A Study of the Relationship between LCD Color Properties and CMS Profile Performance

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Abstract: LCD monitors are gaining popularity in the desktop publishing environment. However, the material and technology differences cause LCD monitors to have different color properties from CRT monitors. Meanwhile, ICC profile specification includes a three-component matrix-based display profile assuming that the CRT monitor can be characterized using a GOG model. Yet it is not clear whether the same profile structure would be applicable to LCD monitors.

Two different LCD monitors were tested with three different characterization methods. The characterization results from ICC profiling, 3x4 model and 3x11 model were compared and analyzed. It was concluded that the 3x11 model is needed to characterize the tested LCD monitors better. The 3x4 model had a similar performance to the three-component matrix-based ICC profile. A more complicated profile structure like multidimensional lookup table tags may be needed to characterize the LCD monitors given their color properties.

Introduction

Soft proofing is an important task in the Graphic Arts Industry. However, it is necessary to have well calibrated and characterized monitors in the proofing system. Accurate ICC monitor profiles are also required for the color management system to function correctly (Fleming, 2003; ICC, 2003). With the improved technology and decreased cost, Liquid Crystal Displays (LCDs) are gradually introduced to the Graphic Arts Industry to replace the Cathode Ray Tube (CRT) monitors as the soft proofing device. It is noted that technology difference between LCD and CRT monitors results in different color performance (Leckner, 2002).

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There are at present no standard characteristics for LCD. Contrast ratio, viewing angle, color filter characteristics, backlight, panel drive electronics and graphic interface card etc. are factors involved (Wright, 2000; Leckner, 2002). From a colorimetric point of view, Yoshida (2002) described four major inherent color properties in current LCD devices as follows.

1. Additive failure due to inter-channel cross talk
2. Non-proportionality due to retardation
3. Leakage of light
4. Residual of S-shape on electro-optical response

These attributes make the color reproduction characteristics appear differently on the LCD monitors from how they appear on the CRT monitors (Yoshida, 2002).

The color management system (CMS) has been used to achieve device independent color reproduction in an open system environment. A color transformation engine in the CMS can take the device characterization information in profiles and perform signal conversion for cross-device color reproduction through the profile connection space (PCS). The ICC profile specifications define the data structures and their corresponding functionalities for color data exchange among computer systems (ICC, 2003). For different devices such as monitor or printer, there are different profile classes to record the color characteristics specifically. The display profile class (in "**mntr**" signature) was designed for the input display device, mostly the CRT monitor. However, with the new introduction of LCD monitors to the CMS workflow it is uncertain that the different LCD color properties can be well characterized by the previously defined ICC display profile. The objective of this study is then to verify the influence of the LCD color properties to the colorimetric accuracy of the ICC display profile in the CMS workflow.

Monitor Characterization and Profiling

The most commonly known monitor characterization model is the GOG model (Katoh, 1997; Berns 2000) in which nonlinear functions are used to describe the gain, offset and gamma parameters as formula (1) for the CRT's characteristics between digital signals and measured values in each of the Red, Green and Blue primaries.

$$Y = aX^{\gamma} + b \quad (1)$$

with,
Y: Measured values (luminance)
X: Digital counts
a: Gain
b: Offset
γ: Gamma

In the GOG model, an additive color mixing matrix is further used to describe the mixing of different levels of primaries into a full range of colors as formula (2).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} Xr & Xg & Xb \\ Yr & Yg & Yb \\ Zr & Zg & Zb \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (2)$$

with,
R, G and B: Digital counts for each primary
Xr, Yr and Zr: Tristimulus values of the Red primary
Xg, Yg and Zg: Tristimulus values of the Green primary
Xb, Yb and Zb: Tristimulus values of the Blue primary
X, Y and Z: Resulting tristimulus values of the color mixing

In the ICC display class profile (ICC, 2003) there are monochrome display profiles, three-component matrix-based display profiles and N-component LUT-based display profiles. Within these display profiles there are two major groups of profile tags, tone reproduction curve (**TRC**) tags and multidimensional lookup table tags. The TRC tags use **curveType** or **parametricCurveType** to record the color information for the primaries, like formula (1). Information in **MatrixColumn** tags are used to perform the color mixing as described in formula (2).

