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Research Article

Variation of LED Display Color Affected by Chromaticity and Luminance of LED Display Primary Colors

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In recent years, the effect of LED display is increasingly important in the LED display field. Primary colors' chromaticity and luminance of LED display as crucial elements influence the LED display color. Therefore, there is a need for color mapping algorithms that indicate the relationship between primary colors and display color's chromaticity and luminance. In this paper, two mathematical models have been developed. One has shown the display color's chromaticity and luminance affected by luminance of primary colors change. The other one has shown a complicated relationship that primary color is mixed by other primary colors to change chromaticity first and then the mixed primary is used as "new LED primary color." In both mathematical models, CIE $\mathbf{x}^*\mathbf{y}^*\mathbf{Y}$ color space was used as the mutual color space; thus, there was a specific variation tendency of colors with luminance or chromaticity of primary colors change in this color space. The newly designed mathematical models can consistently guide us how to acquire the desired display color by changing luminance or chromaticity of primary colors. Therefore, it has important engineering application value.

1. Introduction

Light emitting diode (LED) display is the mainstream display device used in various fields because of the advantages of high color saturation, high brightness, high contrast, and large display [1, 2]. Keeping better display is one of the key research directions.

LED display is composed of lots of display pixels, and each display pixel is composed of three light emitting chips as red, green, and blue (RGB) which are defined as LED display primary colors to show colorful and vivid images in different proportions. Gamut, the range of color that a display can handle, is defined by the chromaticity and maximum luminance of the primary colors [3, 4]. The characteristic of each color such as luminance and chromaticity represented on the LED display is impossible to be beyond gamut and is influenced by LED display primary colors' luminance and chromaticity [5–7]. Actually, the characteristics of display colors are concerned by people in different application scenarios. Therefore, it is essential to adjust the display colors performance corresponding to people demand by changing luminance and chromaticity of primary colors in a specific method rather than arbitrary one. Such as a common condition where high saturation of the LED display primary colors is demanded, variation of display color's luminance and chromaticity is singly related to primary colors' luminance change as well as chromaticity of primary colors constant. Gamut of LED display and saturation of primary colors are still constant after changing [8]. The method in this condition is called primary color luminance match (PCLM). It is obvious that PCLM coefficients are the crucial factors to affect variation of display color's luminance and chromaticity. In order to make the PCLM applicable for all kinds of LED, we establish the mathematical model in the default device-independent color space CIE1931, which relates the tristimulus parameters X, Y, Z to the luminance R, G, and B of the primary colors of the LED display.

There are several well-known mathematical models that demonstrate the relationship between characteristics of display colors and the digital input values (RGB). Mobile Display Characterization and Illumination Model (MDCIM) represented by Kirchner strongly improves color reproduction accuracy of a typical mobile OLED display [9]. This model can predict and control the color performance displays during a large ambient illuminance levels range. One-dimensional look-up tables (LUTs), represented by Ellen A. Day, dynamically recreate the optimization of the matrix coefficients to accurately display colors [10]. LUT model represented by Mark D. Fairchild and David R. Wyble has established a 3×3 primary transform matrix for colorimetric characterization of this display on the LCD [11]. All of the above models describe the transformation of digital input values (RGB) to the XYZ, providing a more accurate mathematical method to predict and control the color performance of mobile displays. However, these models fail represent in detail the track of the display color in the three-dimensional space CIE x^*y^*Y (CIE1931) with the little digital input values change. An additional important reason related to tendency predicting is compensating LED display color drift, which is caused by the temperature, small current, and control device. What is more important is that some requirements aim to reduce gamut by decreasing saturation of primary colors due to the wide gamut of LED display. Hence, it is necessary for primary color mixed by other primary colors to reduce the saturation. Then, the mixed primary color is used as "new LED primary color" [12]. For example, the red primary color, mixed with green primary color, will turn to yellow; then, the yellow color will be a new LED primary color. This implies that every element of the mixed primary color has changed with the percent of mixing when primary color of "new LED primary color" has changed.

At present, there is little research on this case. Thus, in the present article, a mathematical model is developed to illustrate clearly the relationship between "new LED primary color" and display color. This method is called mixed primary color luminance match with primary color chromaticity match (PCCM& MPCLM). Similar to PCLM, PCCM&MPCLM coefficients are the crucial factors to affect variation of display color's luminance and chromaticity too. Consequently, a mathematical model of PCCM&MPCLM coefficients related to variation of display color's luminance and chromaticity is developed.

Both mathematical models are researched in the three-dimensional space CIE x^*y^*Y to represent the relationship between variation of LED display color and the primary colors luminance and chromaticity change.

2. Color Space Transformation and Gamut of LED Display

Color space, as a mathematical model, is presented by three or four values of color components for the purpose of describing the colors under a particular standard, such as the RGB, HSV, CIE x^*y^*Y, and CIE L^*a^*b color space. Color space can be broadly split into two basic types: the device-independent color space and the device-dependent color space [13]. CIE x^*y^*Y color space as the device-independent color space produced the same color whatever color input or output device is used. Therefore, it is necessary to develop both mathematical models in the CIE x^*y^*Y color space so that the same color on different LED displays represents the same luminance and chromaticity. The formula, RGB of the LED display transforming into CIE x^*y^*Y color space, is expressed as follows:

$$[\,X \;\; Y \;\; Z\,]^T = H[\,R \;\; G \;\; B\,]^T, \tag{1}$$

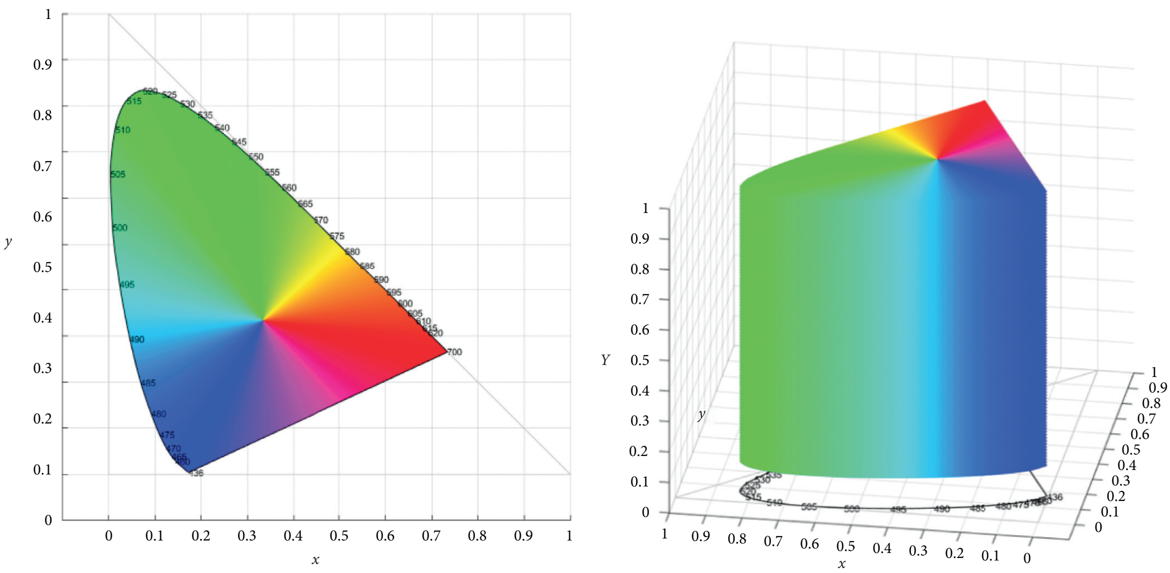
where H represents the coefficient matrix of transformation. $[\,R \;\; G \;\; B\,]^T$ are the percentage of RGB, respectively, and $[\,X \;\; Y \;\; Z\,]^T$ are tristimulus values of CIE x^*y^*Y color space. Besides, Y represents luminance in addition to tristimulus value. According to the principle of chroma, the proportion of tristimulus $[\,X \;\; Y \;\; Z\,]^T$ is actually used to represent chromaticity of the color instead of tristimulus values in CIE X^*Y^*Z color space, as expressed in

$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z}, \quad z = \frac{Z}{X+Y+Z}. \tag{2}$$

However, the chromaticity of the color can be represented using (x, y) on account of $x + y + z = 1$ in CIE x^*y^*Y color space. Hence, it takes x and y as the two chromaticity axes of color, which are perpendicular to each other to form the chromaticity plane. The point on the plane represents the chromaticity information of the color; thus, (x, y) is called the chromaticity coordinate of the color. In addition, it takes Y as the luminance axe of color perpendicular to chromaticity plane. A three-dimensional space, formed by three axes $x - y - Y$, contains both luminance and chromaticity characteristics of the color and each point in this three-dimensional space expresses an independent color. Figure 1(a) shows the chromaticity plane in CIE x^*y^*Y color space. Figure 1(b) shows the three-dimensional space of CIE x^*y^*Y color space.

