Color characterization of twist nematic LC panels by using empirical functions

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ABSTRACT

An empirical exponential equation is proposed to characterize the transfer functions of the image signals to tristimulus values of twist nematic (TN) liquid crystal displays(LCDs). Parameters of the empirical equation can be determined according to the colorimetric measurements of the test panel without knowing the panel's physical details. A two-stage forward model is also proposed to model the color characteristics of TN LCDs by using the empirical function. Moreover, a backward model is derived to reproduce desired colors accurately on TN LCDs. The main benefit of the study is that only 12 colors should be measured to characterize color rendering on TN LCDs.

Keywords : color characterization of liquid crystal display, empirical transfer equation, colorimetric forward and backward model , color prediction, color reproduction

1. INTRODUCTION

High quality color devices require not only that full colors be rendered, but that produce the desired colors accurately. The fundamental work to reproduce colors correctly across color devices is to realize the color characteristics of these color devices. Color characterization of a color device is a procedure to build its colorimetric model which is a mapping method between the signal space defined by device RGB digital analog converter(DAC) values and the color space defined by CIE colorimetry.

Color characterizations of cathode-ray tube(CRT) monitors[1] and color printers[2-6] have been reported previously. These models obtain acceptable results in their respective color devices, but can not fully characterize LCDs because the color mechanisms of LCDs are quite different from those of CRT monitors and color printers.

For analyzing colors of TN LCDs, several physical models[7-10] have been reported to simulate optical properties of LCDs. The main functions of these models are to obtain the dependence of the LC director configuration on driving voltages. Then, the optical response can be derived by the Berreman 4×4 matrix[11] or 2×2 extended Jones matrix method[12,13]. Using these models to determine LC characteristic, physical parameters (such as geometric configurations of each pixel and birefrigence of the LC material, etc.) shall be given. These models are very useful in developing new LCDs, yet, are difficult for LCD users to control LCDs' image digital signals to obtain desired colors because the input parameters of these models become inaccessible after LC cells were packed. Hence, determining the physical parameters of these models according to LC panels' colorimetric characteristics becomes very complicated or impossible. Therefore, a simple LCD's color characteristic model whose parameters can be determined easily by a few color measurements is in demand. In this article, an empirical equation to model the transfer functions of TN LCDs was studied, and, hence, utilized to build the forward and backward models of LCDs for color rendering characterizations.

Part of the SPIE Conference on Display Technologies II • Taipei, Taiwan • July 1998
SPIE Vol. 3421 • 0277-786X/98/$10.00

2. THEORY

2.1 EMPIRICAL EQUATION OF THE TRANSFER FUNCTION OF TN LCD

There are three transfer functions from DAC values to XYZ values in every channel of a display. To explain these functions in the following sections clearly, four abbreviations are first defined as follows:

DNX transfer function : The transfer function relates *D*AC-to-*N*ormalized-*X*-value of a channel.
DNY transfer function : The transfer function relates *D*AC-to-*N*ormalized-*Y*-value of a channel.
DNZ transfer function : The transfer function relates *D*AC-to-*N*ormalized-*Z*-value of a channel.
DNXYZ transfer functions : The abbreviation of DNX, DNY, and DNZ functions of a channel.

The major characteristic of DNXYZ functions of TN LCDs is that these transfer functions will approach constants at low and high driving levels[9]. The exponential function described in Eq.(1) is proposed to model the characteristic of DNXYZ transfer functions of LCDs.

$$\begin{aligned} &V = c_1\left(\frac{dac}{255}\right) + c_2 && dac : RGB\ image\ signals \\ &T = 1 - c_3 \exp\{-V^{\gamma}\} && T : Normalized\ CIE\ X,\ Y,\ Z \end{aligned} \tag{1}$$

where 255 is the maximum DAC value used to defined colors in computers.

The characteristics of Eq.(1) with γ values ranging from 3 to 15 and the coefficient $c_2=0$, $c_{1,3}=1$ are plotted in Fig.1. The steepness of the curves depends on the power term (γ) of the V variable. The larger γ is, the steeper of the curve is. Moreover, T values are always equal to 0.6321 ($1-e^{-1}$) at V=1 regardless of γ value. At V=1, these curves change from concave upward to downward. For modeling TN LCDs' DNXYZ functions, the DAC value changing the curve from concave upward into downward is determined by c_1 and c_2, where the corresponding transmission of the DAC value is determined by c_3.

