行政院國家科學委員會專題研究計畫 成果報告

應用於廣色域視訊的顯示器原色與攝影機光譜響應之研究
研究成果報告(精簡版)

計畫類別：個別型
計畫編號：NSC 96-2221-E-216-014-
執行期間：96年08月01日至97年07月31日
執行單位：中華大學電機工程研究所

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處理方式：本計畫可公開查詢

中華民國 97年10月22日

行政院國家科學委員會補助專題研究計畫成果報告

應用於廣色域視訊的顯示器原色與攝影機光譜響應之研究

計畫類別：■ 個別型計畫　　□ 整合型計畫
計畫編號：NSC　96－2221－E－216 －014
執行期間：　96 年　8　月　1　日至　97　年　7 月　31 日

計畫主持人：溫盛發
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成果報告類型(依經費核定清單規定繳交)：■精簡報告　□完整報告

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中　華　民　國　97　年 7　月　31　日

一、中文摘要

本計畫原先是申請為三年期計畫，研究廣色域顯示器原色與攝影機光譜響應之設計。但國科會僅通過第一年的廣色域顯示器原色設計的部分，因此本報告只涵蓋原計畫中第一年的研究成果。研究成果有兩篇論文發表於資訊顯示器學會期刊(Journal of the SID, vol. 15, no. 12, pp. 1015-1022, 2007. 與 vol. 16, Nov issue, 2008.)。第一篇論文提出廣色域顯示器原色選擇的設計方法，使得顯示器色域在CIELAB 色空間與一目標色域匹配，達到所要希望顯示的色彩表現。第二篇論文即將於 2008 年 11 月登出，其中提出節省廣色域顯示器消耗功率的原色選擇之設計方法。主要概念是在三原色色彩飽和度與消耗功率之間做一折衷的設計，使顯示器節能又可以顯示所希望的色彩表現。本報告針對第一篇論文內容做詳細說明。

關鍵詞：廣色域顯示器，雷射顯示器，發光二極體顯示器。

Abstract

This project was originally proposed to be a three-year research project. However, National Science Council only passed the first year project which studies the primary design for wide-color-gamut displays. Therefore, this report only covers the results of the first year project. There are two published papers for the results, which were published in the Journal of the Society for Information Display (vol. 15, no. 12, pp. 1015-1022, 2007. and vol. 4, no. 11, 2008.) The first paper proposed the primary selection method so that the color gamut of a wide-color-gamut display matches a target color gamut in CIELAB color space so that the display is able to show the desirable color appearance. The second paper, which will be published in Nov. 2008, proposed the primary selection method so that the power consumption of a wide-color-gamut display can be saved. The basic concept is to compromise between the primary saturation and power consumption so that the display is power saving and is able to show the desirable color appearance. The content of the first paper is explicitly described in this report.

Keywords: wide-color-gamut display, laser display, LED display.

二、緣由與目的

The color gamut of a display is determined by color coordinates of the primaries and white point in addition to luminance values of black point and white point [1,2]. The display with larger color gamut is able to show more colorful and attractive images. The color gamut of a display can be expanded by using high saturation primaries. Owing to the advance of display technologies, wide-color-gamut displays have been realized but are not yet popular. Liquid crystal displays backlit with light emitting diodes (LEDs) and laser projection displays are two examples of displays providing high saturation primaries. Primaries are often selected to obtain desirable cost, life time, luminance efficiency, and color coordinates. This paper focuses on the issue of the selection of primary color coordinates. Primary color coordinates are usually selected to provide coverage of a target chromaticity triangle in the CIE xy chromaticity diagram or CIE $u'v'$ chromaticity diagram [3]. Fig. 1 shows examples of the chromaticity triangles of NTSC and HDTV (ITU-R BT. 709) standard primaries together with illuminant C and D65 white [1,2]. As shown, the chromaticity triangle of the NTSC color standard is larger than that of HDTV color standard. However, phosphors of NTSC primaries have been judged to be obsolete due to lower luminance efficiency [1]. Therefore, the HDTV color standard follows the PAL color standard [2]. However, the color gamut of a display is a three-dimensional volume in a color space, e.g. CIE xyY or CIELAB [4]. Because the uniformity of CIELAB color space is better than that of CIE xyY color space [5], color gamut is preferably represented in CIELAB color space. Fig. 2 shows the color gamut of the NTSC with D65 white point in CIELAB color space, in which the loci of primary ramps are also shown.