According to Grassmann's law, H as a coefficient matrix in formula (1) can be expressed as $H = \begin{bmatrix} C_r x_r & C_g x_g & C_b x_b \\ C_r y_r & C_g y_g & C_b y_b \\ C_r z_r & C_g z_g & C_b x_b \end{bmatrix}$. x_r, y_r, z_r are the chromaticity coordinate of R; x_g, y_g, z_g are the chromaticity coordinate of G, and x_b, y_b, z_b are the chromaticity coordinate of B. Generally, the chromaticity of RGB is known and is definite when the LED display is working. Otherwise, C_r, C_g, C_b, as the undetermined coefficient, are indispensable to acquire H. Therefore, this paper selects the CIE D65 illuminant as the reference light source which has the specific tristimulus, substituting the tristimulus and chromaticity coordinates of RGB into formula (1). Then, H has been acquired.

The points (x_r, y_r), (x_g, y_g), and (x_b, y_b), as the three points of the triangle constituting the gamut of LED display, are used to draw a triangle in the chromaticity plane of CIE



(a) (b)

Figure 1: (a) The chromaticity plane of CIE x^*y^*Y. (b) Three-dimensional space of CIE x^*y^*Y.

x^*y^*Y color space. This triangle has been defined as the chroma triangle. Figure 2(a) shows the chroma triangle. Furthermore, $\begin{bmatrix} R & G & B \end{bmatrix}^T$ in formula (1) have been instead of the percentage of the maximum luminance in its maximum luminance. Consequently, the real luminance and chromaticity of RGB have developed a definite mathematical relationship with tristimulus values and chromaticity coordinates as illustrated in

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} C_r x_r & C_g x_g & C_b x_b \\ C_r y_r & C_g y_g & C_b y_b \\ C_r z_r & C_g z_g & C_b x_b \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix},$$
$$x = \frac{X}{X+Y+Z} = \frac{C_r x_r R + C_g x_g G + C_b x_b B}{C_r R + C_g G + C_b B},$$
$$y = \frac{Y}{X+Y+Z} = \frac{C_r y_r R + C_g y_g G + C_b y_b B}{C_r R + C_g G + C_b B}. \quad (3)$$

However, chromaticity of RGB cannot cover the entire visible spectrum and the luminance of RGB cannot be infinite actually. So, the chroma triangle of LED in Figure 2(a) is a subset of the CIE x^*y^*Y color space chromaticity plan, and three-dimensional space is a subset of the CIE x^*y^*Y three-dimensional space too as expressed in Figure 2(b).

According to formula (3), the luminance and chromaticity of RGB in CIE x^*y^*Y color space are related to the luminance and chromaticity of RGB themselves. Consequently, the formula as the basic formula has been used to research and analyze the variation of display color by the primary colors coefficients of PCLM and the variation of the display color by the primary colors coefficients of PCCM&MPCLM in this paper.

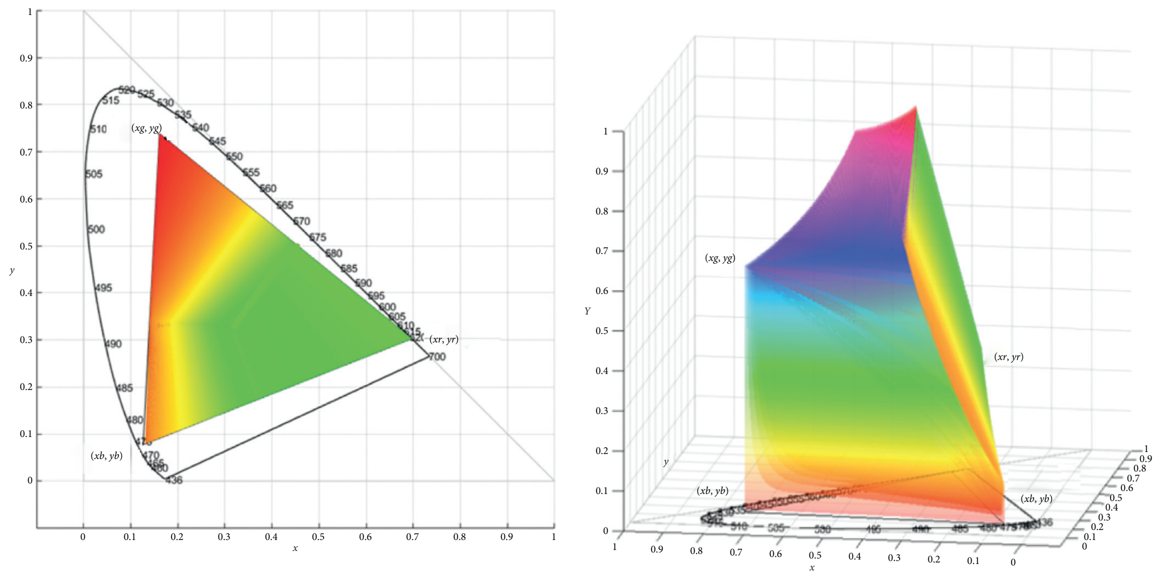
3. Variation of the Display Color by the Primary Colors Coefficients of PCLM

It is well known that LED display is light-emitting by itself against LCD which needs the fluorescent back-light [14]. Chromaticity of primary colors simply influenced by electric current flowing through channels is not subjected to interference of background light. In addition, LED is the passive driven semiconductor device and not the same with AMOLED (active matrix organic light emitting diode) [15]. Each primary color channel is individually controlled by PWM (pulse width modulation), which is derived from driving the control device. It means that the channel of primary colors is independent. Therefore, we can adjust the input value of each channel arbitrarily without affecting other channels.

The initial luminance of the LED is assumed to be R,G, and B and the primary colors coefficients of PCLM are ΔR, ΔG, and ΔB ($\Delta R \le 1$, $\Delta G \le 1$, and $\Delta B \le 1$). Plugging R,G, B, ΔR, ΔG, and ΔB into formula (3) acquires the following formula:

$$\begin{bmatrix} X(\Delta) \\ Y(\Delta) \\ Z(\Delta) \end{bmatrix} = \begin{bmatrix} C_r x_r & C_g x_g & C_b x_b \\ C_r y_r & C_g y_g & C_b y_b \\ C_r z_r & C_g z_g & C_b x_b \end{bmatrix} \begin{bmatrix} R+\Delta R \\ G+\Delta G \\ B+\Delta B \end{bmatrix},$$
$$x(\Delta) = \frac{X(\Delta)}{X(\Delta)+Y(\Delta)+Z(\Delta)},$$
$$y(\Delta) = \frac{Y(n)}{X(\Delta)+Y(\Delta)+Z(\Delta)}. \quad (4)$$

For purpose of acquiring the variation of luminance and chromaticity after PCLM, this can take the difference



(a) (b)

Figure 2: (a) The real chromaticity plane of RGB. (b) The real three-dimensional space of RGB.

between formula (4) and formula (3) to acquire a new formula; then, equations $x_r + y_r + z_r = 1$, $x_g + y_g + z_g = 1A$, and $xb + yb + zb = 1$ have plugged into the new formula to acquire

$$\Delta x = x(\Delta) - x = \frac{\begin{bmatrix} C_r\left[C_bB(x_r - x_b) + C_gG(x_r - x_g)\right] \\ C_g\left[C_bB(x_g - x_b) - C_rR(x_r - x_g)\right] \\ -C_b\left[C_rR(x_r - x_b) + CgG(x_g - x_b)\right] \end{bmatrix}^T \begin{bmatrix} \Delta R \\ \Delta G \\ \Delta B \end{bmatrix}}{\left(C_r(R + \Delta R) + C_g(G + \Delta G) + C_b(B + \Delta B)\right)\left(C_rR + C_gG + C_bB\right)},$$
$$\Delta y = y(\Delta) - y = \frac{\begin{bmatrix} C_r\left[C_bB(y_r - y_b) + C_gG(y_r - y_g)\right] \\ C_g\left[C_bB(y_g - y_b) - C_rR(y_r - y_g)\right] \\ -C_b\left[C_rR(y_r - y_b) + C_gG(y_g - y_b)\right] \end{bmatrix}^T \begin{bmatrix} \Delta R \\ \Delta G \\ \Delta B \end{bmatrix}}{\left(C_r(R + \Delta R) + C_g(G + \Delta G) + C_b(B + \Delta B)\right)\left(C_rR + C_gG + C_bB\right)},$$
$$\Delta Y = Y(\Delta) - Y = \begin{bmatrix} C_r y_r \\ C_g y_g \\ C_b y_b \end{bmatrix}^T \begin{bmatrix} \Delta R \\ \Delta G \\ \Delta B \end{bmatrix}, \tag{5}$$

where $\Delta x(\Delta G)$, $\Delta y(\Delta G)$, and $\Delta Y(\Delta G)$ are variation of x, y, Y with a direction, as the point movement in this three-dimensional space expressing the color's luminance and chromaticity transformation trend. According to the spectral characteristics of the primary colors, the chromaticity coordinates of RGB have the relationship as $x_r > x_g > x_b, y_g > y_r > y_b$, $x_r - x_g > x_g - x_b, y_g - y_r > y_r - y_b$. Otherwise, in the CIE $x^* y^* Y$ color space, the equation $Y = C_r x_r + C_g y_g + C_b z_b = 1$ exists and C_b, C_r, C_g has a relationship that $C_b > C_r > C_g$. Formula (5)clearly illustrates that the variations of chromaticity coordinates x and y have the nonlinear relationship with the coefficients of PCLM as well as RGB initial luminance. On the contrary, the variation of Y which is unrelated to RGB initial luminance has the linear relationship with the coefficients of PCLM.

