行政院國家科學委員會專題研究計畫　成果報告

有原色串音的液晶顯示器色彩特性研究

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行政院國家科學委員會專題研究計畫成果報告

有原色串音的液晶顯示器色彩特性研究
Study of the chromaticity characteristics of the liquid crystal displays with primary crosstalk

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一、中文摘要

有原色偏移與雙原色串音的液晶顯示器之色彩特性可以用一組非線性代數方程式表示。這組方程式成為前向模型，它們將信號轉換成三刺激值。本計畫研究將三刺激值轉換成信號的反向模型，並使用兩台液晶顯示器測試此模型之精確度。結果顯示反向模型的精確度與前向模型相當。研究成果已投稿 IEEE Journal of Display Technology。

關鍵詞：液晶顯示器，色彩模型。

Abstract

Chromaticity characteristics of the liquid crystal displays (LCDs) with primary shift and two-primary crosstalk can be described by the set of simultaneous nonlinear algebraic equations that transfers signals into tristimulus values. The equations are the called the forward model. The backward model that transfers tristimulus values into the required signals by iteration method is studied. Two LCD monitors are taken as examples to show the performance of the iterative method. The results show that the average color differences of backward and forward color device models are of the same level. The result of this project has been submitted to IEEE/LEOS Journal of Display Technology for publication.

Keywords: color, display human factors, displays, liquid crystal displays.

二、緣由與目的

Images are captured and produced by input and output electronic devices, respectively. For examples, scanners and cameras are input devices; and displays and printers are output devices. A color management system converts the data of the captured images into the signals of an output device for a preferred color rendering intent. Figure 1 shows the block diagram of the signal conversion. In the figure, R_s, G_s, and B_s are source signals. The chromaticity characteristics of the input and output devices are mathematically described by color device models. The forward color device model of the input device converts the source signals into the source tristimulus values X_s, Y_s, and Z_s. The gamut mapping algorithm converts the source tristimulus values into the desired target tristimulus values X_t, Y_t, and Z_t that are to be displayed by the output device. The backward color device model of the output device converts the target tristimulus values into the required signals R_o, G_o, and B_o of the output device. Forward and backward color device models are called forward and backward models, respectively, for simplicity. Therefore, there require forward and backward models for input and output devices, respectively.

Conventional color device model of a display is represented by a 3×3 or 3×4 chromaticity matrix and three tonal transfer curves (TRCs) for red, green, and blue primaries. Such a model is a forward model and is called the conventional simple matrix (CSM) model for simplicity. The CSM model is valid for the displays without primary shift and primary crosstalk, such as cathode ray tube (CRT) displays. The backward CSM (BCSM) model can be easily derived from the CSM model because the chromaticity-matrix device model is linear and the TRCs of the three primaries are independent of one another. Unfortunately, there are primary shift and two-primary crosstalk for liquid crystal displays (LCDs) [1,2]. Primary shift is the variant primary chromaticity that is due to the spectral transmittance of liquid crystal cell changed with applied voltage. Two-primary crosstalk may come from the signal interference between neighboring LCD cells [1,2]. Several methods have been used to improve the CSM model for LCDs by optimizing the chromaticity matrix and TRCs for a set of measurement data [2-4]. Reference 2 introduces the parameter optimized simple matrix (POSM) model that optimizing the coefficients of TRCs and the chromaticity matrix by the simulated annealing method and the regression method, respectively. Because their model equations are the same, the backward POSM (BPOSM) model can be easily implemented with the same way as the BCSM model.

Further improvement of the forward model of the LCD with primary shift and two-primary crosstalk can be achieved with the two-primary crosstalk (TPC) model [1]. The TPC model is represented with the set of three simultaneous algebraic equations that comprise the offset constants, one-color terms, and two-color-product terms. The coefficients of the TPC model equations can be obtained from measurement data by regression. However, the TPC model equations cannot be analytically solved for the signals because the equations are nonlinear. Therefore, the backward TPC (BPTC) model equations cannot be explicitly expressed. It was shown that the accuracy of the POSM model is significantly better than that of the CSM model but is less than that of the TPC model [1]. For taking the accurate advantage of the TPC model, in this work we use an iteration method to solve the TPC model equations so that the BTPC model can be implemented.

