行政院國家科學委員會專題研究計畫 成果報告

多原色顯示器色彩轉換方法研究
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行政院國家科學委員會專題研究計畫成果報告

多原色顯示器色彩轉換方法研究
Studies of color transformation methods for multi-primary displays

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一、中文摘要

本計畫研究由標準高解析度電視信號轉換到四原色顯示器信號的方法，以保持信號原有色調並同時獲得四原色顯示器的廣色域之優點。我們使用亮度線性色域映射演算法，將標準高解析度電視的色域映射到四原色顯示器的色域。信號轉換可以使用類神經網路實現，其中使用倒傳遞學習法以訓練網路。我們提出漸進式不均勻訓練方法，以改善類神經網路之品質，使得灰階與所選擇的色階之平均色差能降到可接受的水準。其中代表性的色階為紅、黃、綠、青綠、藍、與洋紅等色階。研究成果正準備投稿發表中。

關鍵詞：多原色顯示器，色域映射，類神經網路。

Abstract

The color signal transformation from the standard HDTV to a four-primary display is studied for preserving color hue and taking the wide-color-gamut advantage of the multi-primary display. Lightness linear gamut mapping algorithm is used to map the HDTV color gamut to the four-primary display color gamut. An artificial neural network with back-propagation learning is used to implement the signal transformation. Progressively non-uniformly training method is proposed to improve the performance of the artificial neural network, in which the average color differences of gray ramp and selected color ramps, which are red, yellow, green, cyan, blue, and magenta ramps, can be reduced to a tolerable level. The result of this project is prepared to be submitted for publication.

Keywords: multi-primary displays, color gamut mapping, artificial neural network.

二、緣由與目的

Conventional color displays comprise red, green, and blue primaries for constructing its color gamut. The displays of larger color gamut are able to show more colorful and attractive images. The color gamut of a display can be expanded by the use of high saturation primaries. The saturations of the primaries of light emitting diode (LED) displays and organic light emitting diode (OLED) displays are high because of narrow primary spectral width. Further expanding color gamut can be realized by adding more primaries [1-5]. The wide-color-gamut display with more than three primaries is usually called multi-primary display. Multi-primary LED backlit liquid crystal displays are under developed owing to their attractive image quality and advances of technology.

There are red, green, and blue signals for conventional images. The RGB signals have to be converted to the *N* signals for driving the *N*-primary displays. There are multiple choices of the rules for converting RGB signals to the *N* driving signals. The chromaticity properties of a color can be represented with CIE XYZ tri-stimulus values. Following the HDTV color standard (ITU-R BT. 709), we can derive the tri-stimulus values from RGB signals. The color conversion can be designed so that the N driving signals produce the color as close to the derived tri-stimulus values as possible. If an object color is captured with a multi-spectral camera, it is possible to design the color conversion so that the spectral properties of reproduced image are close to the original object for avoiding observer metamerism [6-8].

This paper studies the color signal transformation from the HDTV to a multi-primary display so that high saturation advantage of the multi-primary display can be taken and preferred color appearance is shown. Fig. 1 shows a typical workflow of the color signal transformation, in which the four-primary display with red, yellowish green, green, and blue primaries is taken as an example. In the workflow, a color gamut mapping algorithm (GMA) is applied to preserving color hue [9-11]. HDTV signal vector (r_s,g_s,b_s) is first transformed to the tri-stimulus vector (X_s,Y_s,Z_s) with the forward model of HDTV. As CIELAB is a uniform color space that is more suitable for GMA, the vector (X_s,Y_s,Z_s) is transformed to the color coordinates vector in CIELAB, (L^*_s,a^*_s,b^*_s). After applying GMA, we have the target color coordinates vector in CIELAB, (L^*_t,a^*_t,b^*_t), which is to be shown by the four-primary display. For obtaining the red, yellow-green, green, and blue signal vector, (r_o,g_{yo},g_o,b_o), for the four-primary display, the vector (L^*_t,a^*_t,b^*_t) is transformed back to the target tri-stimulus vector (X_t,Y_t,Z_t) and then transformed to the vector (r_o,g_{yo},g_o,b_o) through the backward model of the four-primary display. As the workflow is complicated, it is not suitable for real time signal processing. It is found that the relation of the vectors (r_s,g_s,b_s) and (r_o,g_{yo},g_o,b_o) is highly nonlinear. A multi-dimensional lookup table (MLUT) that directly relates the vector (r_s,g_s,b_s) to the vector (r_o,g_{yo},g_o,b_o) can also be used for the color signal transformation. A MLUT comprises sampled grid points in (r_s,g_s,b_s) vector space. The signals that are not sampled can be transformed by interpolation. However, the use of MLUT suffers from the discontinuity of output signals unless grid points are densely sampled [12]. Ref. [12] also reported that the use of an artificial neural network (ANN) to approximate a MLUT has the advantages of lower cost and avoiding the discontinuity. As an ANN is able to describe a highly nonlinear relation between input and output signals, Ref.[13] has reported the use of an ANN for transforming the signals of a three-primary display to the other three-primary display. In this paper, we use an ANN for the color signal transformation from the HDTV to a four-primary display. The proper GMA and the method for training the ANN are studied.