So, it is assumed that $R(0 > R > 1)$, $G(0 > G > 1)$, and $B(0 > B > 1)$ are equal and constant; $\Delta x(\Delta G)$, $\Delta y(\Delta G)$, and $\Delta Y(\Delta G)$ related to $\Delta R(R + |\Delta R| \leq 1, R - |\Delta R| \geq 0)$, $\Delta G(G + |\Delta G| \leq 1, G - |\Delta G| \geq 0)$, and $\Delta B(B + |\Delta B| \leq 1, B - |\Delta B| \geq 0)$ are expressed in Figures 3(a)–3(c).

When ΔR, ΔG, and ΔB are the same, Δx not only has a bigger variation related to ΔR than ΔG and ΔB but also has the opposite change trend with ΔR to ΔG and ΔB;Δy not only has a bigger variation related to ΔB than ΔR and ΔG but also has the opposite change trend with ΔG to ΔR and ΔB. Moreover, ΔY increasing with positive ΔR, ΔG, and ΔB has a bigger variation related to ΔG than ΔR and ΔB. Else, Δx, Δy, and ΔY influenced by two of ΔR, ΔG, and ΔB at the same time in the three-dimensional space are expressed in Figure 4.

While "a" has illustrated the influence of ΔR and ΔG, "b" has illustrated the influence of ΔG and ΔB; "c" has illustrated the influence of ΔR and ΔB. It is pretty obvious in Figure 4 that the color can reach any point in three-dimensional space by changing ΔR, ΔG, and ΔB in a certain proportion. In conclusion, that variation of the LED display color's luminance and chromaticity depends on the variations proportion of primary colors. Meanwhile, the variation rule fits formula (5).

The aforementioned analysis is aimed at the variation of colors x, y, and Y when the luminance of RGB has been changed. Next, the inverse function of formula (5) has been developed to analyze how to change luminance of RGB to conform with the definite $\Delta x(\Delta G)$, $\Delta y(\Delta G)$, and $\Delta Y(\Delta G)$, as expressed in

$$\begin{aligned}
\Delta R &= \frac{\eta_3\left[D^2\Delta x(\eta_3\gamma_2 - \gamma_3\eta_2) - D^2\Delta y(\eta_3\gamma_1 - \eta_1\gamma_3) + \Delta Y(\eta_2\gamma_1 - \eta_1\gamma_2 + D\Delta\ x(C_2 - B_2) + D\Delta\ y(\eta_1 - \gamma_1))\right]}{-\eta_3(A_1 D\Delta\ y + A_2 D\Delta\ x + A_3)}, \\
\Delta G &= \frac{\tau_3\left[D^2\Delta x(\tau_3\gamma_2 - \gamma_3\tau_2) - D^2\Delta y(\tau_1\gamma_3 - \tau_3\gamma_1) + \Delta Y(\tau_2\gamma_1 - \tau_1\gamma_2 + D\Delta\ x(\gamma_2 - \tau_2) + D\Delta\ y(\tau_1 - \gamma_1))\right]}{\tau_3(A_1 D\Delta\ y + A_2 D\Delta\ x + A_3)}, \\
\Delta B &= \frac{\tau 3\left[D^2\Delta x(\tau_2\eta_3 - \tau_3\eta_2) - D^2\Delta y(\tau_3\eta_1 - \eta_3\tau_1) + \Delta Y(\tau_1\eta_2 - \tau_2\eta_1 + D\Delta\ x(\tau_2 - \eta_2) + D\Delta\ y(\eta_1 - \tau_1))\right]}{\tau_3(A_1 D\Delta\ y + A_2 D\Delta\ x + A_3)},
\end{aligned} \tag{6}$$

where $\eta_1, \eta_2, \eta_3, \tau_1, \tau_2, \tau_3, \gamma_1, \gamma_2, \gamma_3, A_1, A_2, A_3, D$ are composite functions as illustrated in

$$\begin{aligned}
\tau_1 &= C_r C_b B(x_r - x_b) + C_r C_g G(x_r - x_g), \\
\tau_2 &= C_r C_b B(y_r - y_b) + C_r C_g G(y_r - y_g), \\
\tau_3 &= C_r y_r, \\
\eta_1 &= C_g C_b B(x_g - x_b) - C_r C_g R(x_r - x_g), \\
\eta_2 &= C_g C_b B(y_g - y_b) - C_r C_g R(y_r - y_g), \\
\eta_3 &= C_g y_g, \\
\gamma_1 &= C_b C_r R(x_b - x_r) - C_b C_g G(x_b - x_g), \\
\gamma_2 &= C_b C_r R(y_b - y_r) + C_b C_g G(y_b - y_g), \\
\gamma_3 &= C_b y_b, \\
D &= C_r R + C_g G + C_b B, \\
A_1 &= [\gamma_3(\eta_1 - \tau_1) + \tau_3(\gamma_1 - \eta_1) + \eta_3(\tau_1 - \gamma_1)], \\
A_2 &= [\gamma_3(\tau_2 - \eta_2) + \tau_3(\eta_2 - \gamma_2) + \eta_3(\gamma_2 - \tau_2)], \\
A_3 &= [\gamma_3(\eta_2\tau_1 - \eta_1\tau_2) + \tau_3(\gamma_2\eta_1 - \eta_2\gamma_1) + \eta_3(\tau_2\gamma_1 - \tau_1\gamma_2)].
\end{aligned} \tag{7}$$

This formula has a mapping relationship to formula (5). This implies that we can make full use of the equation in formula (7) to adjust the luminance of RGB to reach the point in three-dimensional space we need. According to formulas (5) and (7), there is a definite mapping between RGB's luminance and display color's luminance and chromaticity.

4. Variation of the Display Color by the Primary Colors Coefficients of PCCM&MPCLM

In some special circumstances, it is impossible to simply use PCLM to acquire the display color user desired. Thus, a complicated method called PCCM&MPCLM as an innovative and novel mathematical model developed in this section is used in these circumstances. PCCM&MPCLM means mixing one primary color of RGB with other two primary colors or one primary color; afterwards, mixture color, as the new primary color, will be used to display the color on the LED display instead of the previous RGB. It has different characteristics with PCLM, because PCLM has changed luminance of RGB to transform the chromaticity and luminance of color without changing the chromaticity coordinates of RGB. However, the PCCM&MPCLM has changed the chromaticity coordinates and color saturation of RGB. In practice, it is frequent to change the chromaticity coordinates and color saturation of RGB on account of the wide color gamut which is undesired. Hence, it has firstly used PCCM to change the chromaticity coordinates of RGB and then to transform luminance of the new RGB after PCCM used MPCLM. It is a very complicated and difficult process. In this section, the process has been analyzed.

There is an assumption that G_r and B_r are size of G and B which R has matched; therefore, the real color when LED solely displays R is a mixture color defined as chroma primary color R (CPCR). The mathematical expression of