三、結果與討論

Signals can be represented by the vector (R, G, B), in which R, G, and B are red, green, and blue components, respectively. The values of R, G, and B lie between 0 and MAX, in which $MAX=2^M-1$ for the M-bit digital system. In this work, we consider the 8-bit digital system and $MAX=255$. For simplicity, we normalize signals as $r=R/MAX$, $g=G/MAX$, and $b=B/MAX$ so that the normalized signals $0 \leqq r, g, b \leqq 1$. The TPC model assumes that the relation of the stimulus value S ($S= X, Y, Z$) and the normalized signal vector (r, g, b) can be described by the equation [1]

$$S(r,g,b) = a_0^S + \sum_{k=1}^{P} a_{rk}^S r^k + \sum_{k=1}^{P} a_{gk}^S g^k + \sum_{k=1}^{P} a_{bk}^S b^k + \sum_{l=1}^{Q}\sum_{m=1}^{Q} c_{rglm}^S r^l g^m + \sum_{l=1}^{Q}\sum_{m=1}^{Q} c_{gblm}^S g^l b^m + \sum_{l=1}^{Q}\sum_{m=1}^{Q} c_{brlm}^S b^l r^m \quad (1)$$

where P and Q are the integer constants; $a^S{}_0$ is a constant representing offset value; and the coefficients $a^S{}_{ik}$ and $c^S{}_{ijlm}$ ($i, j= r, g, b$; $k= 1, 2, \ldots P$; $l, m= 1, 2, \ldots Q$) are constants. In Eq.(1), the terms with r^k , g^k , and b^k are one-color terms; and the terms with $r^l g^m$, $g^l b^m$, and $b^l r^m$ are two-color-product terms. Primary shift and two-primary crosstalk can be described by one-color terms and two-color-product terms, respectively. The coefficients in Eq.(1) can be optimized from the measurement data set given below by regression.

The TRC coefficients and chromaticity matrix of CSM model are calculated from the black point corresponding to the signal vector (R, G, B)= (0, 0, 0), and the one-primary data set given by (R, G, B)=($I[i]$, 0, 0), (0, $I[i]$, 0), (0, 0, $I[i]$), where $i= 1, 2,\ldots 7$ and $I[i]=\{36, 72, 109, 145, 182, 218, 255\}$.

The coefficients and chromaticity matrix of POSM model are calculated from the black point, the white point corresponding to (R, G, B)= (255, 255, 255), the one-primary data set, and the two-primary data set (R, G, B)=($J[i]$, $K[j]$, 0), (0, $J[i]$, $K[j]$), =($K[j]$, 0, $J[i]$), where i, j= 1, 2, 3 and $J[i]$ ={36, 109, 218}, and $K[j]$={72, 145, 218}. The two-primary data set is chosen so that the cases of low, medium, and high luminance are included. The TPC model uses the same measurement data of the POSM model. The coefficients of the TPC model equations are optimized from the measurement data by regression. Thus required numbers of the measurement data for CSM, POSM and TPC models are 22, 50 and 50, respectively.

For the BTPC model, we solve the normalized output signals by the iteration equations that are derived by linearlizing the TPC model functions. For the more general derivation of the iteration equations, we consider the relation of the tristimulus value S (S=X, Y, Z) and the normalized signals to be

$$S(r,g,b) = \sum_{0\le l+m+n\le U} d^S_{lmn} r^l g^m b^n \,, \qquad (2)$$

where U is an integer constant; d^S_{lmn} (l, m, n= 0, 1, 2, …U, and $0 \leqq l+m+n \leqq U$) coefficients are constants for the stimulus value S. Note that, when $U \geqq P, 2Q$, all the terms in Eq.(1) is a subset of Eq.(2). First we take the normalized output signals of either the BCSM model or the BPOSM model as the initial trial solutions $r^{(0)}$, $g^{(0)}$ and $b^{(0)}$ of the iteration. The solutions of the k-th iteration are assumed to be