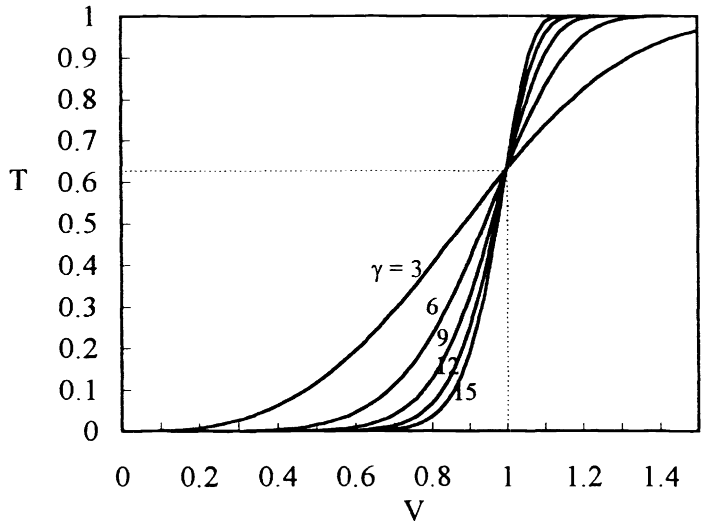

Fig. 1. Plots of $T = 1 - \exp\{-V^{\gamma}\}$

These four parameters, $c_{1,2,3}$ and γ parameters, which are called as "LC system parameters", in the empirical equation can be determined according to results of color measurements, without knowing all the physical details of each component in an LCD. It is expected that at least four training colors per channel are needed to construct four equations such that the solution of each parameter is exist uniquely.

2.2 FORWARD MODEL OF TN LCD

After the "LC system parameters" determined, colorimetric values of any color shown on TN LCDs are derived by a two-stage process. As demonstrated in Fig.2, the first stage is the transfer function stage for each channel. The system parameters $c_{1,2,3}$ and γ of the three DNXYZ functions of each channel are determined individually. The second stage is described briefly by the summation of RGB channels if their interactions are small enough to be neglected. If channel interaction can not be neglected, polynomial regression method[14, 15], which uses polynomials to link two sets of data, is suggested to improve the modeling accuracy of color prediction. The two-stage forward model of TN LCD are expressed as Eqs.(2) and (3).