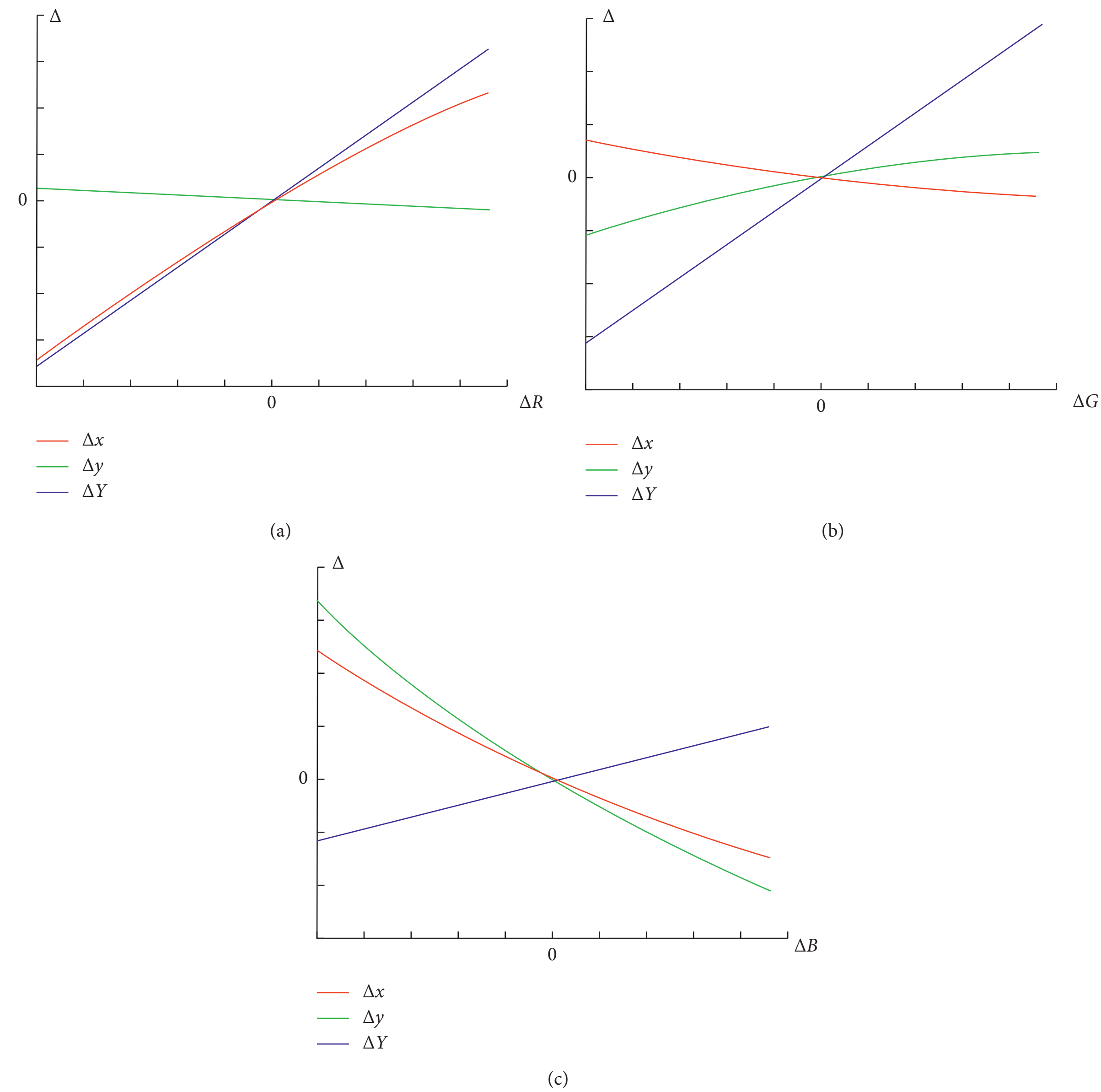


Figure 3: (a) $\Delta x\,(\Delta G)$, $\Delta y\,(\Delta G)$, and $\Delta Y\,(\Delta G)$ related to ΔR. (b) $\Delta x\,(\Delta G)$, $\Delta y\,(\Delta G)$, and $\Delta Y\,(\Delta G)$ related to ΔG. (c) $\Delta x\,(\Delta G)$, $\Delta y\,(\Delta G)$, and $\Delta Y\,(\Delta G)$ related to ΔB.

CPCR is $R_{\text{ori}} = R(1 + G_r + B_r)$ $(G_r < 1, B_r < 1)$, where $G_r + B_r$ is defined as PCCM coefficient of R. Besides , a mixture of G matched by R and B whose sizes are R_g and B_g defined as chroma primary color G (CPCG); $R_g + B_g$ is defined as PCCM coefficient of G for mathematical expression $G_{\text{ori}} = G(1 + R_g + B_g)$ $(R_g < 1, B_g < 1)$; a mixture of B matched by R and G whose sizes are R_b and G_b defined as chroma primary color B (CPCB). $R_b + G_b$ is defined as PCCM coefficient of B for mathematical expression $B_{\text{ori}} = B(1 + G_b + R_b)$ $(G_b < 1, R_b < 1)$. The three mixture colors used as the new primary colors instead of $\begin{bmatrix} R & G & B \end{bmatrix}^T$ expressed by formula (1) to display image have an absolutely mapping relation with PCCM coefficients as expressed in

$$\begin{aligned} \text{Rmix} &= R + GR_g + BR_b, \\ \text{Gmix} &= G + RG_r + BG_b, \\ \text{Bmix} &= B + RB_r + GB_g, \quad R_{\text{mix}}, G_{\text{mix}}, B_{\text{mix}} \le 1, \end{aligned} \tag{8}$$

where R_{mix} is the sum of red in three mixture colors defined as mixture primary color R (MPCR), G_{mix} is the sum of green in three mixture colors defined as mixture primary color G (MPCG), and B_{mix} is the sum of blue in three mixture colors defined as mixture primary color B (MPCB).

Then, taking R_{mix}, G_{mix}, and B_{mix} into formula (3) obtains

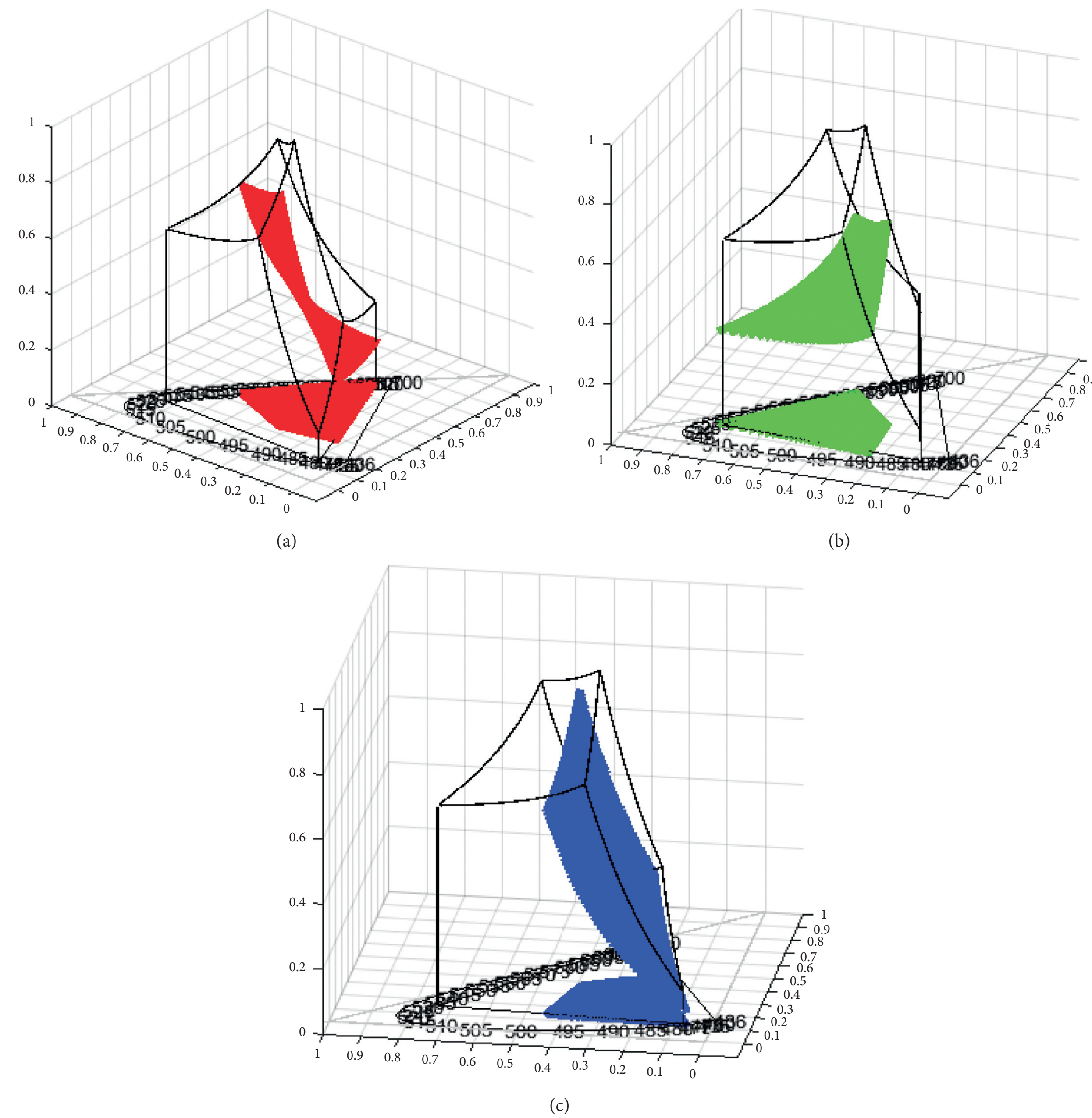


Figure 4: (a) ΔR and ΔG related to Δx, Δy in the three-dimensional space. (b) ΔG and ΔB related to Δx, Δy in the three-dimensional space. (c) ΔR and ΔB related to Δx, Δy in the three-dimensional space.

$$\begin{bmatrix} X_{\text{mix}} \\ Y_{\text{mix}} \\ Z_{\text{mix}} \end{bmatrix} = \begin{bmatrix} C_r x_r & C_g x_g & Cbxb \\ C_r y_r & C_g y_g & Cbyb \\ C_r z_r & C_g z_g & Cbzb \end{bmatrix} \begin{bmatrix} R_{\text{mix}} \\ G_{\text{mix}} \\ B_{\text{mix}} \end{bmatrix},$$

$$x_{\text{mix}} = \frac{X_{\text{mix}}}{X_{\text{mix}} + Y_{\text{mix}} + Z_{\text{mix}}} = \frac{Cr\left(R + GR_g + BR_b\right)xr + C_g\left(G + RG_r + BG_b\right)x_g + C_b\left(B + RB_r + GB_g\right)x_b}{C_r\left(R + GR_g + BR_b\right) + C_g\left(G + RG_r + BG_b\right) + C_b\left(B + RBr + GB_g\right)}, \tag{9}$$

$$y_{\text{mix}} = \frac{Y\text{mix}}{X_{\text{mix}} + Y_{\text{mix}} + Z_{\text{mix}}} = \frac{C_r\left(R + GR_g + BR_b\right)y_r + C_g\left(G + RG_r + BG_b\right)yg + C_b\left(B + RB_r + GBg\right)y_b}{C_r\left(R + GR_g + BR_b\right) + C_g\left(G + RG_r + BG_b\right) + C_b\left(B + RB_r + GB_g\right)},$$