$$r^{(k)} = r^{(k-1)} + e_r^{(k-1)} \,, \qquad (3a)$$

$$g^{(k)} = g^{(k-1)} + e_g^{(k-1)} \,, \qquad (3b)$$

$$b^{(k)} = b^{(k-1)} + e_b^{(k-1)} \,, \qquad (3c)$$

where $r^{(k-1)}$, $g^{(k-1)}$, and $b^{(k-1)}$ are the solutions of the (k-1)-th iteration; $e_r^{(k-1)}$, $e_g^{(k-1)}$, and $e_b^{(k-1)}$ are the iteration errors. Under the assumptions $|e_r^{(k-1)}|$, $|e_g^{(k-1)}|$, $|e_b^{(k-1)}| \ll |r^{(k-1)}|$, $|g^{(k-1)}|$, $|b^{(k-1)}|$, we have the errors derived from Eq.(2)

$$\begin{bmatrix} e_r^{(k-1)} \\ e_g^{(k-1)} \\ e_b^{(k-1)} \end{bmatrix} = \begin{bmatrix} \Delta X_r^{(k-1)} & \Delta X_g^{(k-1)} & \Delta X_b^{(k-1)} \\ \Delta Y_r^{(k-1)} & \Delta Y_g^{(k-1)} & \Delta Y_b^{(k-1)} \\ \Delta Z_r^{(k-1)} & \Delta Z_g^{(k-1)} & \Delta Z_b^{(k-1)} \end{bmatrix}^{-1} \begin{bmatrix} X_t - X^{(k-1)} \\ Y_t - Y^{(k-1)} \\ Z_t - Z^{(k-1)} \end{bmatrix}, \qquad (4)$$

where $X^{(k-1)}$, $Y^{(k-1)}$, and $Z^{(k-1)}$ are the tristimulus values given by substituting $r^{(k-1)}$, $g^{(k-1)}$, and $b^{(k-1)}$ into Eq. (2); the matrix elements of the 3×3 matrix in Eq.(4) are

$$\Delta S_r^{(k-1)} = \sum_{1\le l+m+n\le U} d^S_{lmn}\, l \left(r^{(k-1)}\right)^{l-1} \left(g^{(k-1)}\right)^{m} \left(b^{(k-1)}\right)^{n} , \qquad (5a)$$

$$\Delta S_g^{(k-1)} = \sum_{1\le l+m+n\le U} d^S_{lmn}\, m \left(r^{(k-1)}\right)^{l} \left(g^{(k-1)}\right)^{m-1} \left(b^{(k-1)}\right)^{n} , \qquad (5b)$$

$$\Delta S_b^{(k-1)} = \sum_{1\le l+m+n\le U} d^S_{lmn}\, n \left(r^{(k-1)}\right)^{l} \left(g^{(k-1)}\right)^{m} \left(b^{(k-1)}\right)^{n-1} , \qquad (5c)$$

where S= X, Y, and Z and we have taken the conventions $(r^{(k-1)})^{-1}$= $(g^{(k-1)})^{-1}$= $(b^{(k-1)})^{-1}$= 0 because the terms with $(r^{(k-1)})^{-1}$, $(g^{(k-1)})^{-1}$, or $(b^{(k-1)})^{-1}$ do not exist. Therefore we have the iterative equations, Eqs.(3) and Eqs.(5), for the k-th iteration solutions.

Note that the iteration error can be interpreted as the difference between the successive iteration solutions. The iteration terminates when (i) the absolute values of the three iteration errors are simultaneously less than 0.5/MAX, (ii) one of the absolute values of the three iteration errors is larger than the tolerable maximum error e_{tol}, or (iii) the number of iteration times exceeds the maximum number of iteration times N_{max}. If the iteration terminates due to either condition (i) or condition (iii), the output solutions of the iteration are the normalized output signals of the BPTC model. If the iteration terminates due to condition (ii), the solution cannot converge to the desired result. Because the iteration fails for such a case, the initial trial solutions are taken as the output solutions. If an output solution is negative, we take it as 0.0. If an output solution is larger than 1.0, we take it as 1.0.

