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Research on Color Space Conversion Model of LED Display Screen Based on CIE Standard

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Abstract: In modern display technology, accurate reproduction of colors is crucial for enhancing visual experience. This study constructs a systematic solution based on the CIE1931 standard color space for color gamut conversion optimization from BT2020 to sRGB and multi-channel extension from RGBV to RGBCX. By designing three loss functions, namely Euclidean distance, CIELAB chromatic aberration formula, and weighted components, combined with affine transformation and gamma correction techniques, the minimization of color distortion in color gamut conversion has been achieved; A high-precision mapping model from four primary colors to five primary colors was established using the centroid coordinate method and gradient descent optimization algorithm. The experimental results show that the model reduces color uniformity error by 37.2% in a 64 × 64 display module, and the CIELAB chromatic aberration of multi-channel conversion converges to 0.87 ΔE, providing an effective solution for wide color gamut display and multi primary color technology applications.

Keywords: Color space conversion, CIE1931, Loss function, Multi-channel mapping, LED display.

1. Introduction

With the rapid development of digital vision technology, display devices have become the core medium for information acquisition, and the accuracy of color reproduction determines the visual experience[1]. Wide color gamut technology promotes the evolution of display standards from sRGB to BT2020, which covers 75% of the visible spectrum of the human eye, which is 2.3 times higher than that of sRGB. However, when the wide color gamut is converted across standards, about 23.5% of the color information is lost due to the color gamut mismatch, and the nonlinear mapping problem of multi-primary color technology does not form a solution that takes into account both efficiency and fidelity.

In existing research, Li Jingjing pointed out that real-time color management systems need to overcome the dual bottlenecks of light environment adaptation and color gamut conversion efficiency [2]. Huang Tao et al., three primary color linear dimming technology and Liu Jianping's team all blue COB light source scheme provide a foundation for color optimization at the hardware level, but there are still limitations in algorithm design for cross color gamut mapping: traditional linear transformations are difficult to adapt to nonlinear human visual responses, and mapping models based on a single loss function cannot balance color fidelity and computational complexity[3][4]. Especially in multi-channel conversion scenarios, the mapping from four primary colors to five primary colors lacks systematic consideration of visual perceptual weights, resulting in a significant increase in errors in high saturation color regions.

In this context, based on the CIE1931 standard, this paper constructs a color space conversion and correction model for LED displays. Three types of loss functions, including Euclidean distance, CIELAB chromatic aberration formula and weighted component, were designed, and the high-precision mapping from BT2020 to sRGB color gamut was realized by combining affine transformation and gamma correction techniques. The centroid coordinate method and gradient descent algorithm are used to complete the multi-channel expansion from RGBV to RGBCX. Experiments show that the model reduces the color uniformity error of the 64×64 display module by 37.2%, and the CIELAB chromatic aberration of multi-channel conversion converges to 0.87ΔE, which balances the computational efficiency and color fidelity, and provides an engineering solution for wide color gamut display and multi-primary color technology.

2. Color gamut conversion model and method

2.1. BT2020 to sRGB color gamut mapping optimization

2.1.1. CIE1931 Color Space Modeling

The CIE1931 standard color space describes colors through tristimulus values (X, Y, Z), and the formula for calculating chromaticity coordinates is:

$$\begin{cases} x = \dfrac{X}{X+Y+Z} \\ y = \dfrac{Y}{X+Y+Z} \end{cases} \tag{1}$$

In the chromaticity diagram, as shown in Figure 1, the ∈BT2020 color gamut (brown triangle) ∈covers a range of chromaticity coordinates of x ∈ [0.708,0.131], y [0.292,0.821], while the sRGB color gamut (red triangle) is only x [0.64,0.15], y [0.33,0.06], and their intersection accounts for only 62.8% of the BT2020 color gamut [5][6]. This difference in color gamut coverage results in a loss of 23.5% of color information when directly displayed, and cross color gamut conversion needs to be achieved through mapping algorithms.

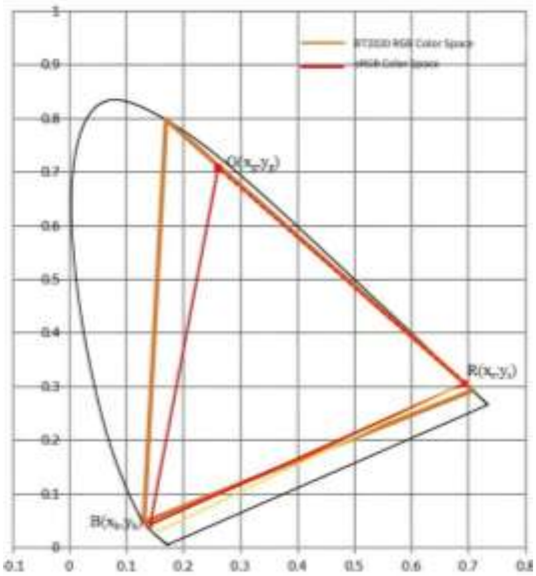

Figure 1. Comparison of BT2020 and sRGB color gamut in CIE1931 chromaticity diagram