where x_{mix} and y_{mix} are chromaticity coordinates of color by PCCM. According to this formula, the chromaticity coordinate x of CPCR is $x_{\text{mix\_}r} = x_r + (C_g(x_g - x_r)G_r + C_b(x_b - x_r)B_r/C_r + C_gG_r + C_bB_r)$ and the chromaticity coordinate y of CPCR is $y_{\text{mix\_}r} = y_r + (C_g(y_g - y_r)G_r + C_b(y_b - y_r)B_r)/(C_r + C_gG_r + C_bB_r)$. Seriously $(C_g(x_g - x_r)G_r + C_b(x_b - x_r)B_r)/(C_r + C_gG_r + C_bB_r)$ and $(C_g(y_g - y_r)G_r + C_b(y_b - y_r)B_r)/(C_r + C_gG_r + C_bB_r)$, as the variation of x and y, have decreased the saturation of R. It means that, after PCCM, the CPCR cannot reach the previous color in any way with gamut lost. Moreover, the luminance of CPCR has a bigger variation than before with some brightness level lost. The chromaticity coordinates x and y of CPCG are $x_{\text{mix\_}g} = x_g + (C_r(x_r - x_g)R_g + C_b(x_b - x_g)B_g)/(C_rR_g + C_g + C_bB_r)$ and $y_{\text{mix\_}g} = y_g + (C_r(y_r - y_g)R_g + C_b(y_b - y_g)B_g)/C_rR_g + C_g + C_bB_r$ and the chromaticity coordinates x and y of CPCB are $x_{\text{mix\_}b} = x_b + (C_r(x_r - x_b)R_b + C_g(x_g - x_b)G_b)/(C_rR_b + C_b + C_gG_b)$. Characteristics of CPCG and CPCB are similar to CPCR indisputably. The gamut constituted by CPCR, CPCG, and CPCB is smaller than the gamut of PCCM as expressed in Figure 5.

It is determined that the hue and luminance LED displaying wholly under the gamut in Figure 5 are less than before. Under these circumstances, any PCCM coefficients changed will cause some variation in mixture primary colors. So, the variations of CPCR, CPCG, and CPCB are defined as $\Delta R_{\text{ori}} = \Delta R + \Delta RG_r + \Delta RB_r$, $\Delta G_{\text{ori}} = \Delta G + \Delta GR_g + \Delta GB_g$, and $\Delta B_{\text{ori}} = \Delta B + \Delta BG_b + \Delta BR_b$. Meanwhile, the variations of MPCR, MPCG, and MPCB, as final color chromaticity variations, are $\Delta R_{\text{mix}} = \Delta R + \Delta GR_g + \Delta BR_b$, $\Delta G_{mix} = \Delta G + \Delta RG_r + \Delta BG_b$, and $\Delta B_{\text{mix}} = \Delta B + \Delta RB_r + \Delta GB_g$. The following formula has shown the complicated relationship:

$$
\Delta x_{\text{mix}} = x_{\text{mix}} + \Delta - x_{\text{mix}} = \frac{\begin{bmatrix} C_r\left[C_bB_{\text{mix}}(x_r - x_b) + C_gG_{\text{mix}}(x_r - x_g)\right] \\ C_g\left[C_bB_{\text{mix}}(x_g - x_b) + C_rR_{\text{mix}}(x_g - x_r)\right] \\ C_b\left[C_rR_{\text{mix}}(x_b - x_r) + CgG_{\text{mix}}(x_b - x_g)\right] \end{bmatrix}^T \begin{bmatrix} \Delta R_{\text{mix}} \\ \Delta G_{\text{mix}} \\ \Delta B_{\text{mix}} \end{bmatrix}}{\left(C_r(R_{\text{mix}} + \Delta R_{\text{mix}}) + C_g(G_{\text{mix}} + \Delta G_{\text{mix}}) + C_b(B_{\text{mix}} + \Delta B_{\text{mix}})\right)\left(C_rR_{\text{mix}} + C_gG_{\text{mix}} + C_bB_{\text{mix}}\right)},
$$

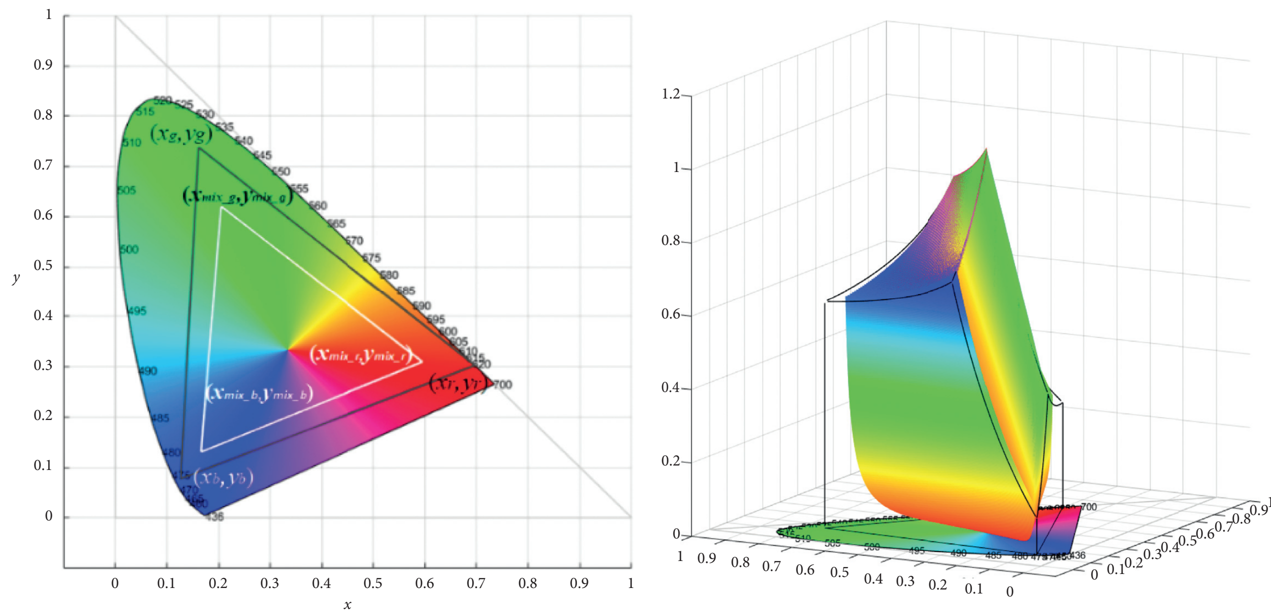
$$
\Delta y_{\text{mix}} = y_{\text{mix}} + \Delta - y_{\text{mix}} = \frac{\begin{bmatrix} C_r\left[C_bB_{\text{mix}}(y_r - y_b) + C_gG_{\text{mix}}(y_r - y_g)\right] \\ C_g\left[C_bB_{\text{mix}}(y_g - y_b) + C_rR_{\text{mix}}(y_g - y_r)\right] \\ C_b\left[C_rR_{mix}(y_b - y_r) + C_gG_{\text{mix}}(y_b - y_g)\right] \end{bmatrix}^T \begin{bmatrix} \Delta R_{\text{mix}} \\ \Delta G_{\text{mix}} \\ \Delta B_{\text{mix}} \end{bmatrix}}{\left(C_r(R_{\text{mix}} + \Delta R_{\text{mix}}) + C_g(G_{\text{mix}} + \Delta G_{\text{mix}}) + C_b(B_{\text{mix}} + \Delta B_{\text{mix}})\right)\left(C_rR_{\text{mix}} + CgG_{\text{mix}} + C_bB_{\text{mix}}\right)},
$$

$$
\Delta Y_{\text{mix}} = Y_{\text{mix}} + \Delta - Y_{\text{mix}} = \begin{bmatrix} C_r y_r \\ C_g y_g \\ C_b y_b \end{bmatrix}^T \begin{bmatrix} \Delta R_{\text{mix}} \\ \Delta G_{\text{mix}} \\ \Delta B_{\text{mix}} \end{bmatrix}, \tag{10}
$$

where Δx_{mix} and Δy_{mix} are variation of color chromaticity by PCCM first and MPCLM second. On account of formula (10), Δx_{mix} , Δy_{mix}, and ΔY_{mix}, affected by more parameters such as R_g, R_b, G_r, G_b, B_r, and B_g than Δx, Δy, and ΔY in the third section, are extremely complicated.