From Fig.2, we can see that the maximum chromas (C^*) at high and low lightnesses (L^*) are smaller than that at medium lightness, which is a typical characteristic of a display color gamut. Thus, even if a chromaticity triangle is selected such that it encloses a set of desired color coordinates in a CIE xy chromaticity diagram as the method shown in Reference [3], the corresponding display is not guaranteed to be able to show all desired colors. Some desired colors may lie outside display color gamut in CIELAB color space, although their xy chromaticity coordinates are enclosed by the triangle on CIE xy chromaticity diagram. To consider the complete chromaticity characteristics of a display, we should select primary color coordinates based on three-dimensional color gamut instead of chromaticity triangle. Here we propose a method for selecting primaries of a wide-color-gamut display according to a target color gamut in CIELAB color space. This method optimizes primary color coordinates such that the shapes of the display and target color gamuts are the most similar [6].

A reasonable choice of the target color gamut is the gamut of all possible object colors. This theoretical maximum, or optimal, color gamut of objects consists of all the perceived colors that are produced by the reflection (or transmission) of an illuminant by objects [5,7,8]. The optimal object color gamut may include colors that do not occur in our natural environment, but it may be suitable for wide-color-gamut displays with monochromatic primaries, i.e. laser displays. For real world surface colors, Pointer measured 4089 samples to investigate their gamut. These samples were all colored with non-fluorescent pigments and illuminated with CIE standard illuminant C [9]. We will refer to these sample colors as Pointer’s real world surface colors and their corresponding color gamut as Pointer’s color gamut. Pointer’s color gamut is limited to the colors of the samples that were measured. The non-fluorescent pigment colors measured by Pointer are usually not highly saturated and will not include high saturation colors in nature including the colors of butterfly wings and fluorescent light. The color chip number of the Munsell Color Tree has increased with technology advancements including the synthesis of new high saturation pigments [10]. However, since an updated version of Pointer’s real world surface colors is not available, we assume Pointer’s color gamut as a target color gamut for representing the gamut of real world surface colors in this paper.

Two selection examples are considered. One example assumes the optimal object color gamut as the target color gamut for selecting primary wavelengths of laser displays. The other example assumes Pointer’s color gamut as the target color gamut for selecting primary wavelengths of LED displays.

三、研究方法

The color device model of a three-primary display can be represented by a 3×3 chromaticity matrix and three tonal transfer curves (TRCs) for red, green, and blue primaries [4,11]. TRCs are applied to convert the input signals into the linear signals that are proportional to primary luminance values. The linear signals are normalized and are designated as r, g, and b for red, green, and blue primaries, respectively, in which $0 \le r,\ g,\ b \le 1$. The relationship of input linear signal vector (r, g, b) to the output tri-stimulus vector (X, Y, Z) of the display can be written as [4,11]

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix} \begin{bmatrix} r \\ g \\ b \end{bmatrix}, \qquad (1)$$

where (X_r, Y_r, Z_r), (X_g, Y_g, Z_g), and (X_b, Y_b, Z_b) are the maximum tri-stimulus vectors of the red, green, and blue primaries, respectively. Note that Y stimulus values relate to the luminance of the primary. The X and Z stimulus values can be derived from the (x, y) color coordinates and Y stimulus.

$$X = \frac{x}{y} Y, \qquad (2)$$

$$Z = \frac{(1 - x - y)}{y} Y. \qquad (3)$$

The 3×3 matrix in Eq.(1) is known as the chromaticity matrix. Normalizing the primary matrix to the luminance of the white point Y_w= 1 ($Y_r + Y_g + Y_b = 1$), provides the white point requirement for the maximum luminance values of the primaries from Eqs.(1)-(3)

$$\begin{bmatrix} Y_r \\ Y_g \\ Y_b \end{bmatrix} = \begin{bmatrix} x_r / y_r & x_g / y_g & x_b / y_b \\ 1 & 1 & 1 \\ z_r / y_r & z_r / y_g & x_b / y_b \end{bmatrix}^{-1} \begin{bmatrix} x_w / y_w \\ 1 \\ x_w / y_w \end{bmatrix}, (4)$$

where (x_r, y_r), (x_g, y_g), and (x_b, y_b) are the color coordinates of the red, green, and blue primaries; wherein z_r=1-x_r-y_r, z_g=1-x_g-y_g , z_b=1-x_b-y_b, and z_w=1-x_w-y_w; (x_w, y_w) provide the color coordinates of the white point and z_w=1-x_w-y_w. NTSC and HDTV standards specify the use of illuminant C and illuminant D65 as white points, respectively. However, the use of illuminant D65 white point is more popular for NTSC in practice [1]. Thus, we take D65 white point for laser displays considered in Section V. For LED displays considered in Section VI, C white point is assumed because target color gamut (Pointer's color gamut) were measured with illuminant C. Color gamut boundary of the display in the XYZ color space can be calculated according to the method given in Reference [12]. The color gamut boundary in CIELAB color space can be calculated from the XYZ color space.