三、結果與討論

The chromaticity triangle of HDTV and the chromaticity quadrilateral of the considered four-primary display are shown in Fig. 2, where D65 white point for the two displays is also shown. The primary color coordinates for the four-primary display are (x, y)= (0.6872, 0.3127), (0.3471, 0.6367), (0.1288, 0.6820), and (0.1416, 0.0423) for red, yellowish green, green, and blue primaries, respectively. Note that the green primary of HDTV is yellowish green in fact. We can see that the chromaticity triangle is enclosed by the chromaticity quadrilateral so that the four-primary display is able to show the images of higher saturation and more colorfulness than the display specified by HDTV.

The input signals of red, yellowish green, green, and blue primaries are taken as r, y_g, g, and b, where the signals are normalized as $0 \leqq r$, g_y, g, and $b \leqq 1$. The normalized output luminance of red, green, and blue primaries can be respectively described by the tonal response curves (TRCs) $R_L(r)$, $G_{YL}(g_y)$, $G_L(g)$, and $B_L(b)$, which are the functions of the normalized input signals. $0 \leqq R_L(r)$, $G_{YL}(g_y)$, $G_L(g)$, and $B_L(b) \leqq 1$. A TRC can be described with a gamma function. Taking red

TRC as an example, we can write the gamma function as $R_L(r) = r^{\gamma_r}$, where gamma value γ_r is a constant [14]. HDTV designates the gamma values of three primaries the same as 2.2, which is also assumed for primaries of the four-primary display.

For a given normalized input signal vector (r, g_y, g, b), the output tri-stimulus vector (X, Y, Z) of the LED display can be calculated from

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_r & X_y & X_g & X_b \\ Y_r & Y_y & Y_g & Y_b \\ Z_r & Z_y & Z_g & Z_b \end{bmatrix} \begin{bmatrix} R_L(r) \\ G_{YL}(g_y) \\ G_L(g) \\ B_L(b) \end{bmatrix}, \quad (1)$$

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 vectors of the red, yellowish green, green, and blue LEDs, respectively. The 3×4 matrix in Eq.(1) is known as the chromaticity matrix. The relative luminance values of the four primaries are specified so that the display color gamut size is the maximum and we have Y_r: Y_y : Y_g : Y_b:= 0.251: 0.28:0.419:0.05 [15]. From Eq.(1), we may calculate the display color gamut boundary according to the method given in [16]. Figs. 3 and 4 show the color gamuts for the HDTV and the four-primary display, respectively, in which primary loci are also shown. For a given tri-stimulus vector (X, Y, Z), there is no unique solution for the required input signal vector (r, g_y, g, b) from Eq.(1). We use the method given in [17] for the backward model of the four-primary display so that the display color gamut can be completely utilized. With this backward model, the required input signal vector (r, g_y, g, b) is uniquely determined for a given tri-stimulus vector (X, Y, Z).

For the applications in color printers, cusp GMA is preferred [11]. We find that it is not suitable for the real time signal processing with a MLUT or ANN because the relation of the vectors (r_s, g_s, b_s) and (r_o, g_{yo}, g_o, b_o) is too complicated. Discontinuity is serious for MLUT. Training error Instead, we use lightness linear (LLIN) GMA [11] in this paper because the relation of the vectors (r_s, g_s, b_s) and (r_o, g_{yo}, g_o, b_o) is not as complicated as that using cusp GMA. Fig. 5 shows the schematic diagram of LLIN GMA, in which the cross sections of the gamut boundaries at 0° hue angle for the HDTV and four-primary display are shown for example. Four color points of the same lightness are shown, in which S and T are the color points in the HDTV and four-primary display gamuts, respectively; B_S and B_T are the gamut boundary points of the HDTV and four-primary display, respectively. Color point S is mapped to color point T through the relation

