrm{r,R}}, y_{\mathrm{r,R}})$, $(x_{\mathrm{r,G}}, y_{\mathrm{r,G}})$, and $(x_{\mathrm{r,B}}, y_{\mathrm{r,B}})$ of red, green, and blue measured by the reference instrument, the relative tristimulus values of the primary colorsfrom the reference instrument are defined by

$$\boldsymbol{N}_{\mathrm{RGB}} = \begin{bmatrix} X_{\mathrm{r,R}} & X_{\mathrm{r,G}} & X_{\mathrm{r,B}} \\ Y_{\mathrm{r,R}} & Y_{\mathrm{r,G}} & Y_{\mathrm{r,B}} \\ Z_{\mathrm{r,R}} & Z_{\mathrm{r,G}} & Z_{\mathrm{r,B}} \end{bmatrix} = \begin{bmatrix} x_{\mathrm{r,R}} & x_{\mathrm{r,G}} & x_{\mathrm{r,B}} \\ y_{\mathrm{r,R}} & y_{\mathrm{r,G}} & y_{\mathrm{r,B}} \\ z_{\mathrm{r,R}} & z_{\mathrm{r,G}} & z_{\mathrm{r,B}} \end{bmatrix} \begin{bmatrix} k_{\mathrm{r,R}} & 0 & 0 \\ 0 & k_{\mathrm{r,G}} & 0 \\ 0 & 0 & k_{\mathrm{r,B}} \end{bmatrix} \quad (3)$$

$$\text{where } k_{\mathrm{r,R}} + k_{\mathrm{r,G}} + k_{\mathrm{r,B}} = 1 .$$

$k_{\mathrm{r,R}}$, $k_{\mathrm{r,G}}$ and $k_{\mathrm{r,B}}$ are the relative factors for luminance of each display color.

Based on the additivity of tristimulus values, and with $(x_{\mathrm{m,W}}, y_{\mathrm{m,W}})$ and $(x_{\mathrm{r,W}}, y_{\mathrm{r,W}})$ being the chromaticity coordinates of the display for the white color measured by the target instrument and the reference instrument, respectively, the following relationships hold:

$$\begin{bmatrix} x_{\mathrm{m,W}} \\ y_{\mathrm{m,W}} \\ z_{\mathrm{m,W}} \end{bmatrix} = \begin{bmatrix} x_{\mathrm{m,R}} & x_{\mathrm{m,G}} & x_{\mathrm{m,B}} \\ y_{\mathrm{m,R}} & y_{\mathrm{m,G}} & y_{\mathrm{m,B}} \\ z_{\mathrm{m,R}} & z_{\mathrm{m,G}} & z_{\mathrm{m,B}} \end{bmatrix} \begin{bmatrix} k_{\mathrm{m,R}} \\ k_{\mathrm{m,G}} \\ k_{\mathrm{m,B}} \end{bmatrix}, \quad \begin{bmatrix} x_{\mathrm{r,W}} \\ y_{\mathrm{r,W}} \\ z_{\mathrm{r,W}} \end{bmatrix} = \begin{bmatrix} x_{\mathrm{r,R}} & x_{\mathrm{r,G}} & x_{\mathrm{r,B}} \\ y_{\mathrm{r,R}} & y_{\mathrm{r,G}} & y_{\mathrm{r,B}} \\ z_{\mathrm{r,R}} & z_{\mathrm{r,G}} & z_{\mathrm{r,B}} \end{bmatrix} \begin{bmatrix} k_{\mathrm{r,R}} \\ k_{\mathrm{r,G}} \\ k_{\mathrm{r,B}} \end{bmatrix}. \quad (4)$$

The white color of the display can be of any intensity combination of the three primary colors. The values $(k_{m,R}, k_{m,G}, k_{m,B})$ and $(k_{r,R}, k_{r,G}, k_{r,B})$ are now obtained by solving Eq.(4) as

$$\begin{bmatrix} k_{m,R} \\ k_{m,G} \\ k_{m,B} \end{bmatrix} = \begin{bmatrix} x_{m,R} & x_{m,G} & x_{m,B} \\ y_{m,R} & y_{m,G} & y_{m,B} \\ z_{m,R} & z_{m,G} & z_{m,B} \end{bmatrix}^{-1} \begin{bmatrix} x_{m,W} \\ y_{m,W} \\ z_{m,W} \end{bmatrix}, \quad \begin{bmatrix} k_{r,R} \\ k_{r,G} \\ k_{r,B} \end{bmatrix} = \begin{bmatrix} x_{r,R} & x_{r,G} & x_{r,B} \\ y_{r,R} & y_{r,G} & y_{r,B} \\ z_{r,R} & z_{r,G} & z_{r,B} \end{bmatrix}^{-1} \begin{bmatrix} x_{r,W} \\ y_{r,W} \\ z_{r,W} \end{bmatrix}. \tag{5}$$