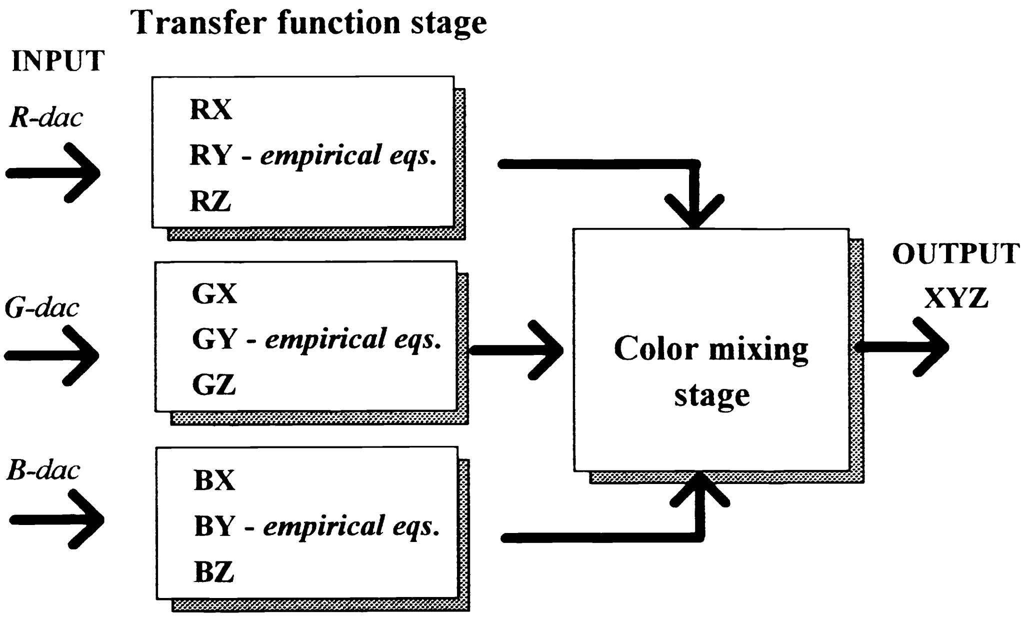

Fig.(2) The two-stage forward model of TN LCDs

1st stage : transfer function stage

$$
\begin{aligned}
X_i &= X_{i\_\max}\left\{1 - c_{3(x,i)}\exp\{-[c_{1(x,i)}(\frac{dac_i}{255}) + c_{2(x,i)}]^{\gamma(x,i)}\}\right\} \\
Y_i &= Y_{i\_\max}\left\{1 - c_{3(y,i)}\exp\{-[c_{1(y,i)}(\frac{dac_i}{255}) + c_{2(y,i)}]^{\gamma(y,i)}\}\right\} \qquad (2) \\
Z_i &= Z_{i\_\max}\left\{1 - c_{3(z,i)}\exp\{-[c_{1(z,i)}(\frac{dac_i}{255}) + c_{2(z,i)}]^{\gamma(z,i)}\}\right\}
\end{aligned}
$$

where i : r, g, b
$dac_{(r,\,g,\,b)}$: *DAC values of an image file*
$\gamma_{(x,\,y,\,z),\,(r,\,g,\,b)}$: *LC system gamma values of R, G, and B channels, respectively.*

$C_{1,2,3\ (x,y,z),(r,g,b)}$: *LC system parameters determine the DAC value changing the curve from concave upward to downward.*

$X_{(r,g,b)\_max}, Y_{(r,g,b)\_max}, Z_{(r,g,b)\_max}$: *The maximum tristimulus values of RGB channels, respectively.*

2nd stage : color mixing stage

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix} \times \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} + \begin{bmatrix} X_{dark} \\ Y_{dark} \\ Y_{dark} \end{bmatrix} \qquad (3)$$

where X_{dark}, Y_{dark}, and Z_{dark} denote the tristimulus values of the color driven by the zero signal state, i.e. $dac_r=0$, $dac_g=0$, and $dac_b=0$.

2.3 BACKWARD MODEL OF TN LCD

For color reproduction on a color output device, it is desired to have a backward model which is used more frequently than its forward model. Building the backward models of TN LCDs needs the auxiliaries of their forward model. An algorithm of the backward model is proposed without additional color measurements except those needed to build the forward model. The flow chart of the backward model is illustrated in Fig.3 and the detail procedures of the TN LCDs backward transform are described as follows:

1: For a given XYZ, its initial solutions of RGB DAC values, dac_r, dac_g, and dac_b, are predicted by Eqs.(4) and (5). The Eq.(5) is the inverse functions of Eq.(2).

$$\begin{bmatrix} Y_{r\_normalized} \\ Y_{g\_normalized} \\ Y_{b\_normalized} \end{bmatrix} = \begin{bmatrix} X_{r\_\max} & X_{g\_\max} & X_{b\_\max} \\ Y_{r\_\max} & Y_{g\_\max} & Y_{b\_\max} \\ Z_{r\_\max} & Z_{g\_\max} & Z_{b\_\max} \end{bmatrix}^{-1} \bullet \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \qquad (4)$$

$$\begin{aligned} dac_i &= \frac{255}{c_{1(y,i)}}\{-\ln[\frac{1}{c_{3(y,i)}}(1-Y_{i\_normalized})]\}^{1/\gamma_{y,i}} - c_{2(y,i)}\} \quad \text{if } 1-Y_{i\_normalized} > 0 \\ &= 0 \qquad\qquad \text{else} \qquad\qquad i = r,g,b \end{aligned} \qquad (5)$$

2: Substitute dac_r, dac_g, and dac_b into Eq.(2) to derive corresponding XYZ values of three primaries.

3: Calculate "modified coefficients" as follows:

$$\begin{aligned} c_{x\_i} &= \frac{X_i}{Y_i}, \quad c_{z\_i} = \frac{Z_i}{Y_i} \qquad if\, Y_i \neq 0 \\ c_{x\_i} &= 1, \quad c_{z\_i} = 1 \qquad if\, Y_i = 0 \end{aligned} \qquad (6)$$

where i=r,g,b and X_i, Y_i, Z_i are the tristimulus values of the DAC values calculated at the step 2.