$$C^*_T = C^*_S \frac{C^*_{BT}}{C^*_{BS}}, \quad (2)$$

where C^*_T, C^*_S, C^*_{BT}, and C^*_{BS} are the chroma values of the color points T, S, B_T, and B_S, respectively. From the LLIN GMA, we calculate $16\times16\times16 =$ 4096 grid points as the training samples for the ANN, in which the grid points are equally spaced in (r_s,g_s,b_s) vector space. For each grid point, there is a pair of the input vector (r_s,g_s,b_s) and output vector (r, g_y, g, b). The colors of the input and output vectors are called the source and target colors, respectively. Fig. 6 shows selected source and target color ramps projected to the a*b* plane in CIELAB color space. 512 samples are randomly chosen as the test samples of the trained ANN.

Back-propagation learning ANN is used because it is suitable for highly nonlinear functional relation and fast reasoning speed [12, 13]. Its cons are slow learning speed and the trained ANN may lie at a local minimum. Because of the latter con, we must take care with the training method. Four-layer ANN is used. There are three and four neurons in the input and output layers, respectively. Between the input and output layers, we take two hidden layers and thirty neurons for each hidden layer. Training samples are feed into the ANN one by one for updating network parameters such that the color difference between the target color and ANN output color for each sample is minimized, in which ANN output color is calculated by substituting the output vector of the ANN into Eq.(1). The training procedure repeats until the average error of training samples cannot be further reduced, in which the average error is the average color difference (CIEDE2000) of target colors and ANN output colors. It requires about 15,000 iterations to complete the training. We find that the use of more hidden layers and neurons in a hidden layer does not appreciably reduce the average error because the increase of the number of network parameters complicates the optimization of the ANN.

Following the methods described above, we have the average color differences 1.26 and 1.30 for the training samples and the test samples, respectively. Although the average color differences are low, it is found that the average color differences of yellow and gray ramps are larger. Fig. 7 shows the average color difference of target colors and ANN output colors for selected color ramps and gray ramp, in which the results are indicated as uniformly training method to tell from the results obtained by the training method shown later. Fig. 8 shows selected target color ramps and the corresponding ANN output color ramps projected to the a*b* plane in CIELAB color space. We can see that the yellow ramp fits worse than the other color ramps.

From the experience of our memories, we can memorize something by practicing more times. The same experience can be applied to reduce the average color differences of yellow and gray ramps. We can significantly reduce the average color differences of the two ramps by further training the ANN with the samples of yellow and gray ramps. However, it is found that the average color differences of the other color ramps significantly increase after the further training. Thus the use of a proper training strategy is necessarily. We propose the progressive non-uniformly training (PNUT) method to reduce the average color differences of yellow and gray ramps while the average color differences of the other color ramps do not appreciably increase. We select a set of samples form the 4096 training samples for enhanced training, which are 15 yellow ramp samples and 15 gray ramp samples in the 4096 training samples. The network parameters obtained by the uniformly training method are taken as the initial network parameters for the PNUT method. The PNUT method includes a number of training rounds. For the first training round, the 15+15+4096= 4126 training samples, which include the yellow and gray ramp samples and 4096 training samples, are used for training. After the first training round, the average color differences of the yellow and gray ramps decrease but the other color ramps slightly increase. For the second training round, we keep the 4126 training samples and add the color ramp samples with the maximum average color difference. The initial network parameters obtained by the first round is taken as the initial network parameters of the second round. The same procedures are applied to the following training rounds. After 5 training rounds, the average color differences of the training samples and the test samples are 1.09 and 1.43, respectively. The average color difference of the training samples is reduced compared with the results using uniformly training method, but the average color difference of the test samples is increased. The average color differences of color ramps and gray ramp after 5 training rounds are also shown in Fig. 7. We can see that yellow and gray ramps fit better at the expense of increasing the color differences of the other color ramps. The average color differences of all the ramps are less than 1.6 using the PNUT method. Fig. 9 shows the target color ramps and the corresponding ANN output color ramps after 5 training rounds. Comparing Fig. 9 with Fig. 8, we can see that the compromised color ramps using the PNUT method fit the corresponding target color ramps better than the color ramps using uniformly training method.