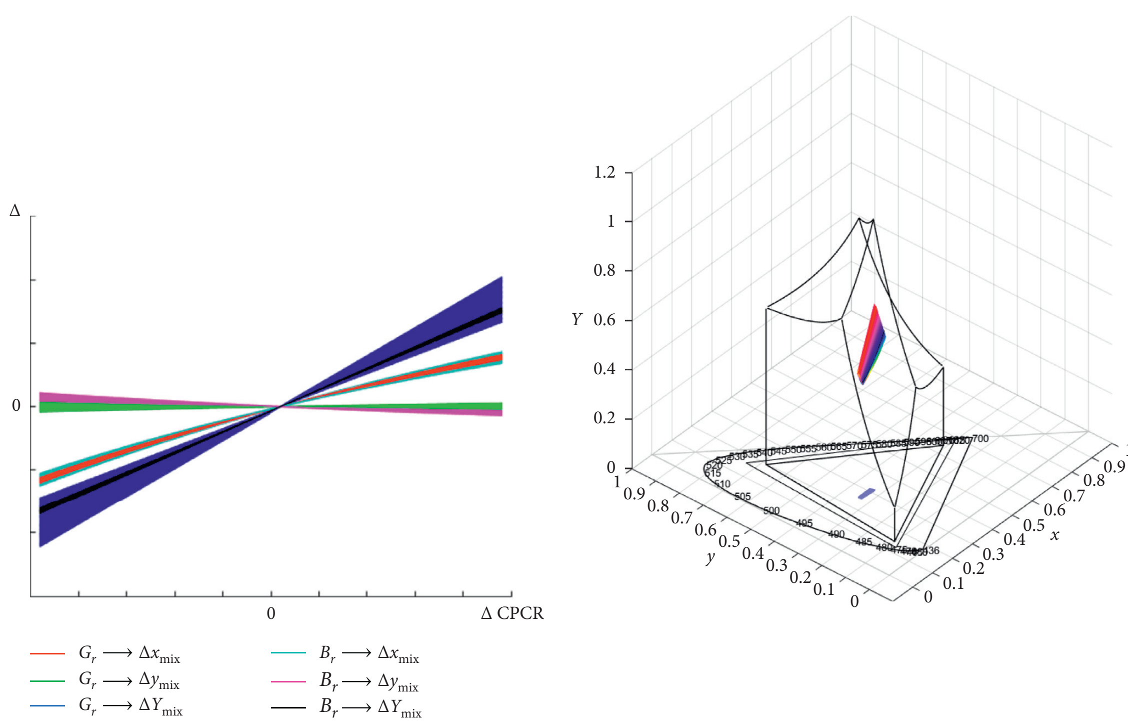
It is obvious that when all of PCCM coefficients are equal to zero, Δx_{mix}, Δy_{mix}, and ΔY_{mix} are the same to Δx, Δy, and ΔY. There is an assumption that the initial value of R, G, and B is equal; in other words, the difference between CPCR, CPCG, and CPCB is mainly due to respective PCCM coefficients. Furthermore, initial values of MPCR, MPCG, and MPCB and the variation of MPCR, MPCG, and MPCB are also affected by PCCM coefficients so that Δx_{mix}, Δy_{mix}, and ΔY_{mix} are only related to PCCM coefficients and the size of CPCR, CPCG, and CPCB change. Hence, Δx_{mix}, Δy_{mix}, and ΔY_{mix} affected by PCCM coefficients and change of CPCR, CPCG, and CPCB have been described in detail in subsequent analysis.

All of PCCM coefficients of RGB are constant without zero conforming to $G_r, B_r, R_g, B_g, R_b, G_b < 1$. The MPCR, MPCG, and MPCB are $R_{\text{mix}} = R + GR_g + BR_b$, $G_{\text{mix}} = G + RG_r + BG_b$, and $B_{\text{mix}} = B + RB_r + GB_g$. To gradually increase the luminance of CPCR, CPCG, and CPCB under the condition of $R_{\text{mix}}, G_{\text{mix}}, B_{\text{mix}} \le 1$, the variation values of MPCR, MPCG, and MPCB are relevant to



(a) (b)

FIGURE 5: (a) Gamut of new primary colors after PCCM. (b) The three-dimensional space of new primary colors after PCCM.



(a) (b)

FIGURE 6: (a) Δx_{mix}, Δy_{mix}, and ΔY_{mix} related to G_r, B_r with CPCR increasing. (b) Δx_{mix}, Δy_{mix}, and ΔY_{mix} related to G_r, B_r with CPCR increasing in three-dimensional space.

their PCCM coefficients and magnitude of the change in CPCR, CPCG, and CPCB, respectively.

According to formula (8), variations of R_{mix}, G_{mix}, and B_{mix} have been influenced by two aspects, one is the luminance change of CPCR, CPCG, and CPCB, and the other one is PCCM coefficients. Meanwhile, luminance changes of CPCR, CPCG, and CPCB are connected with the PCCM coefficients because LED's $R_{\text{mix}} + \Delta R_{\text{mix}}, G_{\text{mix}} + \Delta G_{\text{mix}}, B_{\text{mix}} + \Delta B_{\text{mix}}$ are less than one after changing. First, to change CPCR with CPCG and CPCB constant, the PCCM

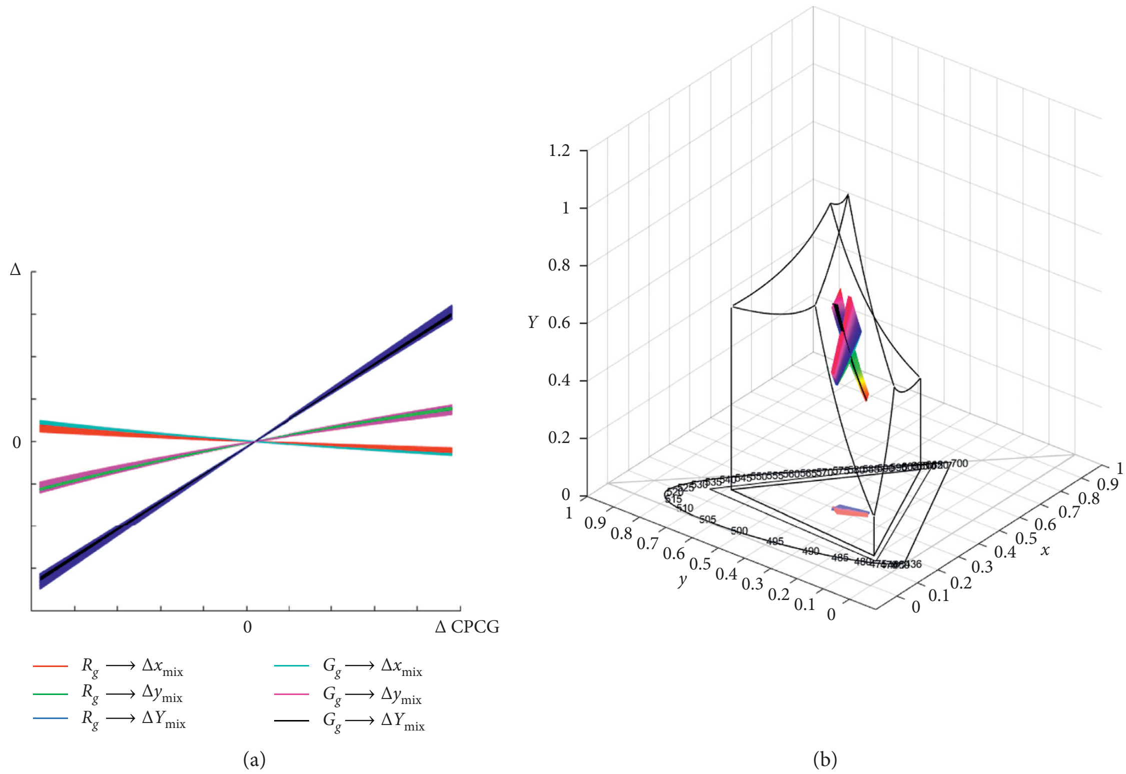


Figure 7: (a) Δx_{mix}, Δy_{mix}, and ΔY_{mix} related to R_g, B_g with CPCR increasing. (b) Δx_{mix}, Δy_{mix}, and ΔY_{mix} related to R_g, B_g with CPCG increasing in three-dimensional space.

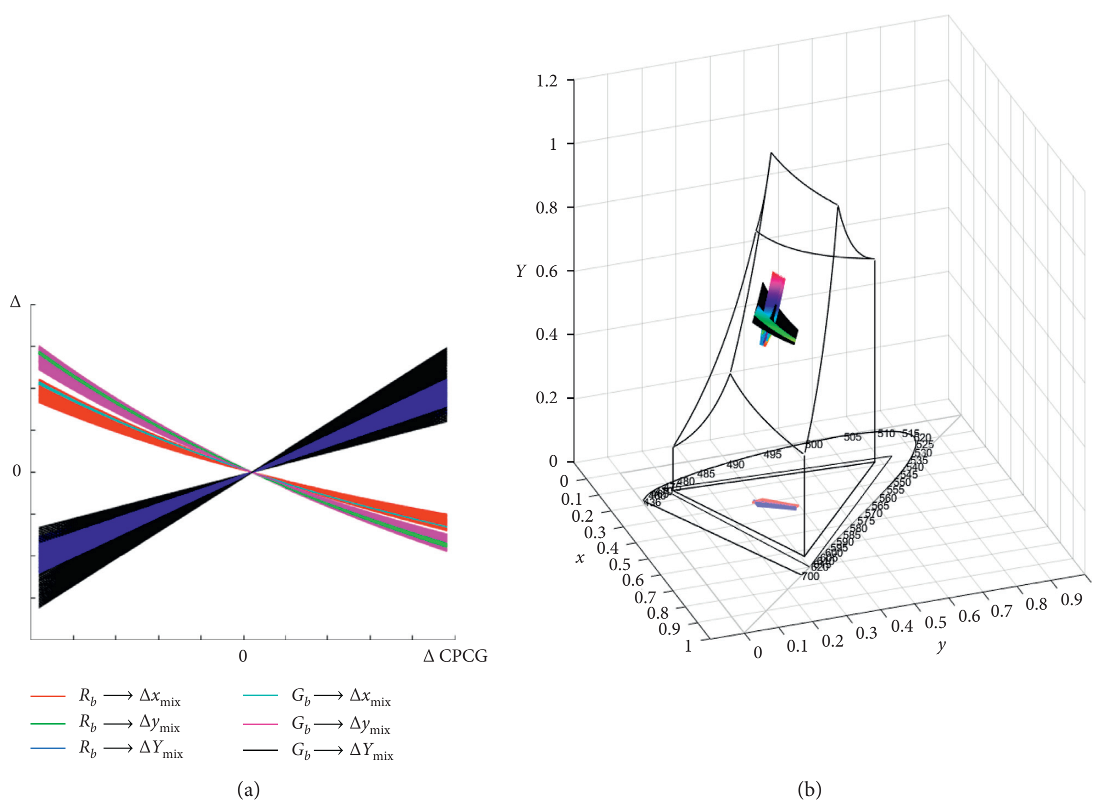


Figure 8: (a) Δx_{mix}, Δy_{mix}, and ΔY_{mix} related to R_b, G_b with CPCR increasing. (b) Δx_{mix}, Δy_{mix}, and ΔY_{mix} related to R_b, G_b with CPCB increasing in three-dimensional space.