For red, green, and blue primaries with spectral power densities $S_r(\lambda)$, $S_g(\lambda)$, and $S_b(\lambda)$, respectively, the required optical power ratios among red, green, and blue primaries are

$$P_r : P_g : P_b = Y_r / \eta_r : Y_r / \eta_g : Y_r / \eta_b, \qquad (5)$$

where $\eta_i = \int S_i(\lambda) V(\lambda) d\lambda / \int S_i(\lambda) d\lambda$, i= r, g, and b; and $V(\lambda)$ is the luminance efficiency of the human eye [5]. If the primary is monochromatic, $\eta_i = V(\lambda_i)$, where λ_r, λ_g, and λ_b are the red, green, and blue primary wavelengths, respectively.

The optimal object color gamut is enclosed by the maximum luminance surface and the boundary surface of monochromatic light in CIE xyY chromaticity space [5,7,8]. It has been shown that the maximum luminance efficiency for a given CIE xy chromaticity coordinates can be obtained if the material has a spectrophotometric curve that is everywhere either zero or unity and has at most two transitions between these values within the region of visible radiation. The reflectance (transmittance) at wavelength λ is

$$R(\lambda) = \begin{cases} R_1 & , \lambda_1 \le \lambda \le \lambda_2 \\ R_2 & , otherwise \end{cases}, \qquad (6)$$

where either R_1= 1, R_2= 0 or R_1= 1, R_2= 0; λ_1 and λ_2 are transition wavelengths. Using Eq.(6) as the reflectance (transmittance) of an object, we can search all possible combinations of λ_1 and λ_2 to find the color gamut boundary in XYZ color space. Fig. 3 shows the contours of the color gamut boundary represented in CIELAB color space for several constant lightness L^* values with illuminant D65. In theory, the required number of primaries is infinite for the ideal display, that is, its color gamut is the same as the optimal object color gamut. To achieve this requirement, every primary of the ideal display must be monochromatic with a maximum luminance that is infinitesimal. The relative maximum luminance values of monochromatic primaries depend on the illuminant of the object color. Because of high primary luminance, comparing Fig. 2 with Fig. 3, we can see that the NTSC color gamut near high chroma red, green, and blue regions is beyond the optimal object color gamut.

The size of a color gamut can be represented with its volume [13]. An accurate metric for representing the size of a color gamut was recently proposed, in which gamut size is represented with discernible color number instead of gamut volume [4]. Discernible color number represents the number of discernible colors as defined based upon calculations with the CIE94 color difference formula in CIELAB color space. We calculate color gamut boundaries of constant lightness $L*$ for the color gamuts considered in this paper. The color gamut boundary of a given lightness $L*_i$ is described with the maximum chroma $C*_{\max}(L*_i, h*_j)$ calculated for the values of hue angle $h*$ from 0°- 359° in steps of 1°, where

$$L*_i = \begin{cases} 0.5, & i = 0 \\ 99.5, & i = 100 \\ i, & otherwise \end{cases}, \qquad (7)$$

for i = 0, 1, 2,…, 100, and $h*_j = j°$ for j = 0, 1, 2,…, 359. The maximum chroma $C*_{\max}(L*_i, h*_j)$ is called the boundary descriptor. The discernible color number of the optimal object color gamut with illuminant D65 is 352,263.

For numerically comparing a display color gamut with the optimal object color gamut, we define a metric referred to as relative maximum chroma which is calculated from

$$f_{ij} = \frac{C*_{\max,d}\left(L*_i, h*_j\right)}{C*_{\max,t}\left(L*_i, h*_j\right)}, \qquad (8)$$

where $C*_{\max,d}(L*_i, h*_j)$ and $C*_{\max,t}(L*_i, h*_j)$ are boundary descriptors of the display and the target color gamuts, respectively. The standard deviation of the relative maximum chroma is

$$\sigma = \left(< f_{ij}^2 > - < f_{ij} >^2\right)^{1/2}, \qquad (9)$$

where

$$< f_{ij}^2 > = \frac{1}{100\times360}\left(\frac{1}{2}\sum_{j=0}^{359} f_{0j}^2 + \sum_{i=1}^{99}\sum_{j=0}^{359} f_{ij}^2 + \frac{1}{2}\sum_{j=0}^{359} f_{100j}^2\right),(10)$$

$$< f_{ij} > = \frac{1}{100\times360}\left(\frac{1}{2}\sum_{j=0}^{359} f_{0j} + \sum_{i=1}^{99}\sum_{j=0}^{359} f_{ij} + \frac{1}{2}\sum_{j=0}^{359} f_{100j}\right).(11)$$

σ is called the gamut standard deviation and is used as a metric of the shape similarity between the display and target color gamuts. The display and target color gamuts are the same for $\sigma = 0$ and $< f_{ij} > = 1$. Considering an NTSC display with a D65 white point and the optimal object color gamut as the target color gamut, the values $\sigma = 0.182$ and $< f_{ij} > = 0.761$ are calculated.

