Customized ICC Display Profile Construction and Concerns

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Abstract

With the advent of modern digital technology, users can capture an image and reproduce it between different media, such as to display it on LCD or CRT monitor, print it on desktop printer, or send it to a printing press. The challenge is then to maintain the accuracy of image colors during this reproduction. This has led to the development of color management systems. Using these systems, the color reproduction across media is accomplished using device ICC profiles that describe each device's color characterization data in a standardized format in terms of a device independent color space (profile connection space or PCS).

ICC display profiles use a matrix transformation or a multidimensional lookup table (LUT) to map the PCS to the device colorant space. The matrix transform may be obtained by linear regression. The LUT, however, is usually constructed based on an estimated characterization device model (using nonlinear regression for interpolation functions fit to a set of measurement data) to speed the transformation performance.

Due to the significant role that monitors play in color management systems, their characterization method needs to be accurate and reproducible. This paper evaluates existing display characterization methods for LCD monitors and uses the evaluation results to develop a new enhanced display characterization method that smooths the display device gamut and reduces measurement noise. A C++ program code is constructed to build a new well-behaved (continuous, differentiable, with continuous derivatives, and invertible) display profile, using

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the resulting values from the new characterization method. The ΔE error is computed to evaluate the accuracy of the characterization.

Introduction

In the imaging system world, where different digital devices exist (e.g., scanners, digital cameras, monitors, and printers), each with its unique color characterization and color space, it is required to have reliable color reproduction among these devices. *Color management* comes into place to assure consistent color transformation and appearance across assorted color devices or media (Adams and Weisberg, 2002).

Controlling and achieving reliable color reproduction across different devices is the main goal of color management systems (CMS). Four main procedures (Sharma et al., 2008) need to be employed, as part of CMS manipulation, to achieve accuracy. Two procedures involve *calibrating* and *characterizing* each device that is involved in the transformation (Adams and Weisberg, 2002). The device needs to be optimized prior to calibration, to achieve *consistency* (the third procedure) in its behavior. Without consistency, especially in forward and reverse transformations, the whole CMS is worth little. Device calibration involves adjustment of device response in order to match an established condition (Wallner, 2002). Characterizing the device involves using instruments, such as a colorimeter and spectrophotometer, to measure the device response for color signals (from color test charts) that are sent to it. As a result of this procedure, the gamut of the device is calculated and the characterization data are used to create a special computer file called an "ICC Profile," which is an important part of the CMS (Bala, 2003).

The *converting* process is the fourth process in CMS, which involves converting an image between two different color spaces via the ICC profile. For instance a printer profile would be employed to convert a displayed RGB image into printer CMYK color space, in order to print it (Sharma et al., 2008). Therefore, an accurate ICC profile would result in an accurate color conversion between different color spaces.

The first version of the ICC (International Color Consortium) profile was developed in 1993, as a result of establishing the ICC (Reinhard at al., 2008). The main reason to create such files is to ease mapping color across different imaging devices (scanners, monitors, printers, etc.) by using each device's color characterizations data that are stored in special tags to remap the device color space to a standard color space (PCS or profile connection space) to establish a communication across different devices.

The data inside an ICC profile are divided into three main parts: a fixed size profile header, which includes homogeneous information that can be found in all profiles, a variable size tag table, and the tagged element data (Wallner, 2002).

For accurate color space conversion to and from the PCS, two algorithm models are used: the matrix/TRC model and the LUT (lookup table) model. Therefore, ICC profiles are divided into two models (matrix-based and LUT-based profiles), based on the calculation algorithm that is used to convert between color spaces (Reinhard at al., 2008). The type of the profile model is determined by the user of the profiling software.

For implementing these models, each model is required to have a special set of data, which are stored in a special tag type (Reinhard at al., 2008). Therefore, the color management model (CMM) will use these data in performing the conversion between different color spaces through the standard PCS color space.

The Matrix/TRC Model

This model structure involves:

PCS (CIEXYZ) ⇨ 3X3 matrix ⇨ one dimensional LUT ⇨ Color component

The three one-dimensional LUTs are represented by the Tone Reproduction curves (TRC) for red, green, and blue channels (Sharma, 2004). To transfer color between input and output tables, a linear interpolation calculation is performed (Rao et al., 2005). In this model the PCS will only use the CIEXYZ standard color space (ICC, 2004). The Matrix/TRC model is generally valid for CRT displays, but it can be useful for any device for which the transformation to the PCS is nearly linear.