The multidimensional lookup table tags use a much more complicated transformation structure to describe the relationship between device signals (digital counts) of the display and the profile connection space (mostly CIE X,Y and Z tristimulus values for display). Usually the data in the lookup table can be gathered by massive measurements of the tested device if implemented by an empirical approach. If a good mathematical model can be derived, the lookup table can be filled with data computed by an analytical approach.

LCD Color Properties

The underlined technology for LCD monitors is quite different from that for CRT monitors. Gibson (2000) presented a detailed comparative analysis between CRT and LCD monitors. Among the properties analyzed, spectral characteristics, chromatic constancy, additivity both in luminance and chromaticity and electro-optical transfer functions are directly linked to the color reproduction ability of the monitor. It is noticed that the "*stable primaries*" as described by Berns (2000) are not always observed in the LCD monitors.

Fairchild (1998) also pointed out the leakage of light contributed to the shift of the chromaticity for the LCD's primaries. The typical chromaticities of Red, Green and Blue primaries of LCD monitors are shown in Figure 1 where the chromaticities of each primary would change at different levels of intensity.

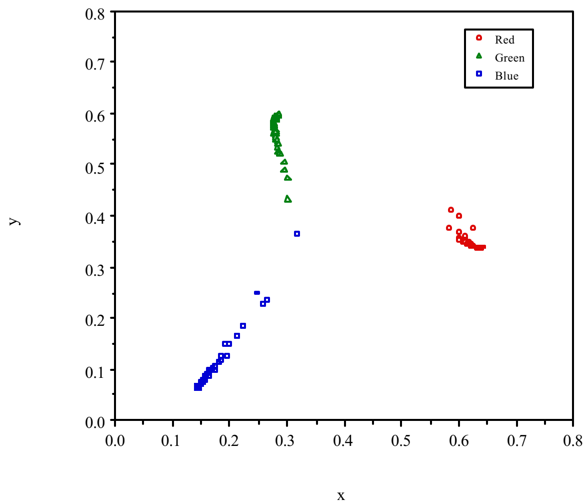

Fig. 1: The distribution of chromaticities of typical LCD's primaries

Another special property of the LCD monitor is the difference of electro-optical transfer function caused by channel interaction. The CIE X, Y and Z tristimulus differences between the sum of each individual Red, Green and Blue primary and the actual displayed mixing white are shown in Figure 2 where the channel interaction causes the nonlinear additive failure shown clearly. Tamura (2002) has proposed a masking model specifically to resolve this issue.

It is known that a 3x3 matrix as formula (2) would not be able to model the non-linear additive error in the color mixing stage, and higher order regression terms were suggested by Katoh (1997). In this study, a 3x4 (3x3 plus constant term) matrix model with three 1-D lookup tables (LUTs) and a 3x11 polynomial model (Hung, 2003) with three 1-D LUTs as described in formula (3) are used as the characterization methods. A commonly used ICC profile software is used first to generate the base-line ICC profile, by which a characterization procedure can be performed throughout a CMS workflow. The CIELAB color difference (dE*ab) is used as the quality metric (Sharma, 2002) between the measured colorimetric values and the predicted values for all these three methods. The results would verify the assumption that some extra effort is needed to make the CMS profile function better, given the current LCD color properties.