The part of the display color gamut within the target color gamut is called the effective display color gamut because only this part of gamut can be used to reproduce target colors. The boundary descriptor of the effective display color gamut is given by

$$C*_{\max,e} = \begin{cases} C*_{\max,d}, C*_{\max,d} \le C*_{\max,t} \\ C*_{\max,t}, C*_{\max,d} > C*_{\max,t} \end{cases}, \ (12)$$

where the variables $L*_i$ and $h*_j$ are not shown for simplicity. From Eqs.(8)-(11) and replacing $C*_{\max,d}(L*_i, h*_j)$ by $C*_{\max,e}(L*_i, h*_j)$, we have the standard deviation of the relative maximum chroma between the effective display color gamut and the optimal object color gamut. This standard deviation is called the effective gamut standard deviation and is denoted as σ_e.

The average value $< f_{ij} >$ is a metric of the relative gamut size of the display color gamut with respect to the target color gamut. In the display industry, the gamut size of a wide-color-gamut display is usually represented with the ratio of its chromaticity triangle area and the chromaticity triangle area of a reference display in the CIE xy chromaticity diagram. This ratio is only a rough estimation of the perceived gamut size because CIE xy is a non-uniform color coordinate system and the perceived display color gamut should be represented by a volume in a perceptually relevant color space. In this paper we take the discernible color number ratio (DCNR) to represent the relative gamut size of display color gamut with respect to the target color gamut [14]

$$DCNR = \frac{N_d}{N_t}, \qquad (13)$$

where N_d and N_t are the discernible color numbers of the display and the target color gamuts, respectively. DCNR= 73.5% for the NTSC color gamut shown in Fig. 2 and the optimal object color gamut shown in Fig. 3, respectively, in which N_d= 258,910 and N_t = 352,263. Note that the value of $< f_{ij} >$ given above for the NTSC primaries and the optimal object colors is close to this ratio. The ratio of the chromaticity triangle area of the NTSC primaries with respect to the chromaticity area of the optimal object colors is only 47.1%, in which the latter area is the area of the horseshoe-shaped region that is bounded by the spectrum locus and the purple line shown in Fig. 1. Thus, the area ratio seriously under estimates the relative gamut size of NTSC primaries with respect to the optimal object colors.

For representing the ratio of the target color gamut that can be reproduced by a display, we define the effective display color number ratio [14]

$$EDCNR = \frac{N_e}{N_t}, \qquad (14)$$

where N_e is the discernible color number of effective display color gamut, i.e. the number of discernible colors in target color gamut that can be reproduced by the display.

四、結果與討論

In this section, the optimal object color gamut is taken as the target color gamut for selecting primary wavelengths of laser displays, in which illuminant D65 white point is used. For a set of given red and green primary wavelengths, we optimize the blue primary wavelength for minimizing σ. Figs. 4 (a) and 4(b) show the optimized blue primary wavelength and the corresponding σ, respectively. From Figs. 4(a) and 4(b), σ is minimized around λ_r= 607 nm, λ_g= 520 nm and λ_b = 455 nm, where DCNR and EDCNR are about 87% and 85%, respectively. The minimum σ= 0.160 is at λ_r = 607.5 nm, λ_g = 520.4 nm and λ_b = 454.7 nm, in which σ_e = 0.1293, DCNR= 86.7% and EDCNR= 84.68%. For the display with the minimum σ, its primary color coordinates (x_r, y_r)= (0.6574, 0.3423), (x_g, y_g) = (0.0774, 0.8341), and (x_b, y_b) = (0.1514, 0.0224); required luminance ratios $Y_r : Y_g : Y_b$ = 0.609: 1: 0.046; required optical power ratios $P_r : P_g : P_b$ = 0.817: 1: 0.696. Although the required luminance of the blue primary is low compared with that of red and green primaries, the required optical power of the blue primary is comparable with that of red and green primaries. Fig. 5(a) shows the color gamut of this display. Comparing the color gamut boundaries shown in Fig. 3 and Fig. 5(a), we can see that they are similar as expected.