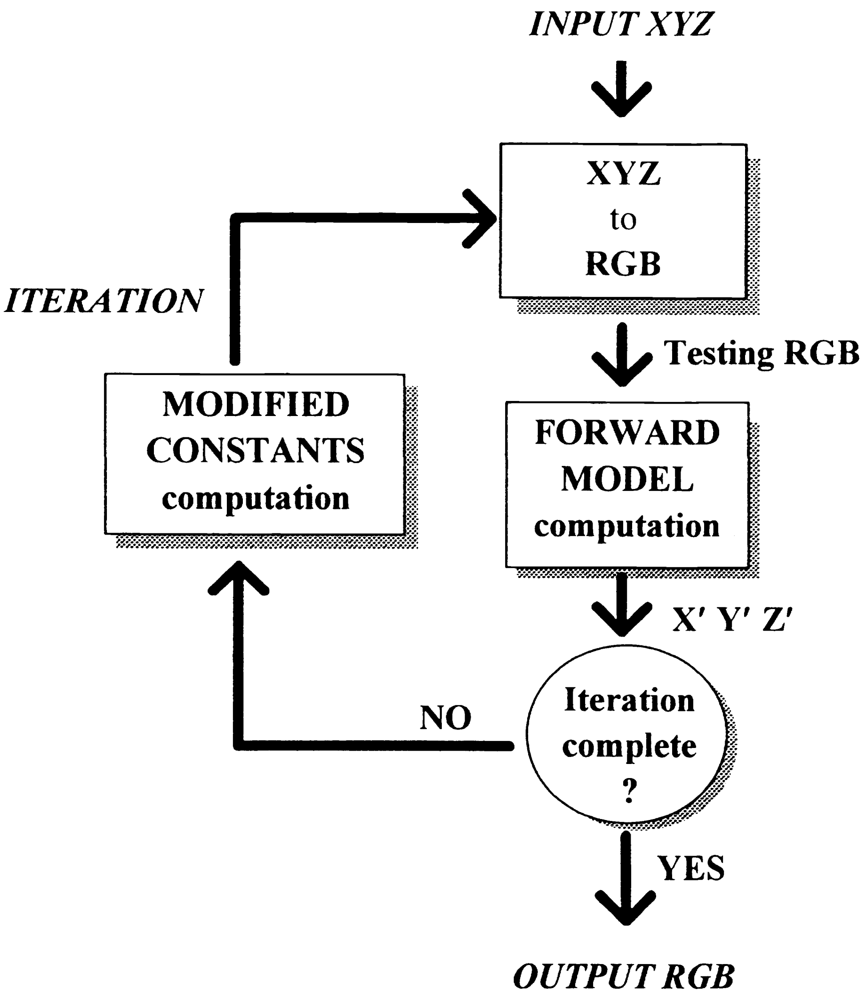

Fig. 3. The algorithm of the proposed backward mode of TN LCDs

4: Substitute "modified coefficients" into Eq.(7) to construct a new 3×3 matrix; and calculate new testing dac_r, dac_g, and dac_b, RGB signals by Eq.(5).

$$\begin{bmatrix} Y_{r\_normalized} \\ Y_{g\_normalized} \\ Y_{b\_normalized} \end{bmatrix} = \begin{bmatrix} c_{x\_r} X_{r\_\max} & c_{x\_g} X_{g\_\max} & c_{x\_b} X_{b\_\max} \\ Y_{r\_\max} & Y_{g\_\max} & Y_{b\_\max} \\ c_{z\_r} Z_{r\_\max} & c_{z\_g} Z_{g\_\max} & c_{z\_b} Z_{b\_\max} \end{bmatrix}^{-1} \times \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \qquad (7)$$

5: Repeat the step **2** to **4** with a specified number of iterations to achieve acceptable results.

6: Round the decimal dac_r, dac_g, and dac_b to be the nearest integers because only integer DAC values are allowed in color image files.

This algorithm of the backward model takes that the DNXYZ transfer functions of TN LCDs may be different into consideration . If the DNX, DNY, and DNZ transfer functions of a channel are the same, the backward model of TN LCDs can be simplified to be the first step. Then the backward model is the same as that of CRT monitors except the mathematical expressions of the inverse DNXYZ transfer functions.