The correction matrix $\boldsymbol{R}$ is then given by

$$\boldsymbol{R} = \boldsymbol{N}_{RGB} \ \boldsymbol{M}_{RGB}^{-1} . \tag{6}$$

If the relative tristimulus values $\boldsymbol{M}$ for any colors measured by the target instrument are given by

$$\boldsymbol{M} = \begin{bmatrix} X_m \\ Y_m \\ Z_m \end{bmatrix} = k \begin{bmatrix} x_m \\ y_m \\ z_m \end{bmatrix}, \tag{7}$$

where k is an arbitrary factor, then the relative tristimulus values $\boldsymbol{M}$ from the target instrument are corrected to $\boldsymbol{M}'$ by using the correction matrix $\boldsymbol{R}$ as

$$\boldsymbol{M}' = \boldsymbol{R} \ \ \boldsymbol{M} . \tag{8}$$

The corrected chromaticity coordinate (x, y) is computed from $\boldsymbol{M}'$.

3. SIMULATION

In order to evaluate how errors in luminance (Y) may affect the error in chromaticity (x, y), a computer simulation was carried out using the spectral responsivity data of a real tristimulus colorimeter and the spectral power distributions of the primary colors of a real color display monitor. CIE $f_1{}'$ values of the colorimeter with respect to $\dot{x}(\lambda)$, $\dot{y}(\lambda)$, and $\dot{z}(\lambda)$ were 7.6 %, 3.8 %, and 7.7 %, respectively. The model colorimeter was first calibrated against CIE Illuminant A. The intensity scales of red, green, and blue were adjusted so that a mixture of these primary colors, each at 100 % intensity, created a white color of approximately 9000 K. Then, 16 different colors were created by different intensities of the primary colors. The values of x, y, and Y of each color as measured by the colorimeter, as well as their true values, were calculated. Then, random noise of 1.7 % rms (3 % maximum) were imposed on Y. This does not affect x, y values. These x, y, and Y values were converted into tristimulus values, and the corrected tristimulus values (and the chromaticity coordinates) were computed using (1) $\boldsymbol{R}$ matrix in ASTM E1455-92 [1] (denoted as RGB method), (2) $\boldsymbol{R}'$ matrix in ASTM E1455-92 [1] (denoted as ASTM-92), (3) $\boldsymbol{R}'$ matrix in ASTM E1455-96 [2] (denoted as ASTM-96), and (4) the Four-Color Method. Figure 1 shows the average results of 10 repetitions of the entire computation since there were variations in results at each randomization of the Y noise. The bars show the rms and the maximum of

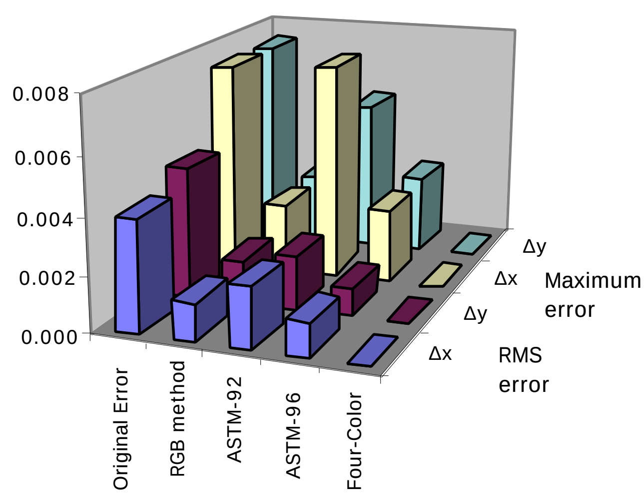

Fig.1. Errors (Δx, Δy) for the 16 CRT colors, with 1.7 % rms random noise in Y, after correction by each method.

the errors (Δx, Δy) for all the 16 colors after correction by each method. These results verify that luminance errors affect chromaticity using the conventional methods (especially ASTM-92), but the Four-Color Method is not affected by luminance errors.