四、計畫成果自評

The color signal transformation from the

HDTV to a four-primary display is studied for preserving color hue and taking the wide-color-gamut advantage of the multi-primary display. An artificial neural network with back-propagation learning is used for the transformation. The proper gamut mapping algorithm and the method for training the artificial neural network are given. It is found that the lightness linear gamut mapping algorithm is more suitable than the cusp gamut mapping algorithm for this application because the relation of the input signal vector and output signal vector is less complicated. It is also shown that the conventional uniformly training method is able to reduce the average color difference of training samples to a low level for the considered four-primary display, but the average color differences of yellow and gray ramps are large. Progressively non-uniformly training method is proposed to improve the performance of the artificial neural network, in which the average color differences of gray ramp and selected color ramps, which are red, yellow, green, cyan, blue, and magenta ramps, can be reduced to a tolerable level.

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六、圖表

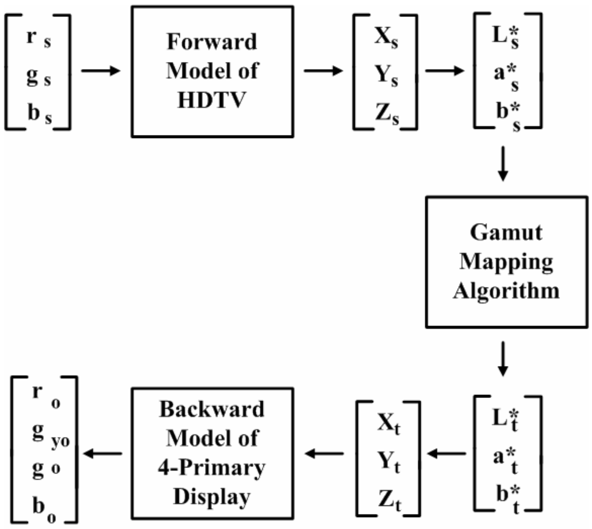

Fig. 1: A typical workflow of the color signal transformation.

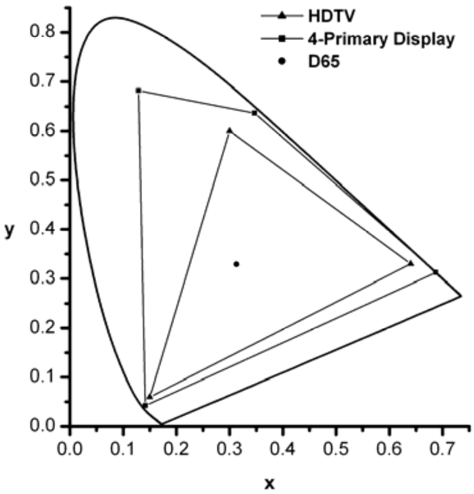

Fig. 2: The chromaticity triangle of HDTV and the chromaticity quadrilateral of the four-primary display considered in this paper, where the D65 white point is also shown.

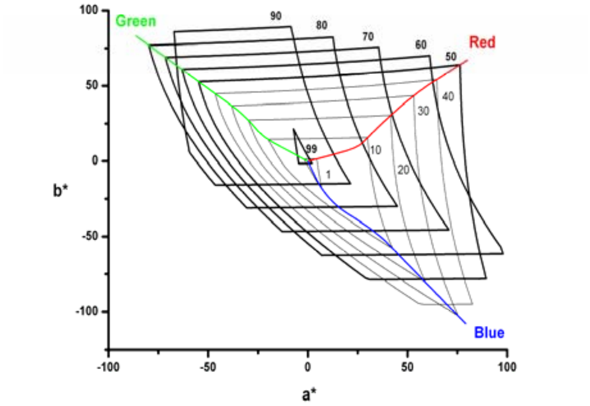

Fig. 3: Color gamut of the HDTV, in which primary loci are also shown.

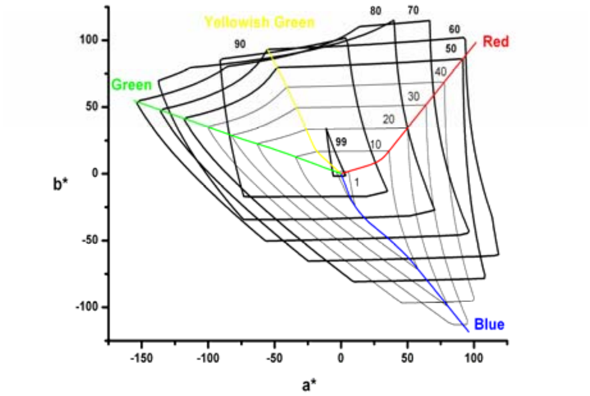

Fig. 4: Color gamut of the four-primary display considered in this paper, in which primary loci are also shown.