For displays, the TRC curves also determine the gamma value of the display. Therefore, matrix-based profiles are generally used in monitors, or RGB devices, and they are simple and produce small size profiles (Sharma, 2004).

LUT Model

In contrast with the matrix-based profiles, the LUT-based profiles are complex and large-size profiles. The following is the LUT model structure (Sharma, 2004):

PCS ⇨ 3X3 matrix ⇨ 1D input LUT ⇨ multi-DLUT ⇨ 1D output LUT ⇨ Color component

The LUT-based profile can be used for all kinds of device profiles, such as input, display, and especially output (Wallner, 2002).

To achieve a consistent color appearance for an image across media, each digital device needs to be accurately calibrated and characterized. The characterization methods for input, display, and output devices are different, depending on the device physical properties. Understanding the fundamentals of each device characterization method is essential for achieving consistent results in a color reproduction system. CRT (cathode ray tube) and LCD (liquid crystal display) are two widespread types of display technologies. E-papers (electronic papers), LED (light-emitting diode display) and OLED (organic light-emitting diode display) are some new developments of display technologies. LCDs have more advantages than CRT in terms of stability, brightness, and sharpness, besides their high resolution, which make them more acceptable as a display device (Bala, 2003). The aim of this research is to develop a new accurate approach for characterizing display devices that smooth the device gamut by minimizing any measurements errors or noise.

Experimental Design

A dual quad tower Mac Pro with two LCD monitors was used to assist this experiment with the following specifications:

Monitors	24-in. Apple Cinema Display, 1920×1200, LED backlight
	20-in. Acer, 1680×1050, Fluorescent backlight
Video Card	ATI Radeon HD 4870
Operating systems	MacOS and Windows

Recalling the fact that the matrix-based profiles are a special case of LUT-based profiles, as their structures are less complex, it is easier to control the transformation matrix in the matrix-based profiles to avoid any noise or error that could affect the transformation procedure. Therefore, the focus of this study was finding the appropriate way to control the native matrix-based profile of different displays.

This study is divided into three phases: (1) evaluating the physical behavior of the monitors, (2) determining the system gamma value and constructing ICC matrix-based profiles based on it, and (3) evaluating the local transformation matrix of the newly constructed profiles. GretagMacbeth ProfileMaker Pro 5.0.8

and X-Rite Monaco PROFILER 4.8.3 software were used to construct all the profiles in this study, with the assistance of an Eye-One Pro spectrophotometer as a measuring instrument.

For the first phase, a set of native white point ICC profiles were constructed for each display using the two profiling software. The constructed profiles represent the two ICC profiles models, i.e., matrix and LUT-based profiles. All the profiles had the same gamma setting (a 1.8 gamma value). The profiles were then selected as the system monitor profile for each display. The main goal of using native profiles was to evaluate the real behavior of the display without any color corrections.

Each evaluated display has a different backlight (LED and fluorescent backlights), and therefore, warm-up and brightness tests were applied to evaluate both displays. For the warm-up test, a uniform square white (255,255,255) and a gray (100,100,100) patch were constructed in Adobe Photoshop CS4 software and displayed alternatively every two minutes. The patches' tristimulus values were measured by the Eye-One Pro Spectrophotometer in the intermediate of each period starting from a cold powered up to a total of 2 hours. For the brightness test, the same white patch was displayed on each monitor. Both displays were set to different brightness levels and the tristimulus value of the white patch was measured at each brightness level.

Phase two starts with controlling the video card gamma of the two displays through the Video Card Gamma Tag (vcgt), which is part of the monitor ICC profile structure. The actual task that is performed by this tag is to adjust the contrast (or the gamma) of the display by adjusting the contents of the video card lookup table (Apple Computer, 1998).

New native white point profiles were constructed, but with a gamma value of 1. The vcgt tag data were read from all the newly constructed profiles by a customized C++ code (designed using Microsoft Visual Studio 2008 VC++ 9.0). The contents of the vcgt tag were constructed as RGB channels. Linear regression, in Minitab 15, was then used to find the slope between each range and the respective vcgt channel value. The inverse value of the graph slope represents the actual displayed gamma for each RGB channel. The average gamma value of the RGB channels will be considered as the native gamma of that certain display. Therefore, new native white point matrix-based profiles were constructed, again for each display, using the newly calculated gamma value as a native gamma. Knowing the primaries' value from the last set of the constructed ICC profiles, local transformation matrices would be obtained and evaluated as the last phase of this study.