Next, we consider the minimization of the effective gamut standard deviation σ_e. Figs. 6 (a) and 6(b) show the optimized blue primary wavelength and the corresponding σ_e, respectively. From Figs. 6(a) and 6(b), σ_e is minimal around λ_r > 637 nm, λ_g = 518 nm and λ_b = 460 nm. In this region, DCNR and EDCNR are about 92% and 87.5 %, respectively. The minimum σ_e = 0.1083 is at λ_r = 649.7 nm, λ_g = 518.1 nm, and λ_b = 462 nm, in which σ = 0.1949, DCNR= 92.4% and EDCNR= 87.5%. For the display with the minimum σ_e, its primary color coordinates (x_r, y_r)= (0.7258, 0.2742), (x_g, y_g) = (0.0601, 0.8298), and (x_b, y_b) = (0.1408, 0.0332); required luminance ratios $Y_r : Y_g : Y_b$ = 0.404: 1: 0.059; and required optical power ratios $P_r : P_g : P_b$ = 2.499: 1: 0.605. Figs. 7(a) and 7(b) show the display color gamut and effective display color gamut of this optimized display, respectively. For comparison, we show the effective display color gamut of the display with the minimum σ in Fig. 5(b). Comparing Figs.

5(b) and 7(b) with Fig. 3, we can see the high similarity between the color gamut shown in Fig. 7(b) and the optimal object color gamut.

From the results shown above, primary selection considering the minimization of σ_e is preferred because its effective color gamut is highly similar to the optimal object color gamut in shape and its gamut size is larger. However, the required optical power of red primary P_r is high for the display with the minimum σ_e because of low luminance efficiency at long wavelength. We may reduce P_r by the use of shorter λ_r at the expense of slightly increasing σ_e. For example, taking λ_r = 625 nm and λ_g = 518.1 nm, we have the optimal λ_b = 459 nm for the minimum σ_e, in which σ_e = 0.1097, DCNR= 90.5%, EDCNR= 86.7%, $Y_r : Y_g : Y_b$ = 0.474: 1: 0.052, and $P_r : P_g : P_b$ = 0.992: 1: 0.607. For this example, P_r is about the same as P_g and the shape of the corresponding effective display color gamut is also similar to the optimal object color gamut in shape because σ_e is only slightly increased. However, the optimal design of display primaries should further take other practical issues into account, e.g. available wavelengths and optical powers.

In this section, Pointer's color gamut is taken as the target color gamut for selecting primary wavelengths of LED displays, in which illuminant C white point is used. The spectral power density of an LED is assumed to be Gaussian [14]. Red, green, and blue LED bandwidths are taken to be 20 nm, 40 nm, and 30 nm, respectively [15]. The boundary descriptor of Pointer's color gamut were given in the Table II of Reference [9], in which hue angle and lightness resolutions are 10° and 5, respectively. The resolutions are too rough for calculating discernible color number. Thus, Pointer's data are linearly interpolated for calculating discernible color number. The discernible color numbers of Pointer's color gamut and the optimal object color gamut with illuminant C are 186,783 and 347,729, respectively. Therefore, the discernible color number ratio of Pointer's color gamut with respect to the optimal object color gamut is only 53.72%. It is also found that 97.3% and 85.7 % of Pointer's surface colors are enclosed within the color gamuts of NTSC and HDTV with C white point. Fig. 8 shows Pointer's color gamut. We can see that its gamut shape is quite different from the gamut shape of a display with three primaries. Thus we only consider the minimization of effective gamut standard deviation σ_e in this section.

Figs. 9(a) and 9(b) show the optimized blue primary wavelength and the corresponding σ_e, respectively. From Figs. 9(a) and 9(b), σ_e is low around $\lambda_r >$ 628 nm, λ_g = 528 nm and λ_b = 467 nm. In this region, DCNR and EDCNR are about 155% and 99.7 %, respectively. The minimum σ_e = 0.01206 is at λ_r = 658 nm, λ_g = 528.2 nm, and λ_b = 467.97 nm, in which σ = 7.63, DCNR= 156%, and EDCNR= 99.76%. It is noticed that σ is very large. For the display with the minimum σ_e, its primary color coordinates (x_r, y_r)= (0.7272, 0.2728), (x_g, y_g) = (0.1914, 0.7407), and (x_b, y_b) = (0.1283, 0.0647); required luminance ratios $Y_r : Y_g : Y_b$ = 0.349: 1: 0.133; required optical power ratios $P_r : P_g : P_b$ = 3.729: 1: 1.038. Fig. 10 shows the color gamut of this optimized LED display, in which the corresponding effective display color gamut is nearly the same as Pointer's color gamut shown in Fig. 8 because the minimum σ_e is very small and EDCNR is nearly 100%.