4. EXPERIMENT

To verify the effectiveness of the proposed method, an experiment was conducted using a commercial tristimulus colorimeter as the target instrument and a scanning-type spectroradiometer (employing a double monochromator) as the reference instrument. A video signal generator created 14 different colors on a broadcast-quality color CRT. After changing to a new color, the monitor was allowed to stabilize for ~ 2 min. Both instruments were equipped with lens systems that collected light from the center area of ~3 cm diameter on the screen. Measurements took place with each instrument sequentially. All measurements were taken in a darkened environment. From the raw data, the corrected (x, y) values for the target instrument for all colors were computed by using four methods: (1) RGB method, (2) ASTM-92, (3) ASTM-96, and (4) Four-Color method. The data for the first 8 colors, which included primary colors and white, were used to compute the correction matrices for the ASTM methods. The other 6 colors were measured as test colors. The differences (Δx, Δy) between the corrected chromaticity values and those measured with the reference instrument were calculated. Also, the same computation was conducted for the set of data published in reference [2] which consists of 18 CRT colors measured by a target instrument and a reference instrument. Figures 2 and 3 show the rms values and the maximum values, respectively, of the differences (Δx, Δy) of all 14 or 18 colors after corrections using the four methods. These data demonstrate a considerable improvement of chromaticity accuracy with the Four-Color Method over other methods.

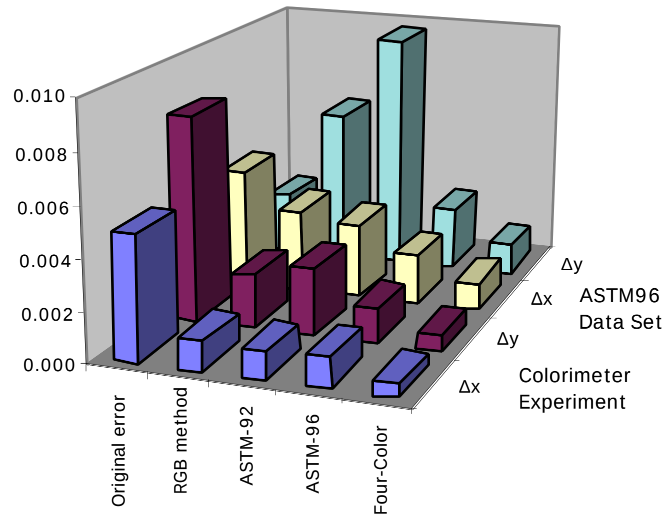

Fig. 2 : RMS differences (Δx, Δy) for all the CRT colors after corrections.

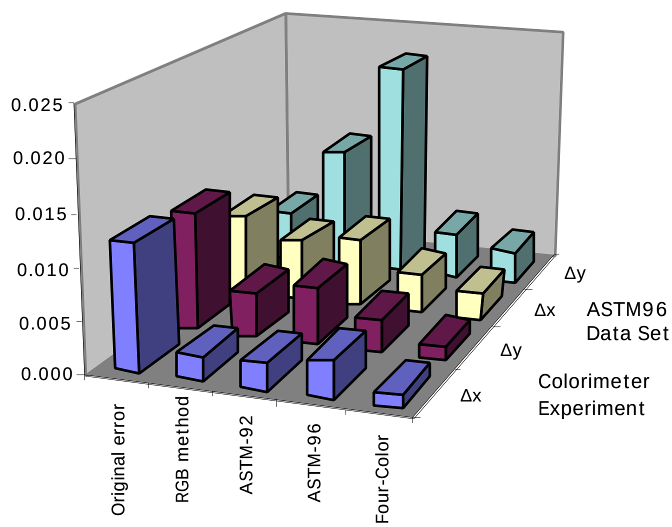

Fig. 3: Maximum differences (Δx, Δy) for all the CRT colors after corrections.

5. CONCLUSION

A new method (Four-Color Method) has been developed to improve the accuracy of chromaticity measurements of displays using tristimulus colorimeters. This method is independent of *Y* values, thus eliminating errors due to luminance measurement errors. The analysis using two sets of experimental data demonstrated a considerable improvement with this method over conventional methods. In addition, this new method has an advantage of simplicity when compared with the ASTM-96 method.

Each set of experimental data was taken with one particular CRT. Further study is required to show how sensitive this method might be to displays employing different phosphor sets having different spectral power distributions. Luminance values (*Y*) can also be corrected by this method. The accuracies of luminance corrections compared with other conventional methods are being investigated. The details will be published elsewhere.

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References

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