Design of relative primary luminances for four-primary displays

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Abstract

◆ Determination of relative primary luminances

– Three primary display
  • Unquely employing the white point

– Four primary display
  • N-3 degrees of freedom for choosing relative primary luminances of an N-primary LED display
  • Base on the white point
  • Using compromise of two additional requirements
    – Maximum display luminance
    – Maximum color gamut
Introduction

◆ Expansion of color gamut
  – Being expanded by the use of high saturation primaries
    • LED and OLED displays
      – Spectral widths of primaries: narrower
  – Addition of more primaries
    • Multi-primary display
  – Prospect of multiprimary OLED and LCD displays
    • Being popular in the future
      – Attractive image quality
      – Advances of technology
◆ **Color conversion**
  - Conversion of RGB to the N signals for drive
  - Aim
    • Producing the color as close to the derived tri-stimulus values as possible

◆ **Relative luminances of primaries**

\[
\begin{align*}
C_r &= \frac{Y_r}{Y_r + Y_g + Y_b} \\
C_g &= \frac{Y_g}{Y_r + Y_g + Y_b} \\
C_b &= \frac{Y_b}{Y_r + Y_g + Y_b}
\end{align*}
\]

\[
\begin{bmatrix}
C_r \\
C_g \\
C_b
\end{bmatrix} = \begin{bmatrix}
x_r & x_g & x_b \\
y_r & y_g & y_b \\
1 & 1 & 1
\end{bmatrix}^{-1} \begin{bmatrix}
x_w \\
y_w \\
z_w
\end{bmatrix}
\]

where: \((x_r, y_r), (x_g, y_g), (x_b, y_b)\) are the color coordinates of red, green, and blue primaries

\[z_r = 1 - x_r - y_r, \quad z_g = 1 - x_g - y_g, \quad z_b = 1 - x_b - y_b, \quad \text{and} \quad z_w = 1 - x_w - y_w\]
Four-primary LED display

◆ Attributes
  – Primary spectra

Fig. 1. Primary spectra of the considered four-primary LED display.
Chromaticity quadrilateral

Fig. 2. Chromaticity quadrilateral of the considered four-primary LED display, where the chromaticity triangle and white point of ITU-R BT. 709 are also shown for comparison.
− Normalized input signals
\[ 0 \leq r, g, b \leq 1 \]

− Normalized output luminance described by tonal response curves
\[ 0 \leq R_L, G_{yl}, G_L, B_L \leq 1 \]

− Tone response curves
\[ R_L(r) = r^\gamma \]  \hspace{1cm} (2)

where: gamma value \( \gamma \) is a constant
Four-primary : 2.2
– Output tri-stimulus vector \((X,Y,Z)\) of the display

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \begin{bmatrix}
X_r & X_y & X_g & X_b \\
Y_r & Y_y & Y_g & Y_b \\
Z_r & Z_y & Z_g & Z_b
\end{bmatrix} \begin{bmatrix}
R_L \\
G_{YL} \\
G_L \\
B_L
\end{bmatrix}
\]

(3)

where \( (X_r,Y_r,Z_r), (X_y,Y_y,Z_y), (X_g,Y_g,Z_g), \) and \( (X_b,Y_b,Z_b) \) are the maximum tri-stimulus of the red, yellowish-green, and blue LEDs

– Deriving \(X\) and \(Z\)

\[
X = \frac{x}{y} Y \\
Z = \frac{(1 - x - y)}{y} Y
\]

(4a)

\[
\begin{bmatrix}
Y_r \\
Y_g \\
Y_b
\end{bmatrix} = \begin{bmatrix}
x_r & x_g & x_b \\
y_r & y_g & y_b \\
z_r & z_g & z_b
\end{bmatrix}^{-1} \begin{bmatrix}
x_w - x_y \\
y_w - y_y \\
1 - Y
\end{bmatrix}
\]

(4b)
White point requirement

- **Essential condition**
  - By definition
    - \( r = g_y = g = b = 1 \) at white point
    - \( R_L(1) = G_{yl}(1) = G_L(1) = B_L(1) \)
  - Normalization of the luminance of white point \( Y_w = 1 \)
    - \( Y_r + Y_y + Y_g + Y_b = 1 \) \( (5) \)
  - N-1 degree of freedom of N primary
    - 1 degree of freedom (4 primaries)
    - Choosing the luminance of Y-G primary
      - Variable representing one degree of freedom
**White point requirement**