From Fig. 9(b), we can see that the in the low σ_e region, the use of shorter red primary wavelength only slightly increases σ_e. Thus, it is desirable to select a red primary of shorter wavelength so that the required optical power of red primary can be reduced, while the increase of σ_e is not appreciable. For example, taking λ_r = 628 nm, λ_g = 528 nm, we have the optimal λ_b =

465.6 nm for the minimum σ_e, in which σ_e = 0.015, DCNR= 152.4%, EDCNR= 99.7%, $Y_r : Y_g : Y_b$ = 0.413: 1: 0.118, and $P_r : P_g : P_b$ = 1.115: 1: 1.011. For this example, the effective display color gamut is also nearly the same as Pointer’s color gamut because σ_e is still very small.

五、計畫成果自評

A method is proposed for selecting primaries of a wide-color-gamut display according to a target color gamut in CIELAB color space. We define the gamut standard deviation that is the standard deviation of the relative maximum chroma of display and target color gamuts. A small gamut standard deviation value represents display and target color gamuts that are similar in shape. The selection method optimizes the display primaries for the minimum gamut standard deviation. It is shown that the color gamut of a laser display can be designed to be similar to the optimal object color gamut in shape. The part of the display color gamut that is within the target color gamut is called the effective display color gamut. We also define the effective gamut standard deviation that is the standard deviation of the relative maximum chroma of the effective display and the target color gamuts. It is found that, for the laser display, primaries designed by minimizing the effective gamut standard deviation, are highly similar to the optimal object color gamut in shape. Design examples for LED displays are also shown, in which red, green, and blue LED bandwidths are assumed to be 20 nm, 40 nm, and 30 nm, respectively. The gamut of Pointer’s real world surface colors is assumed as the target color gamut for the LED displays. Because the gamut shape of Pointer’s real world surface colors is quite different from that of typical three-primary displays, we only consider the primary selection that minimizes the effective gamut standard deviation. It is shown that 99.7% of Pointer’s color gamut can be enclosed by the color gamut of an LED display. For both the laser and LED displays, it is necessary to constrain the red primary wavelength to avoid excessively high optical powers for the red primary. In practical applications, less saturated primaries are preferred for increasing display brightness. The selection method minimizing gamut standard deviation can be applied to selecting less saturated primaries, in which the target color gamut is derived from a set of preferred and less saturated colors.

六、參考文獻

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七、圖表

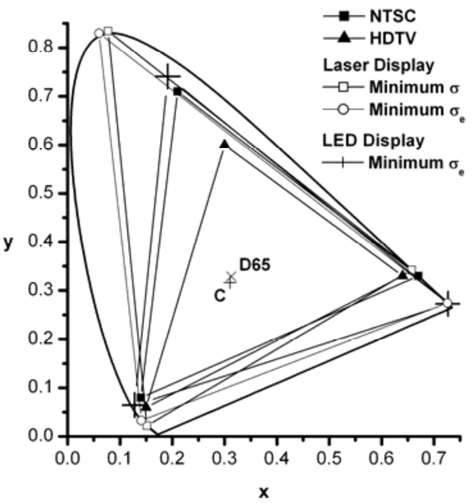

Fig. 1: Chromaticity triangles of NTSC and HDTV color standards, chromaticity triangles of the laser displays with the minimum standard deviations σ and σ_e, and the chromaticity triangle of the LED display with the minimum standard deviation σ_e. Illuminant C and D65 white points are also shown.

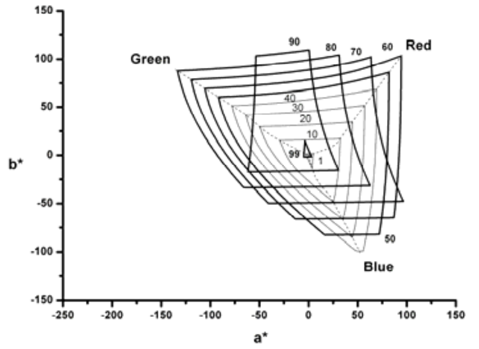

Fig. 2: Color gamut cross-sections of constant lightness (L*) in CIELAB color space for the NTSC standard display with illuminant D65. Corresponding values of L* are shown near boundaries of the cross-sections. Dashed lines show the loci of primary ramps.

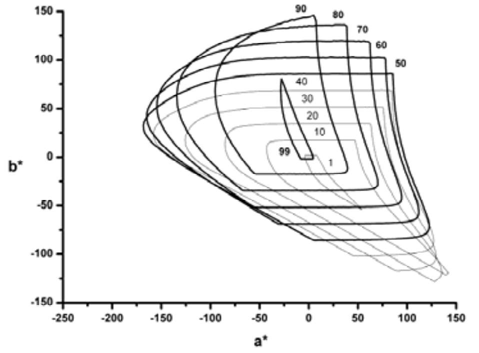

Fig. 3: Color gamut cross-sections of constant lightness (L*) in CIELAB color space for the optimal object color gamut with illuminant D65. Corresponding values of L* are shown near boundaries of the cross-sections.