3. EXPERIMENTS

Both the proposed forward and backward colorimetric models of LCDs were examined by characterizing a selected LCD which is a notebook PC with maximum resolution of 800 × 600 pixels The testing LCD was tested by the LMT C1210 colorimeter in a dark room. Because of low luminance emitting from the notebook panel, the detector of the LMT C1210 was positioned as close the panel as possible so that enough luminance can be detected. The LMT C1210 cannot make contact with the panel without pressuring on the LC panel.

The test color patches were displayed as a 450 pixel× 450 pixel square in the middle of the panel; the rest of the screen was left black. For each measured color, six measurements were taken within two seconds and averaged to an output file. Then, the next test color patch was subsequently displayed for measurement.

Two groups of training colors (used to build the DNXYZ transfer functions) and testing colors (used to evaluate the model) were measured. The first consists of 48 RGB primary colors (sixteen per channel) which were chosen from 0 to 255 with increments of every 17 DAC values. The second group consists of 729 colors which are the digital combinations of the following RGB image DAC values: 0, 32, 64, 96, 128, 160,.192, 224 and 255. These digital image signals were chosen with increments of every 32 DAC values (the maximum is 255 instead of 256) and were different from those used to build the forward model to ensure the fairness of the evaluation.

After measurements, the XYZ values of the zero signal state were subtracted form every measurement result. Then, the 1st, 6th, 11th, and 16th colors (with every five order increments) per channel of the first group were extracted as the training colors of the empirical equations. So, there were only twelve training colors to construct the colorimetric models of TN LCDs in the experiments.

4. RESULTS

4.1 TESTING OF CHANNEL INTERACTIONS

The amount of channel interactions were examined first to check whether they can be neglected. If RGB channels of the display are independent, the additive law of color mixing will be valid in the display. In general, the "additive color mixing" is not always valid for displays because of channel interactions and others.

The channel interactions were examined by the color differences between the measurement and theoretic XYZ values of 729 testing colors. For evaluating the channel interactions, the XYZ values of RGB primaries are extracted from the 729 testing colors, then the other 729 XYZ values can be calculated by the additive principle of color mixing. From Fig.4 which plots the distribution of 729 color differences, the average and maximum color differences between the 729 actual and theoretical values are 1.37 and 5.31 ΔE_{uv}^{*} for the testing LCD. The standard deviation of color prediction is also small with a value of 1.12 ΔE_{uv}^{*}. As shown in Fig.4, the percentages of color differences of less than 1 ΔE_{uv}^{*} are up to 87.8%. These color differences caused by channel interactions of the testing LCD are small enough, so the proposed forward and backward models are proper.