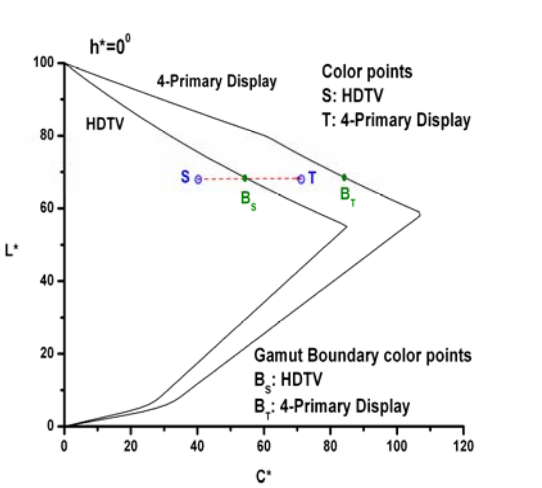

Fig. 5: A schematic diagram of LLIN GMA, in which the cross sections of the gamut boundaries at 0° hue angle for the HDTV and four-primary display are shown for example.

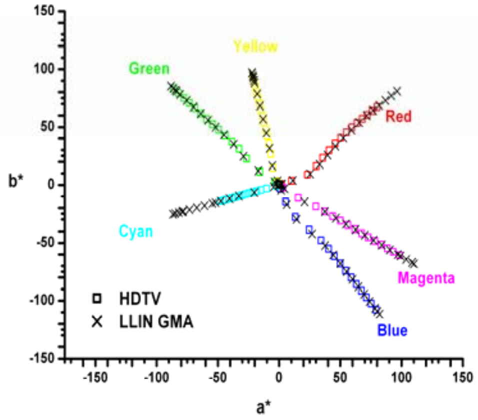

Fig.6 Selected source color ramps (HDTV) and target color ramps (LLIN GMA) projected to the a*b* plane in CIELAB color space.

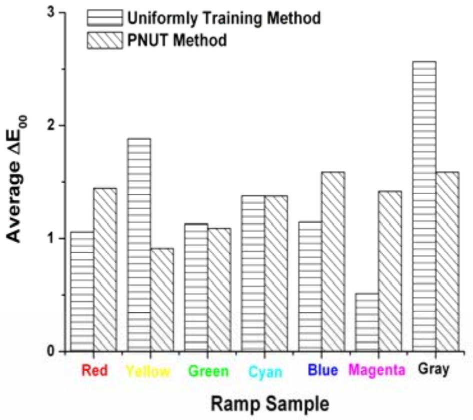

Fig.7 Average color difference of target colors and ANN output colors for selected color ramps and gray ramp. The results with the ANNs trained by the uniformly training method and progressive non-uniformly training (PNUT) method are shown.

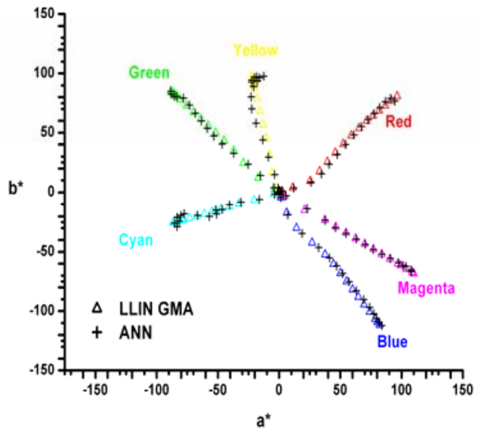

Fig.8 Selected target color ramps (LLIN GMA) and the corresponding ANN output color ramps projected to the a*b* plane in CIELAB color space. The ANN is trained by the uniformly training method.

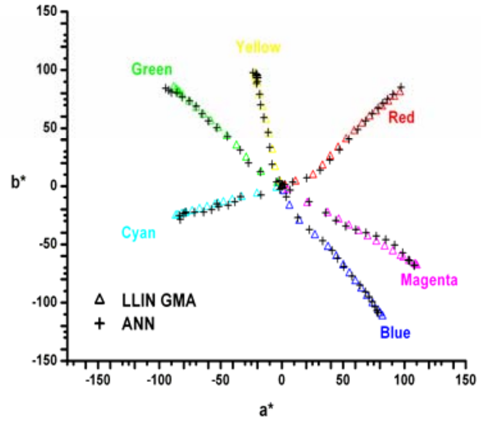

Fig.9 Selected target color ramps (LLIN GMA) and the corresponding ANN output color ramps projected to the a*b* plane in CIELAB color space. The ANN is trained by the progressive non-uniformly training (PNUT) method.