Table 1: Variation of color by changing primary colors coefficients of PCLM.

PCLM	Calculated			Measured		
$[\Delta R\ \ \Delta G\ \ \Delta B]$	Δx	Δy	ΔY	Δx	Δy	ΔY
[−0.2 0 0]	−0.0538	0.0035	−0.0570	−0.0590	0.0095	−0.0623
[−0.2 −0.2 0]	−0.0404	−0.0558	−0.1817	−0.0448	−0.0508	−0.1792
[−0.2 −0.2 0.2]	−0.0664	−0.0916	−0.1634	−0.0708	−0.0855	−0.1600
[−0.2 0 −0.2]	−0.0228	0.0645	−0.0753	−0.0185	0.0723	−0.0822
[−0.2 0 0.2]	−0.0749	−0.0380	−0.0388	−0.0721	−0.0430	−0.0452
[−0.2 0.2 −0.2]	−0.0394	0.1116	0.0494	-0.0384	0.1001	0.0556
[−0.2 0.2 0]	−0.0642	0.0495	0.0676	−−0.0612	0.0425	0.0697
[−0.2 0.2 0.2]	−0.0818	0.0053	0.0859	−0.0788	0.0094	0.0935
[0 −0.2 0]	0.0182	−0.0515	−0.1247	0.0156	−0.0485	−0.1198
[0 −0.2 −0.2]	0.0652	−0.0042	−0.1430	0.0640	−0.0041	−0.1420
[0 −0.2 0.2]	−−0.0140	−0.0838	−0.1064	−0.0121	−0.0812	−0.0988
[0 0 −0.2]	0.0372	0.0513	−0.0183	0.0311	0.0552	−0.0234
[0 0 0.2]	−0.0266	−0.0366	0.0183	−0.0264	−0.0326	0.0200
[0 0.2 −0.2]	0.0157	0.0938	0.1064	0.0132	0.0920	0.0999
[0 0.2 0]	−0.0146	0.0412	0.1247	−0.0126	0.0392	0.1198
[0 0.2 0.2]	−0.0369	0.0024	0.1430	−0.0365	0.0012	0.1425
[0.2 0 0]	0.0420	−0.0027	0.0570	0.0401	−0.0024	0.0580
[0.2 0 −0.2]	0.0817	0.0415	0.0388	0.0798	0.0412	0.0420
[0.2 0 0.2]	0.0125	−0.0355	0.0753	0.0146	−0.0325	0.0800
[0.2 −0.2 0]	0.0625	−0.0482	−0.0676	0.0644	−0.0468	−0.0655
[0.2 −0.2 −0.2]	0.1114	−0.0072	−0.0859	0.1110	−0.0068	−0.0822
[0.2 −0.2 0.2]	0.0274	−0.0776	−0.0494	0.0245	−0.0770	−0.0452
[0.2 0.2 −0.2]	0.0581	0.0801	0.1634	0.0511	0.0822	0.1688
[0.2 0.2 0]	0.0251	0.0346	0.1817	0.0240	0.0321	0.1810

coefficients G_r, B_r are the major factors impacting Δx_{mix}, Δy_{mix} , and ΔYmix. In this condition that CPCR is increasing, Δx_{mix} is more than zero no matter which one of G_r, B_r is larger. Meanwhile, absolute value of Δx_{mix} gradually decreases as G_r or B_r increases. Δy_{mix} has different relation between G_r and B_r such that Δy_{mix} is less than zero at the beginning and then it is equal to zero at some point, going to be greater than zero at the end as G_r increases. But when B_r is increasing, Δy_{mix} is always less than zero with a decreasing trend. In other condition that CPCR is decreasing, Δy_{mix} is less than zero no matter which one of G_r, B_r is larger. Absolute value of Δx_{mix} gradually decreases as G_r or B_r increases. Δy_{mix} will be more than zero at the beginning and then it is equal to zero at some point, going to be less than zero at the end as G_r increases. However, as B_r increases, Δy_{mix} is always more than zero and is gradually increasing. Figure 6 shows this relationship.

Second, to change CPCG with CPCR and CPCB constant, the PCCM coefficients Rg, Bg are the major factors impacting Δx_{mix}, Δy_{mix}, and ΔY_{mix}. In this condition that CPCG is increasing, Δx_{mix} is less than zero no matter which one of R_g, B_g is larger. Meanwhile, absolute value of Δx_{mix} gradually decreases as R_g increases or B_g decreases. Δy_{mix} is always more than zero and absolute value gradually decreases as R_g or B_g increases. In other condition that CPCG is decreasing, Δx_{mix} is always more than zero and absolute value gradually is increasing as R_g decreases or B_g increases. Δy_{mix} is always less than zero and absolute value gradually decreases as R_g or B_g increases. Figure 7 shows this relationship.

Third, to change CPCB with CPCR and CPCG constant, the PCCM coefficients R_g, B_g are the major factors impacting Δx_{mix}, Δy_{mix}, and ΔY_{mix}. In this condition that CPCB is increasing, Δx_{mix} is always more than zero and absolute value gradually is increasing as R_g decreases or B_g increases. In other condition that CPCB is decreasing, Δx_{mix} is always less than zero and absolute value is gradually decreasing as R_b or G_b increases. Δy_{mix} is always more less zero and absolute value gradually decreases as R_b or G_b increases. Figure 8 shows this relationship.

The above analysis mainly explains the variation trend and variation value of the color which is affected by the primary colors coefficients of PCCM&MPCLM in the three-dimensional space. When the variation trend and variation value of the color are known, how to change the primary colors coefficients of PCCM&MPCLM is similar to the analysis in part three. So, there will not be a detailed analysis in this paper.

5. Experimental Verification and Error Analysis

There are a large number of very famous LED manufacturers all over the world, such as Samsung, Sony, Leyard, and Cedar. A module or a box manufactured by these manufacturers as the basic part consists of a whole display screen. A module or box can be assembled into variety sizes display in a certain amount and manner conforming to application requirement of users, such as the monitor display in the conference room, stage screen, and cinema screen. Chroma and luminance characteristics of all modules or boxes under the same production condition such as machine, materials, and technique are extremely similar.

Therefore, in this present article, we implement the experiment using a box manufactured by Cedar, in which chroma and luminance characteristics can represent the

Table 2: Variation of color by changing primary colors coefficients of PCCM&MPCLM.

PCCM&PCLM $[G_r\ B_r\ R_g\ B_g\ R_b\ G_b][\Delta R_{ori}\ \Delta G_{ori}\ \Delta B_{ori}]$	Calculated Δx	Calculated Δy	Calculated ΔY	Measured Δx	Measured Δy	Measured ΔY
$[0.02\ 0.02\ 0\ 0\ 0\ 0][-0.2\ 0\ 0]$	−0.0533	0.0035	−0.0570	−0.0590	0.0070	−0.0640
$[0\ 0\ 0.02\ 0.02\ 0\ 0][0\ 0.2\ 0]$	−0.0145	0.0409	0.1247	−0.0128	0.0392	0.1197
$[0\ 0\ 0\ 0\ 0.02\ 0.02][0\ 0\ 0.2]$	−0.0265	−0.0366	0.0183	−0.0280	−0.0326	0.0218
$[0.02\ 0.02\ 0\ 0\ 0.02\ 0.02][0.2\ 0\ 0.2]$	0.0125	−0.0353	0.0753	0.0148	−0.0335	0.0804
$[0.02\ 0.02\ 0.02\ 0.02\ 0\ 0][0.2\ 0.2\ 0]$	0.0248	0.0342	0.1817	0.0245	0.0316	0.1830
$[0\ 0\ 0.02\ 0.02\ 0.02\ 0.02][0\ 0.2\ 0.2]$	−0.0367	0.0024	0.1430	−0.0364	0.0024	0.1426
$[0.02\ 0\ 0.02\ 0\ 0.02\ 0][0.2\ 0.2\ 0.2]$	−0.0011	0.0005	0.2000	−0.0013	0.0010	0.2035
$[0.02\ 0\ 0\ 0.02\ 0.02\ 0][0.2\ 0.2\ -0.2]$	0.0570	0.0786	0.1634	0.0522	0.0811	0.1680
$[0\ 0.02\ 0\ 0.02\ 0.02\ 0][0.2\ -0.2\ -0.2]$	0.1083	−0.0078	−0.0859	0.1111	−0.0068	−0.0832
$[0\ 0.02\ 0.02\ 0\ 0.02\ 0][-0.2\ 0.2\ -0.2]$	−0.0378	0.1084	0.0494	−0.0382	0.1031	0.0536
$[0\ 0.02\ 0.02\ 0\ 0\ 0.02][-0.2\ 0.2\ 0.2]$	−0.0804	0.0052	0.0859	−0.0790	0.0084	0.0910
$[0\ 0.02\ 0\ 0.02\ 0\ 0.02][-0.2\ 0\ 0.2]$	−0.0732	−0.0372	−0.0388	−0.0721	−0.0434	−0.0450
$[0\ 0.02\ 0\ 0.02\ 0.02\ 0][-0.2\ 0.2\ 0]$	−0.0628	0.0484	0.0676	−0.0618	0.0430	0.0688