The two LCD monitors tested in References 1 and 2 are taken as examples in this work, which are ViewSonic VA520 and VG151 LCDs. The same data measured in the two references are used so that the detailed characteristics of the CSM, POSM and TPC models of the two monitors can be referred from the two references. The monitors are respectively controlled by the same desktop computer. They are wormed up for an hour before they are measured so that measurement data do not drift with time. The monitors are measured at the center of the display and perpendicular to the face. Tristimulus values are measured with Photo Research PR650 spectroradiometer. The accuracies of the color device models are measured with the CIEDE2000 color difference formula for 224 test samples, which are chosen by randomly selecting R, G, and B values for their signals. The average color difference of the test samples is denoted as $\Delta E_{00,avg}$. For the minimum $\Delta E_{00,avg}$, the optimal TRC and SNT orders of CSM and POSM models, respectively, are the same and the optimal order N= 4. For the CSM and POSM models of VA520, $\Delta E_{00,avg}$ = 2.88 and 1.33, respectively. For the CSM and POSM models of VG151, $\Delta E_{00,avg}$ = 2.93 and 2.02, respectively. With the same forward model, the accuracy of VA520 is better than that of VG151 because its primary crosstalk is lower [1,2]. It was found that, for VA520 (VG151), the average color difference of the TPC model is the minimum when the orders P= 5 (6) and Q=2 (2), in which $\Delta E_{00,avg}$ = 1.19 (1.21).

The accuracy of a backward model is estimated from the 224 test samples as the method used in Reference 2. The backward model is used to convert the measured tristimulus values of the test samples to the output signals, and the tristimulus values of the output signals are interpolated from the three-dimensional look-up-table (3D-LUT) model using an 8×8×8 lattice. The measurement data set of the 3D-LUT model is (R, G, B)=($L[i]$, $L[j]$, $L[k]$), where i, j, k= 1, 2, 3, …8; $L[i]$= {0, 36, 72, 109, 145, 182, 218, 255}. The number of the measurement data is 512 for the 3D-LUT model. The data that is not measured can be calculated from the measurement data by the tetrahedral interpolation. The average color differences of the 3D-LUT model are 0.89 and 1.04 for VA520 and VG151, respectively. For the BCSM and BPOSM models of VA520, $\Delta E_{00,avg}$= 2.95 and 1.27, respectively. For the BCSM and BPOSM models of VG151, $\Delta E_{00,avg}$= 2.96 and 2.32, respectively.

The average color difference of the BTPC model depends on the values of e_{tol} and N_{max} set for the termination conditions of the iteration. Empirically, we take e_{tol} = 1.0 and 0.55 for VA520 and VG151, respectively. The output solutions can converge in the presence of larger iteration errors in the iteration for VA520. Figures 2, 3, and 4 show the average color difference, average number of iteration times, and number of failure counts versus the maximum number of iteration times N_{max} for the BTPC model, respectively. The number of failure counts is the number of the test samples that their iterations terminate due to the termination condition (ii). The BTPC models taking the normalized output signals of BCSM and BPOSM models as initial trial solutions are denoted as the BTPC[BCSM] and BTPC[BPOSM] models, respectively. In Figure 2, the average color difference of the case with N_{max}= 0 is the average color difference of initial trial solutions. Because the TPC model of VA520 is more accurate than that of VG151, the BTPC model of VA520 is also more accurate than that of VG151. Figure 2 shows that the accuracies of BTPC[BCSM] and BTPC[BPOSM] models are about the same. But, for VG151, the accuracy of the BTPC[BCSM] model is not as stable as that of the BTPC[BPOSM] model with respect to N_{max}. From Figure 2, one can also see that the average color difference converges when the maximum numbers of iteration times are larger than 3 and 5 for VA520 and VG151, respectively. Note that the average color difference does not necessarily decrease as N_{max} increases. Therefore the proper setting of N_{max} saves the number of iteration times without the expense of the accuracy.