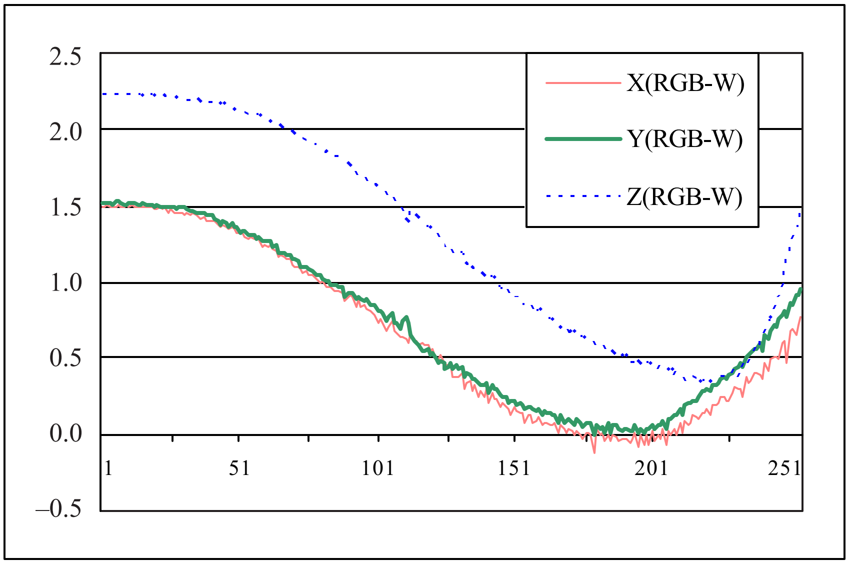

Fig. 2: Example of nonlinear additive failure (Sum of individual R, G and B minus White) caused by the channel interaction (X-axis is the digital counts from 0 to 255, Y-axis is the CIE X, Y and Z values)

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M_{interaction}(3x11) \begin{bmatrix} 1 \\ R \\ G \\ B \\ R^2 \\ G^2 \\ B^2 \\ RG \\ GB \\ RB \\ RGB \end{bmatrix} \tag{3}$$

with,
X, Y, Z: Measured tristimulus values
M: Interaction matrix by regression terms
R, G, and B: Tristimulus values related to the 1-D LUTs by digital counts

Experiment Procedure

Two TFT/LCD monitors were used as the testing bases. One was a common off-the-shelf 17-inch LCD monitor for PC in DVI interface (referred to as LCD A). Another LCD monitor (referred to as LCD B) was a straight 17-inch LCD monitor directly from panel manufacture driven by a DVI circuit board without any gamma correction. An IBM-compatible PC running Microsoft Window XP and Adobe Photoshop 7.0 was used as the platform. A Minolta CA210 display color analyzer was used to measure the LCD monitors. A Gretagmacbeth Eye-One Monitor package was used to generate ICC profiles.

After sufficient warm-up for the LCD monitors (Hung, 2003), the experiment with CMS profiling was first performed by calibrating and characterizing the LCD monitors. Following the calibration procedure of Eye-One Monitor software, LCD A was set to custom display mode and consequently brightness level, contrast and color temperature (D65) were set. An ICC monitor profile (profile A) was generated accordingly. For LCD B there was no adjustment available for calibration purposes but the default color temperature was D65. Another profile (profile B) was made for LCD B.

A set of 648 colors in R, G and B combinations was used as the testing data set, and two TIFF files containing 8x81 pixels in these RGB values were generated. After the ICC monitor profiles were loaded into the system, profiles A and B were assigned to these two TIFF files by Photoshop "Image/Mode/Assign profile" command. These two RGB TIFF files were then converted into LAB color mode in absolute colorimetric rendering intent by Photoshop "Image/Mode/Convert to Profile" command. A program was used to read out the LAB values in these two TIFF/LAB files into text files as the predicted colorimetric values by CMS profiling. The same 648 colors were then displayed on each of the LCD monitors and measured by CA210 in CIE X, Y and Z values. Two sets of CIELAB values were calculated using each of the white values (R=G=B=255) as the reference white. These values were the measured colorimetric values.

An additional 768 colors (0, 1, 2 to 255 for each R, G and B ramp) were measured for each LCD monitor by CA210. These ramp values for each primary were used as the 1-D LUTs in the color mixing model as described in formula

(3). The measured tristimulus values of the 648 colors were used to run the 3x4 and 3x11 regressions respectively. The CIELAB color differences between predicted values and measured values were computed for each LCD in both regressions.

Results and Analysis

The 648 color combinations were used as the testing data set. The CIELAB color difference between the calculated LAB values and corresponding measured LAB values are listed in Table 1. It was found that the 3x11 models resulted in less color difference for both LCD A and LCD B. The 3x4 model resulted in a similar average color difference to that of the CMS profiling method. The 3x4 model resulted in a larger maximum error.