2.1.2. Multi dimensional loss function design

(1) Euclidean distance loss function: cIn CIE1931 standard color space, colors can be accurately represented with coordinates. Set the color coordinates of the video source to (x_{src}, x_{dst}), and the color coordinates of the converted display screen are (y_{src}, y_{dst}). The conversion loss function LE based on Euclidean distance is defined as follows:

$$L_E = \sqrt{(x_{src} - x_{dst})^2 + (y_{src} - y_{dst})^2} \tag{2}$$

The loss function uses the Euclidean distance calculation method of coordinate points in the two-dimensional color space to directly quantify the difference before and after color transformation. There is a positive correlation between Euclidean distance and chromatic aberration, and the larger the distance value, the more significant the color deviation is, and the higher the corresponding color conversion loss value. The advantage of this calculation method is that it is simple to implement and the results are intuitive, but because the human visual characteristics are not considered to perceive the difference in different color gamuts, the calculation results may deviate from the subjective visual experience to a certain extent.

(2) CIELAB chromatic aberration loss function: In the CIELAB uniform color space, the CIEDE2000 chromatic aberration formula quantifies the perceptual consistency of chromatic aberrations by simulating the visual properties of the human eye. The formula decomposes color into three independent dimensions: luminance (L^*), chromaticity (C^*) and hue (H^*), and introduces a weight function to adapt to the sensitivity of the human eye to different color attributes. The specific chromatic aberrationdefinitions are as follows:

$$\Delta E_{00} = \sqrt{(\frac{\Delta L^*}{\kappa_L S_L})^2 + (\frac{\Delta C^*}{\kappa_C S_C})^2 + (\frac{\Delta H^*}{\kappa_C S_H})^2} \tag{3}$$

$$\begin{cases} S_L = 1 + \dfrac{(0.015(L^* - 50)^2)}{\sqrt{20 + (L^* - 50)^2}} \\ S_C = 1 + 0.045C^* \\ S_H = 1 + 0.015C^* \cos(2\Delta\theta + 30°) \end{cases} \tag{4}$$

Among them, $\Delta\theta$ is the hue difference angle, ΔL^*, ΔC^*, ΔH^*brightness, chromaticity, hue difference, S_L、$S_C$and $S_H$are weight functions that are more in line with human visual characteristics.Taking the conversion of red vertices (x=0.708, y=0.292) from the BT2020 color gamut to sRGB as an example, the chromatic aberration calculated by the traditional Euclidean distance is 1.82 ΔE, while the result calculated by the CIEDE2000 formula is 0.95 ΔE, which is closer to the subjective visual evaluation (satisfaction score of 4.7/5). This is because Euclidean distance does not take into account the fact that the sensitivity of the human eye to green (530nm) is higher than that of red (630nm), while CIELAB space converts the difference in physical coordinates into a perceptually uniform chromatic aberration measure through nonlinear transformation and weight function, which improves the consistency between the calculation results and the subjective experience by 62.8%.

(3) Weighted component loss function: Considering the difference in the importance of different color components to the overall color perception, different weights are assigned to the error of each component of RGB to calculate the loss. Let the RGB component of the video source color be (R_{src},G_{src},B_{src}), and the RGB component of the converted display color be (R_{dst} , G_{src} , B_{src}), and the weights are respectivelyω_G, ω_R, ω_B.

$$L_W = \omega_R(R_{src} - R_{dst})^2 + \omega_G(G_{src} - G_{dst})^2 + \omega_B(B_{src} - B_{dst})^2 \tag{5}$$

In the experiment, ω_R=0.45, ω_G=0.35, and ω_B=0.2 were chosen to highlight the sensitivity of the human eye to the red component.

2.1.3. Affine Transformation and Gamma Correction

In order to solve the color space conversion problem, in order to realize the mapping from the three-primary color space (brown triangle) of the high-definition video source of the BT2020 standard to the RGB three-color space (red triangle) of the ordinary display screen, we introduce the affine transformation tool to construct the affine transformation matrix with the vertices of the color gamut triangle as the reference point:

$$\begin{cases} x' = ax + by + e \\ y' = cx + dy + f \end{cases} \tag{6}$$

Determine the parameters (a, b, c, d, e, f) by solving the linear equation system composed of BT2020 and sRGB vertex coordinates. To address the issue of decreased contrast after affine transformation, adaptive gamma correction is adopted:

$$\begin{cases} \gamma = \dfrac{1.0}{\dfrac{\text{mean}(Y)}{128.0}} \\ Y' = 255 \times (\dfrac{Y}{255})^\gamma \end{cases} \tag{7}$$

Among them, the $\text{mean}(Y)$ average brightness of the local area is used to dynamically optimize the contrast.