For VA520 with N_{max}= 4, $\Delta E_{00,avg}$= 0.93 and 0.91 for BTPC[BCSM] and BTPC[BPOSM] models, respectively; the average numbers of iteration times are 3.2 and 2.8 for BTPC[BCSM] and BTPC[BPOSM] models, respectively; and the numbers of failure counts are 6 and 1 for BTPC[BCSM] and BTPC[BPOSM] models, respectively. Figure 5 shows the color difference ΔE_{00} statistics of the 224 test samples with several backward models for VA520, in which N_{max} = 4. The test samples with ΔE_{00} larger than 5.0 are counted in the slot from 4.5 to 5.0. It is noticed that, for VA520, the average color differences of BTPC[BCSM] and BTPC[BPOSM] models are less than that of the TPC model. This result is not reliable because the average color differences of the two BTPC models are close to the average color difference of the 3D-LUT model. However, the results indicate that the BTPC model is accurate and the accuracies of the BTPC and TPC models are of the same level.

For VG151 with N_{max}= 6, the average color differences for BTPC[BCSM] and BTPC[BPOSM] models are the same and $\Delta E_{00,avg}$= 1.27; the average numbers of iteration times are 3.7 and 3.4 for BTPC[BCSM] and BTPC[BPOSM] models, respectively; and the numbers of failure counts are 6 and 3 for BTPC[BCSM] and BTPC[BPOSM] models, respectively. Figure 6 shows the color difference ΔE_{00} statistics for VG151, in which N_{max} = 6. The accuracies of BTPC and TPC models are also of the same level for VG151. Comparing with the accuracies of the BCSM and BPOSM models, one can see that the accuracy of the BTPC model is significantly improved for VG151.

四、計畫成果自評

The chromaticity characteristics of the LCDs with primary shift and two-primary crosstalk can be described by the TPC model that comprises a set of simultaneous algebraic equations. For implementing the BTPC model, an iteration method for solving the TPC model equations is studied. The iteration equations are derived by linearlizing the TPC model equations. The normalized output signals of BCSM and BPOSM models are taken as the initial trial solutions of the BTPC model. Viewsonic VA520 and VG151 LCD monitors are used for testing the performance of the BTPC model, in which the two-primary crosstalk of VG151 is more serious. It is found that, although the accuracy of the BPOSM model is higher than that of the BCSM model, the accuracies of the BTPC models taking the normalized output signals of BCSM and BPOSM models as initial trail solutions are about the same. However, the use of the normalized output signals of the BPOSM models as initial trail solutions has the advantages that the number of the iteration failure counts is less and the accuracy of the BTPC model with respect to the maximum number of iteration times is more stable. The results show that the average color differences of BTPC and TPC models are of the same level. The required maximum numbers of iteration times are only 4 and 6 for VA520 and VG151, respectively. Because the required number of iteration times is small, it is possible to implement the iteration process in hardware for real time applications.

五、參考文獻

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六、圖表

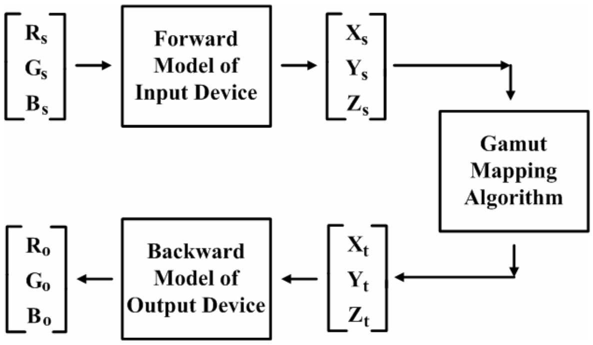

Figure 1: Block diagram of signal conversion for a color management system.

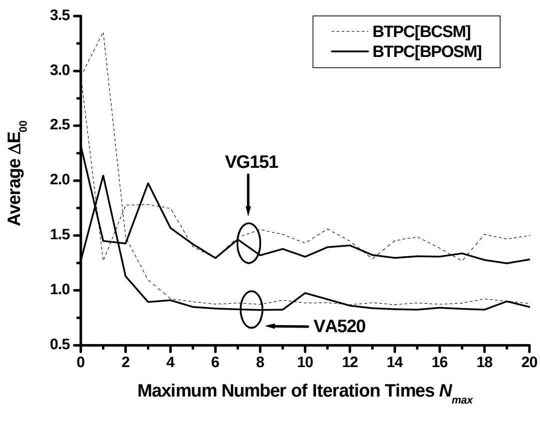

Figure 2: Average color differences versus the maximum number of iteration times N_{max} with BTPC[BCSM] and BTPC[BPOSM] models.