Monitor	Delta E*ab	CMS Profile	3x4 Model	3x11 Model
LCD A	Average	3.98	4.25	1.52
	Maximum	13.31	44.42	9.08
LCD B	Average	3.48	3.42	1.35
	Maximum	15.34	32.95	13.63

Table 1: The resulting CIELAB color differences for the experiments

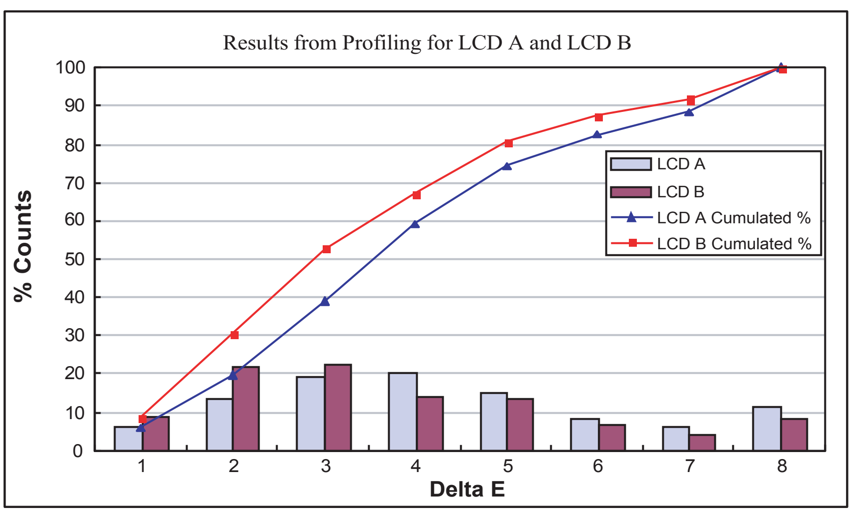

Fig. 3: Histogram of color difference distribution by CMS profiling for LCD A and LCD B

The distribution of color differences calculated between the CIELAB values characterized by CMS profiling and measured CIELAB values for both LCD A and LCD B is further analyzed in Figure 3. It was found that the distribution in both has a similar trend, and that the cumulated percentages for values under delta E of 7 are both around 90%. This verifies that the performance of the profiling software is consistent in characterizing both LCD monitors.

The distribution of color differences for LCD A calculated through 3x4 and 3x11 models is further analyzed in Figure 4. It was found that 90% of the cumulated values for 3x4 model are around delta E of 6, which is slightly better than the results by from CMS profiling. A higher sampling numbers (256x3) in the 1-D LUTs during the characterization process in the 3x4 model may have contributed to this. However, 90% of the cumulated distribution for the 3x11 model are reached much faster around delta E of 3 in Figure 4. Given the fact that the 3x4 and 3x11 models are using the same data for 1-D LUTs, this significant performance improvement must have been caused by the more complicated 3x11 polynomial terms in the 3x11 model.

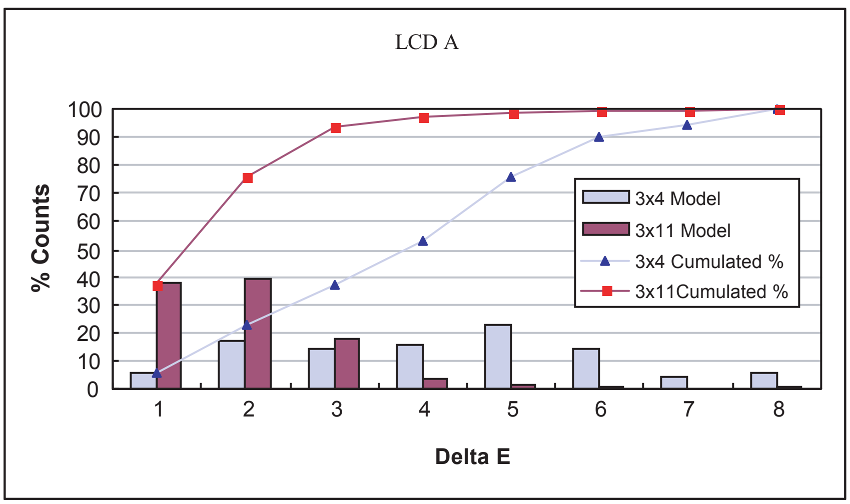

Fig. 4: Histogram of color difference distribution of 3x4 and 3x11 models for LCD A