- From Eqs. (3) to (5)

\[
\begin{bmatrix}
Y_r \\
Y_g \\
Y_b
\end{bmatrix} = \begin{bmatrix}
x_r & x_g & x_b \\
y_r & y_g & y_b \\
1 & 1 & 1 \\
z_r & z_g & z_b \\
y_r & y_g & y_b
\end{bmatrix}^{-1} \begin{bmatrix}
x_w - x_y Y_y \\
y_w - y_y Y_y \\
1 - Y_y \\
z_w - z_y Y_y \\
y_w - y_y Y_y
\end{bmatrix}
\]

where: \((x_y, y_y)\) are the color coordinates of yellowish green primary

: \(z_y = 1 - x_y - y_y\)
Fig. 3. Luminances $Y_r, Y_g,$ and $Y_b$ versus under the white point requirement. $Y_r, Y_g, Y_b$ and $Y_w$ are the luminances of red, green, blue, and yellowish-green primaries, respectively. The white point $(x_w, y_w) = (0.3127, 0.3291)$
Maximum luminance requirement

- **Display luminance**
  - Luminance of the display at the white point

- **Maximum luminance requirement**
  - Designing the largest display luminance from the available primary luminances
  - Available primary luminance
    - Being limited by display technology or primary cost
      - $Y_{rm}, Y_{ym}, Y_{gm}$, and $Y_{bm}$

\[
\frac{a_r Y_{rm}}{Y_r} = \frac{a_y Y_{ym}}{Y_y} = \frac{a_g Y_{gm}}{Y_g} = \frac{a_b Y_{bm}}{Y_b} = \eta
\]

where: $0 \leq a_r, a_y, a_g, a_b \leq 1$ tuning factor

$\eta$ is a proportional constant
– Maximizing display luminance
  • Choosing $\eta$ as large as possible
– From (7) and (8)

\[ \eta \leq \frac{Y_{rm}}{Y_r}, \frac{Y_{ym}}{Y_y}, \frac{Y_{gm}}{Y_g}, \frac{Y_{bm}}{Y_b} \]  

(9)

\[ \eta_{\text{max}}(Y_y) = \text{Min}\left\{ \frac{Y_{rm}}{Y_r}, \frac{Y_{ym}}{Y_y}, \frac{Y_{gm}}{Y_g}, \frac{Y_{bm}}{Y_b} \right\} \]  

(10)

where : $\text{Min}\{\}$ is the minimum function.
Fig. 4. Luminance ratios $Y_m / Y_r$, $Y_m / Y_y$, $Y_m / Y_g$, and $Y_m / Y_b$ versus $Y_y$, where $Y_m = 0.25$, $Y_m = 0.4$, $Y_m = 0.3$ and $Y_m = 0.05$; $Y_r$, $Y_g$, $Y_b$ and $Y_y$ are taken from Fig.3.
Maximum color gamut requirement

**Maximizing color gamut**
- Definition of gamut volume

\[
V = \iiint G\left(L^*, a^*, b^*\right) dL^* da^* db^*
\]  

where \(G(L^*, a^*, b^*)\) represents the gamut of the LED display.

Using the ref.12

![Image of graph showing gamut volume versus luminance of yellowish-green primary.](image-url)
Fig. 6, 7, 8-1. Gamut cross section of constant lightness in CIELAB color space for the display $Y \in \{0.2, 0.37, 0.5\}$ for $L \leq 50$.

The corresponding values of $L$ are shown near the boundaries of the cross sections. Dashed lines are the loci of primary ramps.
Fig. 6, 7, 8-2. Gamut cross section of constant lightness in CIELAB color space for the display $Y_\gamma = 0.2, 0.37, 0.5$ (b) $L' > 50$

The corresponding values of L are shown near the boundaries of the cross sections. Dashed lines are the loci of primary ramps.
Conclusion

◆ **Purpose method**
  – Designing the relative primary luminances of four-primary LED
  – Using base on white point requirement
    • Maximum display luminance
    • Maximum color gamut