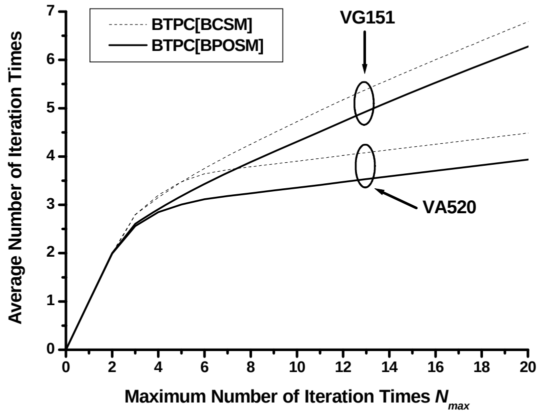

Figure 3: Average number of iteration times versus the maximum number of iteration times N_{max} for the cases shown in Figure 2.

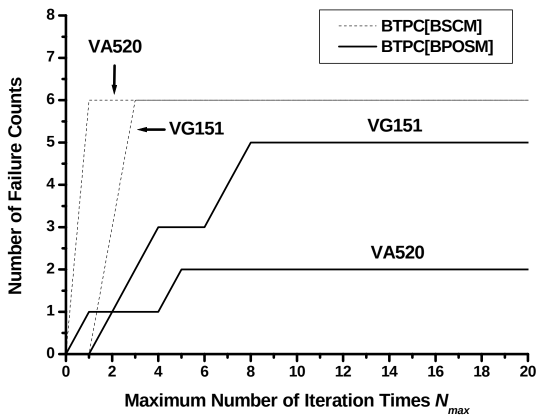

Figure 4: Number of failure counts versus the maximum number of iteration times N_{max} for the cases shown in Figure 2.

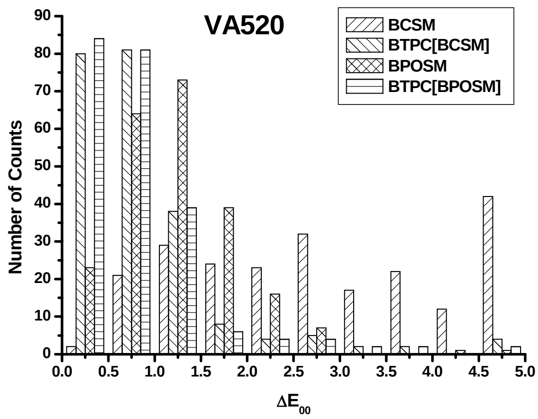

Figure 5: Color difference ΔE_{00} statistics of 224 test samples for ViewSonic VA520 LCD with BCSM, BPOSM, BTPC[BCSM], and BTPC[BPOSM] models, where N_{max}= 4.

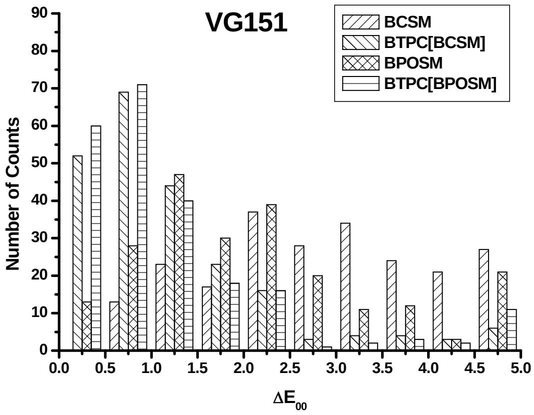

Fig.6 Color difference ΔE_{00} statistics of 224 test samples for ViewSonic VG151 LCD with BCSM, BPOSM, BTPC[BCSM], and BTPC[BPOSM] models, where N_{max}= 6.