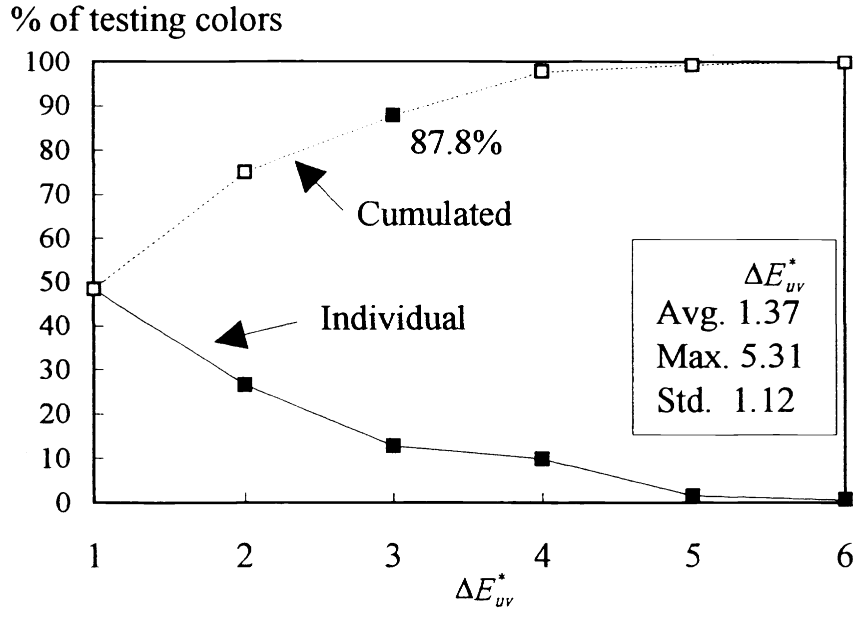

Fig. 4. The distribution of color differences caused by channel interactions

4.2 FITTING ACCURACY OF THE EMPIRICAL EQUATION

The characterization accuracy of the forward model is dominated by the fitting accuracy of DNXYZ functions by the proposed empirical equation since small color differences resulted from channel interactions. The DNXYZ transfer functions of the green channel of the testing LCD are illustrated in Fig.5. The DNX and DNY transfer functions of the green channel are about the same, but are different from that of the DNZ function. The characteristic causes that γ parameter of the DNZ transfer function is different from those of the DNX and DNY transfer functions as revealed in Table I. The empirical equations can well fit DNXYZ transfer functions of the testing LCD.

The different DNXYZ transfer functions imply that the system parameters of the empirical equation should be determined individually to fit these three transfer functions of a channel. This characteristic is different from that of CRT characterization for which DNXYZ transfer functions are regarded as the same, so that only parameters of DNY transfer function should be determined in a channel[1].

Table.I System parameters of the green channel of the testing LCD.

	c_1	c_2	c_3	γ
X	0.1897	0.8606	1.0029	37.0947
Y	0.1900	0.8611	1.0033	36.6182
Z	0.2519	0.8226	1.0046	27.3017

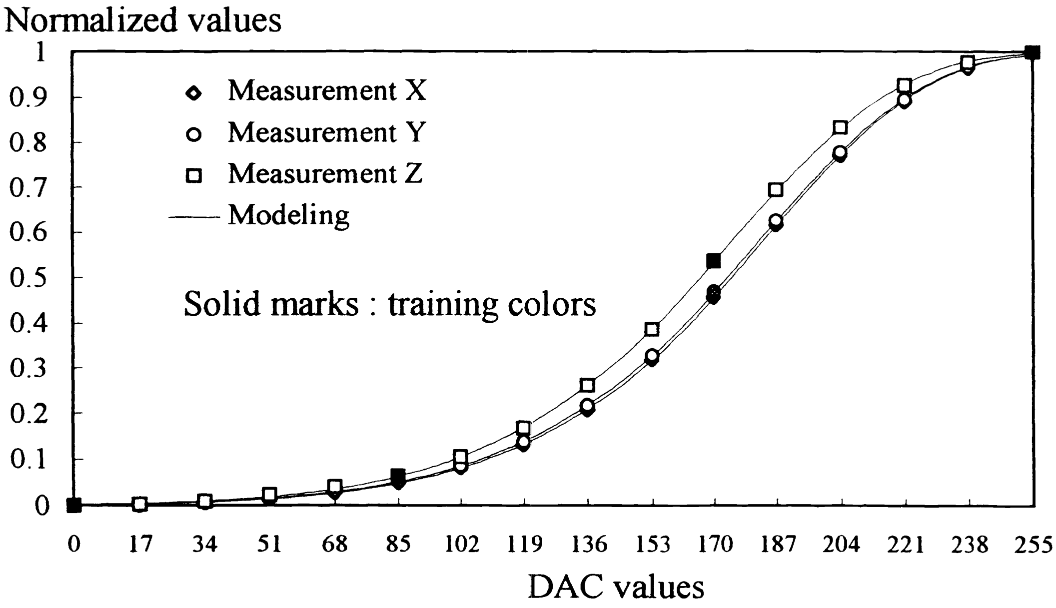

Fig. 5. The DNXYZ transfer functions of green channel for the testing LCD. Marks and lines denote the measurement and modeling results, respectively.

4.3 CHARACTERIZATION ACCURACY OF THE FORWARD MODEL

The accuracy of the color characterization model was evaluated by the average and maximum color difference (ΔE^*_{uv}) between prediction and measured values of the 729 testing colors. Fig.6 reveals the average ΔE^*_{uv}, maximum ΔE^*_{uv}, and standard deviation of 729 color predictions are small. The distributions of color differences illustrated in Fig.6 shows that there are 77.1 % colors can be predicted within 3 ΔE^*_{uv} from the measurement values. Because color difference of 3.0 or less are adequate for most color characterizations[16], the empirical equation enables the forward model to characterize LCD effectively by only 12 training colors.