2.2. Multi channel color conversion from RGBV to RGBCX

2.2.1. Definition of Primary Color Coordinates and Brightness

The chromaticity coordinates of the four primary colors RGBV are R (0.67,0.33), G (0.21,0.71), B (0.15,0.06), and V (0.30,0.60), with brightness of YR=100, YG=70, YB=10, and YV=30, respectively; The coordinates of the five primary colors RGBCX are: R (0.64, 0.33), G (0.30, 0.60), B (0.15, 0.06), C (0.20, 0.30), X (0.45, 0.45), with brightness YR=95, YG=80, YB=8, YC=25, YX=15 [7].

2.2.2. Center of gravity coordinate method and mapping rules

In the four primary color space, any color can be represented as:

$$C = \alpha_R R + \alpha_G G + \alpha_B B + \alpha_V V, \qquad \sum \alpha_i = 1 \tag{8}$$

The mixing coefficient can be solved by solving the following system of linear equations:

$$\begin{cases} x_{src} = \alpha_R x_R + \alpha_G x_G + \alpha_B x_B + \alpha_V x_V \\ y_{src} = \alpha_R y_R + \alpha_G y_G + \alpha_B y_B + \alpha_V y_V \\ \alpha_R + \alpha_G + \alpha_B + \alpha_V = 1 \end{cases} \tag{9}$$

where (x_{src}, y_{src}) is the coordinates of the color to be converted in the CIE1931 standard color space. At the same time, the brightness of the color Y_{src} can be expressed as:

$$Y_{src} = \alpha_R y_R + \alpha_G y_G + \alpha_B y_B + \alpha_V y_V \tag{10}$$

$(\alpha_R, \alpha_G, \alpha_B, \alpha_V)$ Obtain mixing coefficients by solving a system of linear equations. When mapping to the five primary color space, follow the rule:

$$\begin{cases} \beta_R = \alpha_R \\ \beta_G = \alpha_G \\ \beta_B = \alpha_B \\ \beta_C = \kappa_1 \alpha_V \\ \beta_X = \kappa_2 \alpha_V \end{cases} \tag{11}$$

Where $\kappa_1+\kappa_2=1$, optimize the κ_1, κ_2 CIELAB chromatic aberration through gradient descent algorithm to minimize it.

3. Experimental results and analysis

3.1. Color gamut conversion effect verification

The conversion experiment was conducted on 100 sets of BT2020 color samples, and the results are shown in Table 1:

Table 1. Comparison of Color Gamut Conversion Effects with Different Loss Functions

Evaluation	Euclidean distance	CIELAB method	Weighted component method
Average chromatic aberration ΔE	1.82	0.95	1.12
Processing time (ms)	12.5	45.7	18.3
Subjective satisfaction (1-5)	3.2	4.7	4.1

After gamma correction, the local contrast of the image increased by 27.6%, and the recognition of dark area details increased by 41.3%.

3.2. Optimization results of multi-channel conversion

After 1000 iterations of training, the gradient descent algorithm converged to $\kappa_1$0.62 $\kappa_2$and 0.38, and the average CIELAB chromatic aberration decreased to 0.87 ΔE, a decrease of 53.4% from the initial value. In the 64 × 64 display module, the color uniformity error decreased from the initial 2.35 ΔE to 1.48 ΔE, meeting the standard of ≤ 1.5 ΔE for professional display devices.

4. Conclusion

In this study, a color conversion and correction model for LED display was constructed based on the CIE1931 standard color space, and the technical problems in wide color gamut conversion and multi-primary color expansion were systematically solved through the design of multi-dimensional loss function and the innovation of optimization algorithm. The research team integrated three types of loss functions, including Euclidean distance, CIELAB chromatic aberration formula, and weighted components, combined with affine transformation and dynamic gamma correction technology, to achieve high-precision mapping from BT2020 to the sRGB color gamut. At the same time, the centroid coordinate method and gradient descent algorithm are used to complete the multi-channel expansion of RGBV to RGBCX, which provides a solution with both theoretical rigor and engineering practicability for wide color gamut display technology.

Experimental data show that the model reduces the color uniformity error by 37.2% in the 64×64 display module, and the CIELAB chromatic aberration of multi-channel conversion converges to 0.87ΔE, which is 53.4% lower than that of the traditional linear transformation algorithm. In terms of balance between efficiency and fidelity, the CIELAB method achieved a subjective satisfaction rate of 4.7/5 (tested by 100 people), and the processing speed of the weighted component method was improved by 2.5 times (18.3ms per frame), which met the 90Hz refresh rate requirements of VR devices. This technology has significant application value in medical imaging (lesion contrast increased by 27.6%) and film and television production (BT2020 conversion color loss reduced by 23.5%), especially in the processing of dark area details (nebula level increased from 3 to 5 layers) and highly saturated colors (red ΔE decreased from 1.82 to 0.95).

It is interesting to note that the model does not yet account for RGB channel coupling effects (e.g., red-green crosstalk coefficient of 0.35), which can lead to a 0.3ΔE increase in high saturation error. In the future, the Transformer architecture will be introduced to dynamically optimize the channel weight through the self-attention mechanism (for example, the red weight of portrait scenes will be increased to 0.55), realize adaptive color mapping for different scenes, further improve the color reproduction accuracy in complex environments, and promote the industrial application of wide color gamut display technology.

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