The distribution of color differences for LCD B calculated through 3x4 and 3x11 models is further analyzed in Figure 5. It was found that 90% of the cumulated values for 3x4 model are around delta E of 6 and 90% of the cumulated distribution for 3x11 model were reached faster again around delta E of 3. From the results it was also found that the 3x11 model performs much better than the 3x4 model, and that the 3x4 model is slightly better than the CMS profiling.

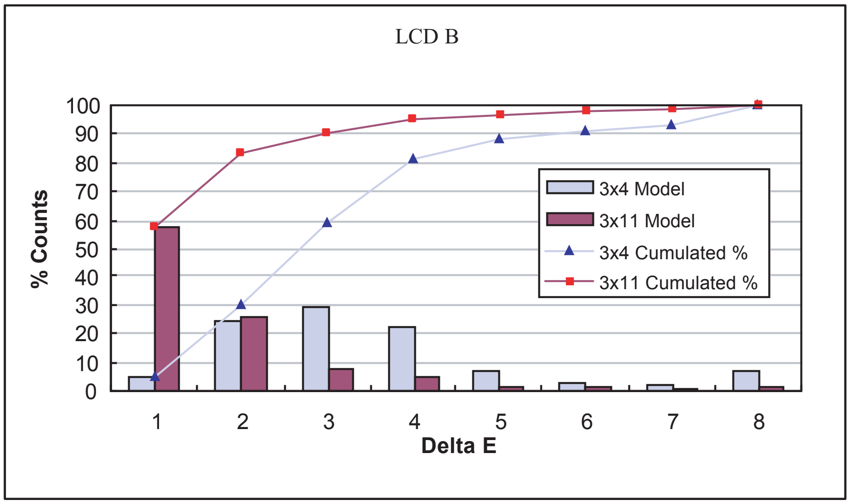

Fig. 5: Histogram of color difference distribution of 3x4 and 3x11 models for LCD B

Comparing the results for LCD A and LCD B one can conclude that the 3x11 model performed better in characterizing both LCD monitors than either the 3x4 model or CMS profiling. The 3x4 model had a similar performance to that of CMS profiling. Mathematically, the more complicated 3x11 model has an inherent advantage over the simpler 3x4 model in modeling the non-linear additive failure in color mixing for LCD monitors. It is assumed then that the CMS profile has a similar structure to the 3x4 model. A further analysis in the ICC profiles used in the experiment was done by using ColorSync Profile Inspector (Apple Computer, 1995). It revealed that the TRC and MatrixColumn tags were used in these profiles, which would result in a performance similar to that of the 3x4 model. This leads to the conclusion that, in this experiment, a matrix mixing model may not be sufficient to characterize the LCD monitors, given their distinct color properties. However, using the 3x11 model can improve the performance in characterizing the LCD monitors.

Conclusions

Two different LCD monitors were tested with three different characterization methods. The 3x11 model resulted in an average color difference of less than delta E of 2 with 90% cumulated around delta E of 3. The 3x4 model had an average color difference around 4 with 90% cumulated around delta E of 6. The CMS profiling method resulted in an average color difference of less than delta E of 4 with 90% cumulated around delta E of 7. It was concluded that the 3x11 model is needed to characterize the tested LCD monitors better, and that the 3x4 model has a similar performance to that of the tested three-component matrix-based ICC profile. By testing these two LCD monitors, it was verified that a good performance in characterizing the CRT monitors may not be applicable to all the LCD monitors for the same kind of CMS profiling tool. A more complicated profile structure like multidimensional lookup table tags may be needed to characterize the LCD monitors better, given their color properties.

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