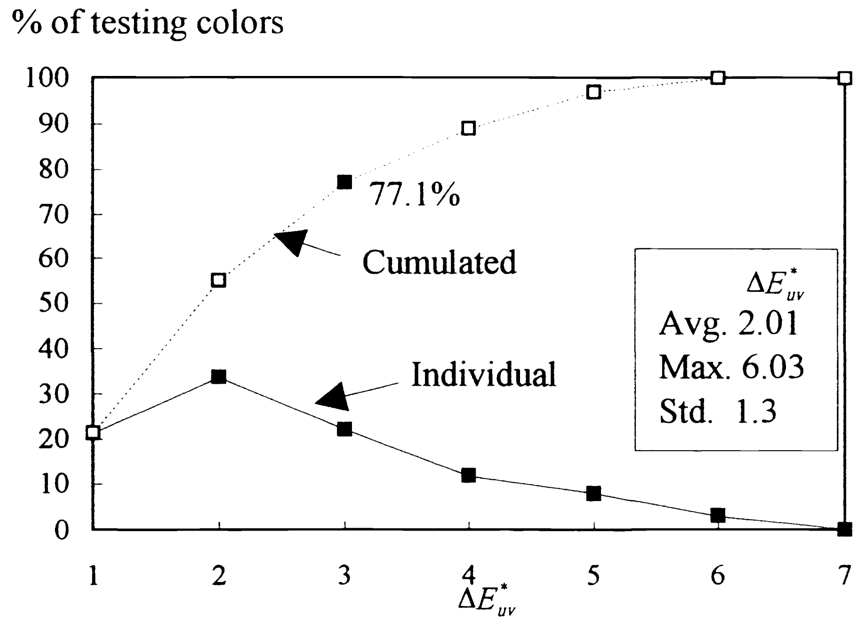

Fig.6 : The distribution of 729 color differences of the ***forward model***

4.4 CHARACTERIZATION ACCURACY OF THE BACKWARD MODEL

To examine the backward model's performance, image DAC values, dac_r, dac_g, and dac_b, which can produce tristimulus values XYZ of 729 colors measured previously were predicted by the backward model. Next, the calculated DAC values were input into the test displays to perform the same colorimetric measurement mentioned above. The color differences between the measurement and those measured previously were compared.

The characterization accuracy of the backward model depends on the number of iterations to calculate the "modified coefficients". As shown in Fig.7, the average color difference is also less than 3 ΔE^*_{uv} after only one iteration of computing "modified coefficients" where the accuracy approaches constant. Cumulating the probabilities, 82.6% desired colors can be reproduced within 3 ΔE^*_{uv} for the testing LCD. Without any iteration, the average and maximum color differences of the backward model are larger than those of utilizing only one iteration by a factor of larger than two. The proposed backward model using the proposed empirical equation can effectively improve the accuracy of rendering desired colors.

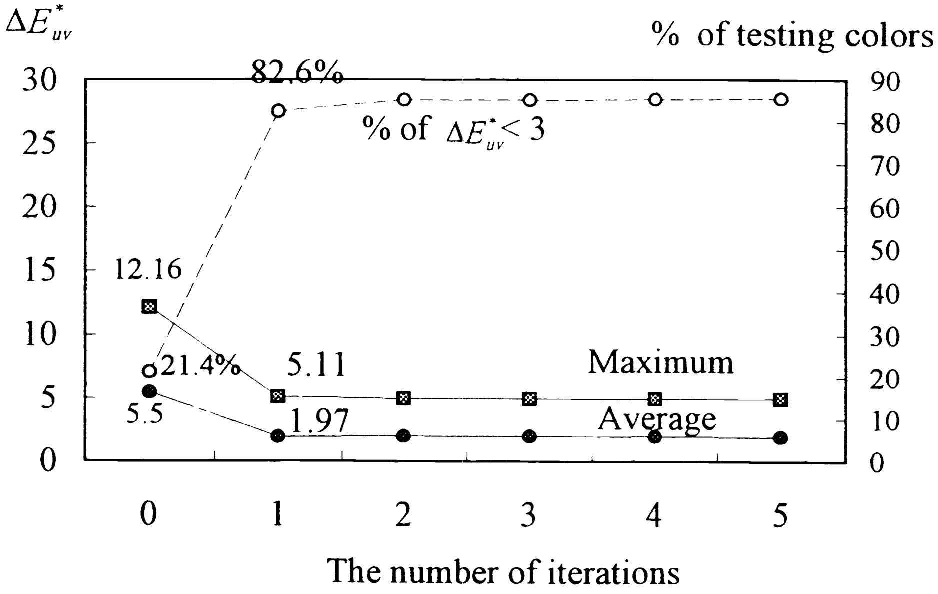

Fig.7: Characterization accuracy of the ***backward model*** examined by 729 colors.