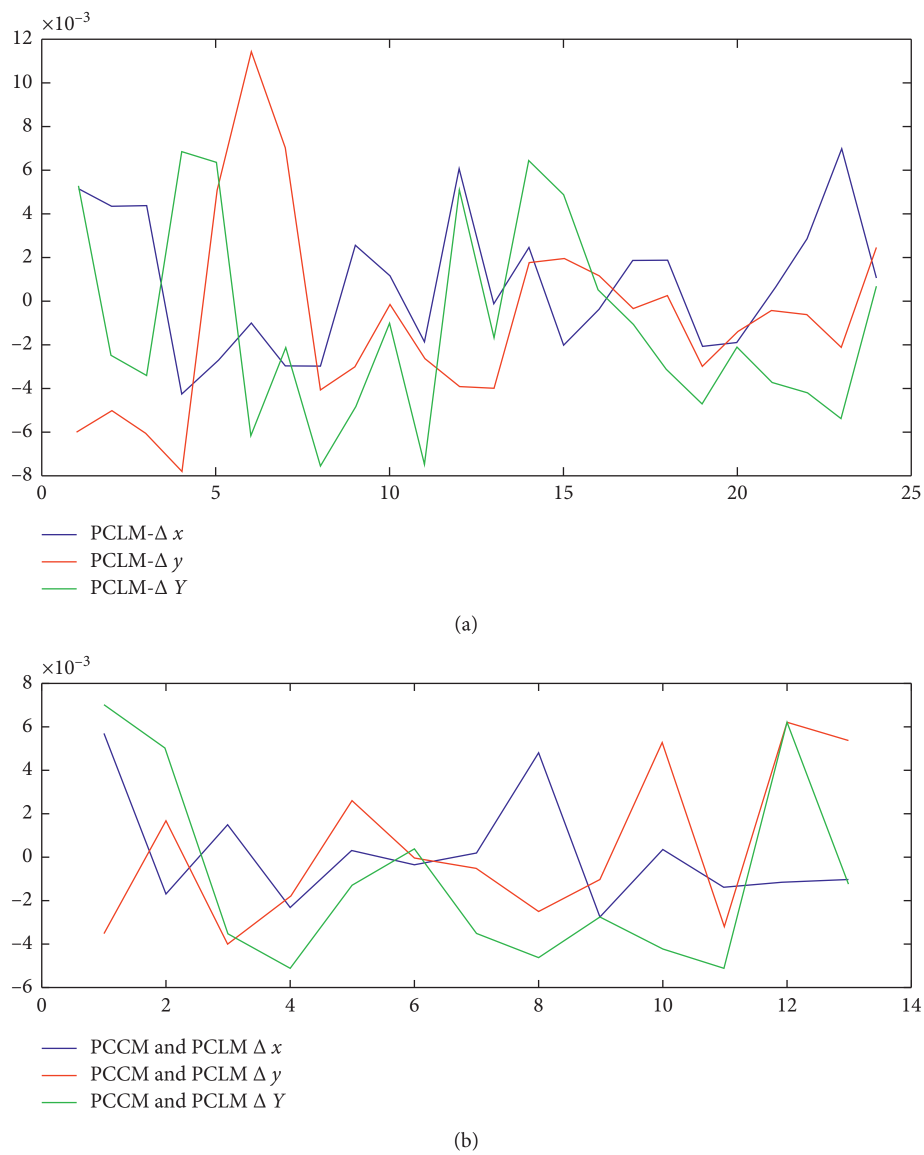


Figure 9: Error of difference between calculated value and measured value. (a) Sequence number of Table 1. (b) Sequence number of Table 2.

whole display screen. The red, green, and blue light chips of the box are manufactured by HC SEMITEK, a Chinese company. The characteristics of the red, green, and blue light chips such as electric current, wavelength coverage, and luminance range are demonstrated in the specification [16]. However, since chromaticity coordinates of the red, green, and blue are not illustrated in the specification, we perform the measure to red, green, and blue, respectively, using the Konica Minolta spectroradiometer CS-2000, according to the International Electrotechnical Commission (IEC) standards [17]. Luminance measurement range of the spectroradiometer is from 0.003 cd/m^2 to 5,000 cd/m^2 at one degree. Precision of chromaticity coordinate x is $\pm$ 0.0015 and precision of chromaticity coordinate y is $\pm$ 0.001. In the present article, we adjust the digital inputs of red, green, and blue channels to the maximum used control system under normal light conditions, so that luminance of each primary color is maximized. Then, we use CS-2000 to measure the luminance and chromaticity coordinate of each primary color, respectively. Therefore, primary chromaticity coordinates of LED display used in experiment are $x_r = 0.6949$, $y_r = 0.3043$, $x_g = 0.1659$, $y_g = 0.7445$, and $x_b = 0.1264$, $y_b = 0.0723$. The value of C_r, C_g, C_b is obtained by substituting the value of D65 light source triple stimulus into formula (1). So, C_r is equal to 0.9372, C_g is equal to 0.8373, and C_b is equal to 1.2644. The max luminance of R is equal to 720 nit, max luminance of G is equal to 1200 nit, and max luminance of G is equal to 500 nit. Then, luminance of RGB is normalized separately. The initial luminance of RGB is defined as 0.5. Then, to change the primary colors coefficients of PCLM first and the primary colors coefficients of PCCM&MPCLM second, we have the following.

First, the step size of changing the primary colors coefficients of PCLM is equal to 0.2 from −0.2 to 0.2. So, the chromaticity and luminance variation of the color calculated by formula and measured actually have been illustrated in Table 1.

Second, the step size of changing the primary colors coefficients of PCCM is equal to 0.02. Then, changing the primary colors coefficients of MPCLM used the new primary colors after PCCM. There is a huge number of different combinations of primary colors coefficients PCCM&MPCLM. So, we just pick a few cases at random where the chromaticity and luminance variation of the color calculated by formula and measured actually have been illustrated in Table 2.

In Table 1, we differ the calculated value from the measured value to acquire the normalized error, as illustrated in the following:

$$\begin{aligned} \sigma\Delta Y &= \Delta Y_{\text{calculated}} - \Delta Y_{\text{measured}}, \\ \sigma\Delta x &= \Delta x_{\text{calculated}} - \Delta x_{\text{measured}}, \\ \sigma\Delta y &= \Delta y_{\text{calculated}} - \Delta y_{\text{measured}}, \end{aligned} \tag{11}$$

where $\sigma\Delta x, \sigma\Delta y, \sigma\Delta Y$ are errors of $\Delta x, \Delta y, \Delta Y$ between calculated value and measured value as shown in Figure 9.

In Figure 9, the max error of PCLM between calculated value and measured value is 0.76% and the max error of PCCM and PCLM between calculated value and measured value is 0.70%.

6. Conclusions

Two mathematical models have been developed specifically to indicate the variation of LED display color affected by chromaticity and luminance of LED display primary colors. The derivation of two models accounts for the fact that LED primary colors are variable in different application environments. It is necessary to establish an appropriate model for mapping LED primary colors (RGB) to tristimulus values such as XYZ, as well as backward mapping from XYZ to LED primary colors. Although other papers have indicated characterization models to establish the transformation between RGB and XYZ, an important case that one primary color mixed by the other one or two primary colors to reduce the saturation as well as mixing primary colors as “new LED primary colors” has been ignored. Therefore, the mathematical models are beneficial to investigate the relationship between variation of primary colors (luminance and chromaticity) and variation of LED display colors.

The first mathematical model represents variation of LED display color affected by the luminance of LED display primary colors. Based on this mathematical model, LED display color can be adjusted as users preferring by changing LED primary colors luminance. The second mathematical model used in some special circumstances represents variation of LED display color affected by the chromaticity and luminance of LED primary colors. It has illustrated that a complicated process luminance of LED primary colors is adjusted with chromaticity of LED primary colors changing, so that the LED display color variation is complicated. Nevertheless, in this mathematical model, the gamut of LED display is smaller than the first mathematical model and it will lose the same colors after changing. Therefore, users can adjust the LED primary colors by using the appropriate mathematical model to acquire the display color users need.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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