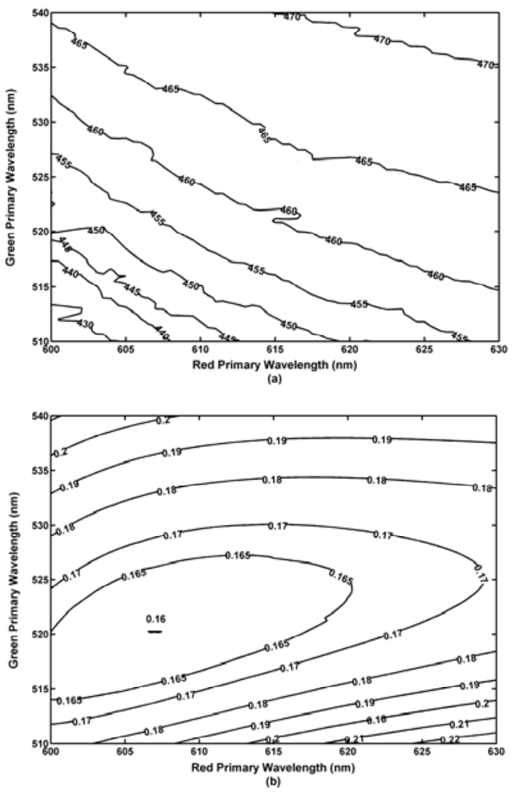

Fig. 4: (a) Optimized blue primary wavelength and (b) corresponding gamut standard deviation σ for laser displays.

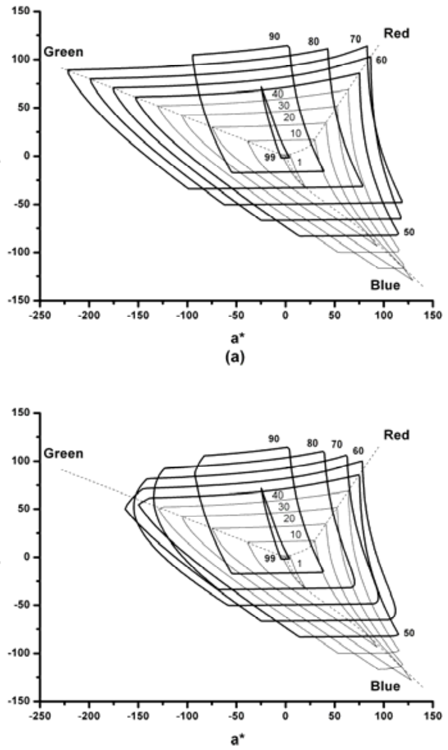

Fig. 5: Color gamut cross-sections of constant lightness (L*) in CIELAB color space for the (a) color gamut and (b) effective color gamut of the laser display with λ_r = 607.5 nm, λ_g = 520.4 nm and λ_b = 454.7 nm. Corresponding values of L* are shown near boundaries of the cross-sections. Dashed lines show the loci of primary ramps. The gamut standard deviation σ of this display is the minimum.

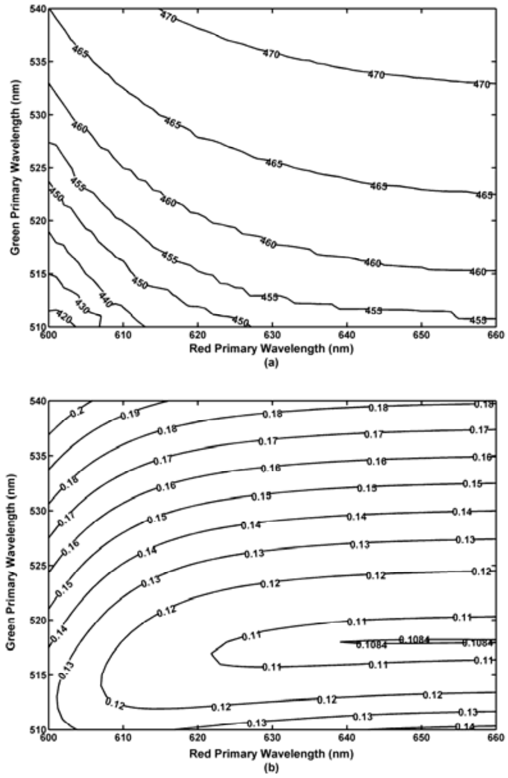

Fig.6 (a) Optimized blue primary wavelength and (b) corresponding effective gamut standard deviation σ_e for laser displays.