5. CONCLUSIONS

An empirical equation is implemented successfully to reduce the number of training colors to characterize color rendering of TN LCDs. Using the empirical equation, a proposed two-stage forward model and an algorithm of the backward model were shown to characterize color rendering well of the display devices, and to obtain desired colors, respectively. The proposed model is more convenient than other models reproted[7-10] for TN LCDs' users to obtain desired colors since no physical details about TN LCDs are needed and only twelve colors (including three RGB primary colors which are driven by the maximum DAC values) are needed to measured.

From the color measurements and characterizations of TN LCDs, channel interactions of TN LCDs are found small enough to be neglected, hence, the color mixing stage can be approximated by additive color mixing principle. It is also found that the DNXYZ transfer functions of a channel are different for TN LCDs, hence, the three DNXYZ transfer functions of any channel are suggested to be fitted separately. Moreover, if the backward model of TN LCDs is implemented by the same algorithm of CRT, i.e. without iteration of adjusting RGB signals, color differences will become two times larger than those obtained even by one iteration.

6. ACKNOWLEDGMENTS

The authors would like to thank OES/ITRI, Taiwan, for the use of the LMT C1210 and Photo Research PR 650 and the support of a program package for the measurement. The work is partially supported by ERSO/ITRI through contract No. E87016.

7. REFERENCES

1. R. S. Berns, R. J. Motta, and M. E. Gorzynski, "CRT Colorimetry. Part I : Theory and Practice". *Color Res. and Appl.* 18, 299-314(1993).

2. I. Pobboravsky and M. Pearson, "Computation of dot areas required to match a colorimetrically specified color using the modified Neugebauer equations", *Proc. TAGA*, 65-77(1972).
3. J. A. C. Yule and W. J. Nielsen, "The penetration of light into paper and its effect on halftone reproduction", *Proc. TAGA*, 65-75(1951).
4. F. R. Clapper and J. A. C. Yule, "The effect of multiple internal reflections on the densities of half-tone prints on paper", *J. Opt. Soc. Am.*, 43, 600-603(1953).
5. J. A. C. Yule, *Principle of color reproduction*, New York, John Wiley & Sons, Inc., 205(1967).
6. H. R. Kang, "Kubelka-Munk modeling of ink jet ink mixing", *J. Imaging Technology*, 17, 76-83(1991)
7. R. Herke, S. H. Jamal, and J. R. Kelly, "LCD Modeling as a Display Characterization Tool", *SID95 DIGEST*, 544-547(1995).
8. K. Ohkubo, J. Ohtsubo, and N. Izumi, "Color modulation properties of a Liquid-Crystal Device", *Appl. Opt.*, Vol. 33, No.25, 5895-5901(1994).
9. L. D. Silverstein, "Colorimetric and Photometric Modeling of Liquid Crystal Displays". *Proc. of IS&T and SID's Color Imaging Conference*. 149-156(1993)
10. T. Fiske, M. Hack, R. A. Martin, and H. Steemers, "Analysis of Transient Optical Response of Active-Matrix LCDs", *SID 95 DIGEST*, 743-746(1995).
11. W. D. Berreman, "Optics in Stratified and Anisotropic Media : 4×4-Matrix Formulation", *J. Opt. Soc. Am.*, Vol.62, No.4, 502-510(1972).
12. P. Yeh, "Extended Jones Matrix Method", *J. Opt. Soc. Am.*, Vol.72, No.4, 507-513(1982).
13. C. Gu and P. Yeh, "Extended Jones Matrix Method. II", *J. Opt. Soc. Am. A*, Vol.10, No.5, 966-973(1993).
14. H. R. Hang, "Color Scanner Calibration", *J. Imaging Science and Technology*, Vol.36, No.2, 162-170(1992).
15. P. C. Hung, "Colorimetric Calibration for Scanners and Media", *SPIE*, Vol.1448, 164-174(1991).
16. H. R. Kang, *Color technology for electronic imaging devices*, SPIE. Press. (1997) p.112