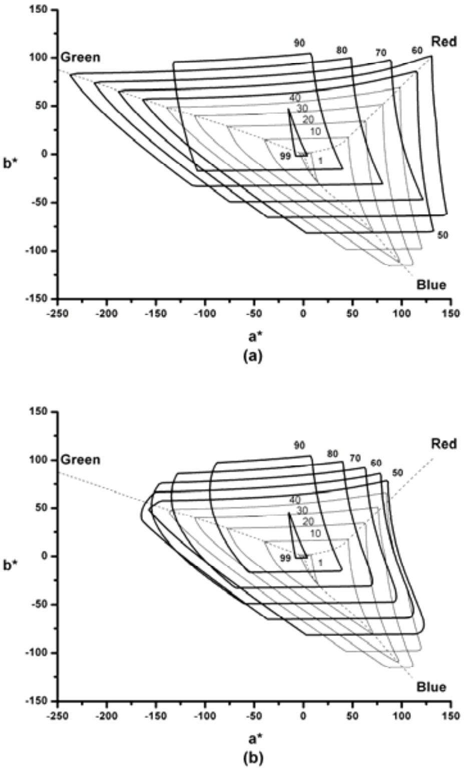

Fig.7 Color gamut cross-sections of constant lightness (L*) in CIELAB color space for the (a) color gamut and (b) effective color gamut of the laser display with λ_r = 649.7 nm, λ_g = 518.1 nm and λ_b = 462 nm. Corresponding values of L* are shown near boundaries of the cross-sections. Dashed lines show the loci of primary ramps. The effective gamut standard deviation σ_e of this display is the minimum.

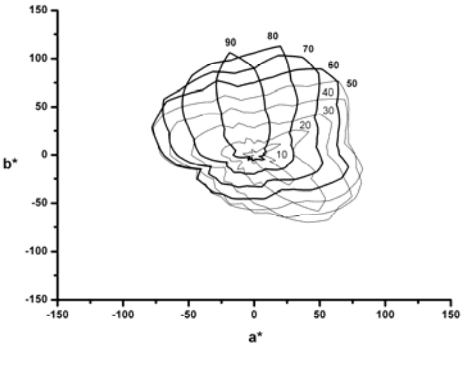

Fig.8 Color gamut cross-sections of constant lightness (L*) in CIELAB color space for Pointer's color gamut. Corresponding values of L* are shown near boundaries of the cross-sections.

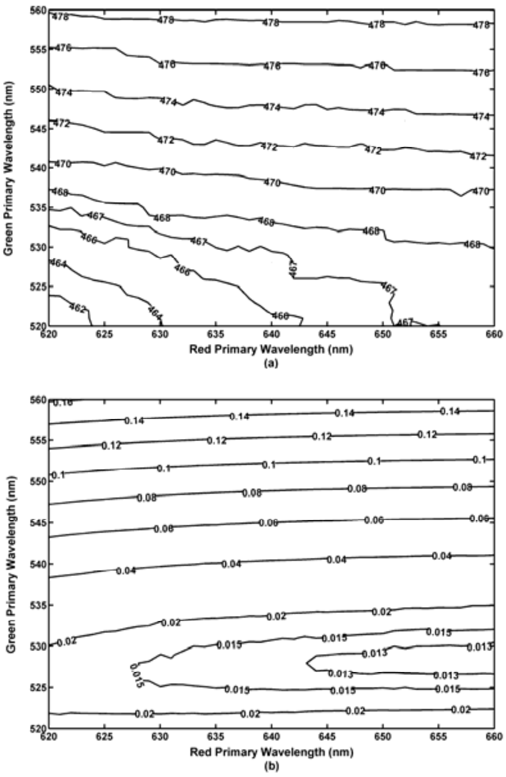

Fig.9 (a) Optimized blue primary wavelength and (b) corresponding effective gamut standard deviation σ_e for LED displays.

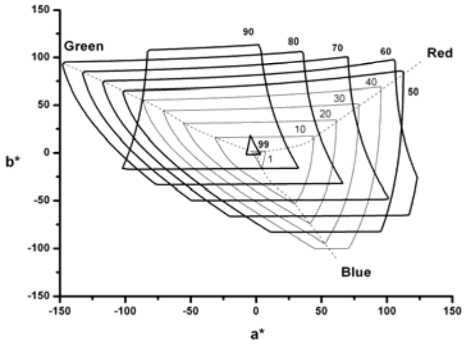

Fig.10 Color gamut cross-sections of constant lightness (L*) in CIELAB color space for the color gamut of the LED display with λ_r = 658 nm, λ_g = 528.2 nm, and λ_b = 467.97 nm. Corresponding values of L* are shown near boundaries of the cross-sections. Dashed lines show the loci of primary ramps. The effective gamut standard deviation σ_e of this display is the minimum.