Results and Discussions

Figure 1 illustrates the tristimulus values of the displayed white patch under different brightness levels for both tested displays (Acer and Apple cinema). As expected, the XYZ values of the white patch that was displayed on the Apple cinema display decreased with the decreasing of the display's brightness levels. The fluorescent backlight has a different behavior where the XYZ values of the white patch remain stable and then start decreasing when the brightness level reaches 60%. In addition, despite that the brightness level was "0%," the measured XYZs value of the white patch at that level were higher than those for the Apple cinema display and wasn't even close to 0!

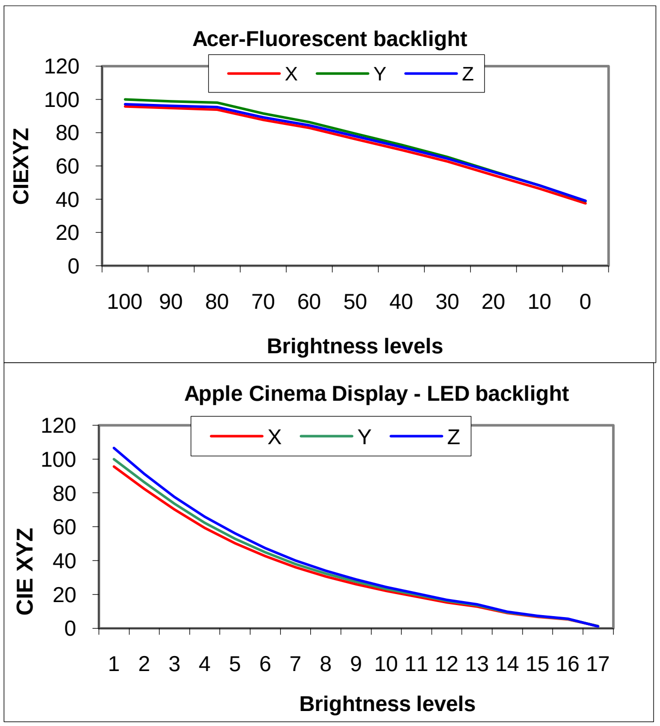

Figure 1. *Brightness levels for both tested displays.*

Figures 2-3 show the tristimulus values of both displayed white and gray patches over the 2-hour warm-up test for Acer and Apple cinema display, where the applied profiles were the matrix-based profiles that were constructed by MonacoProfiler software.

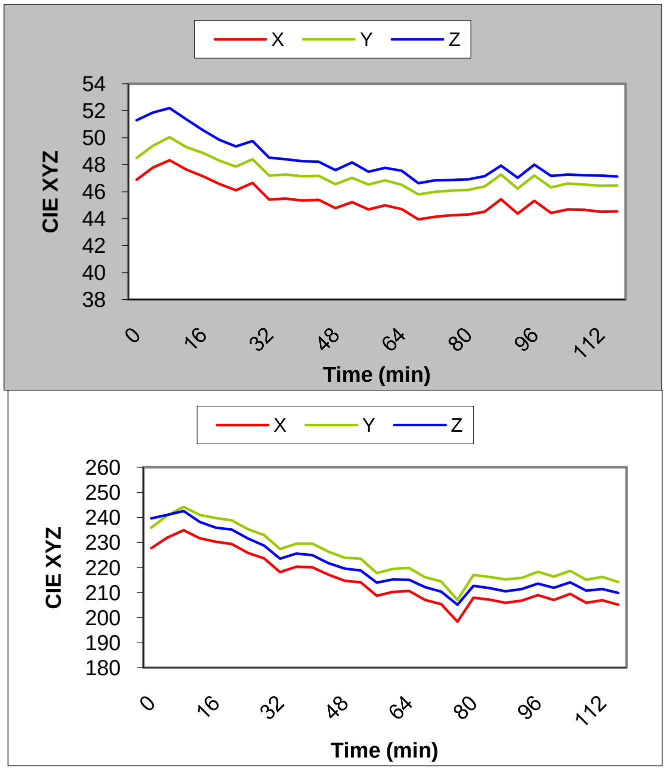

Figure 2. *Warm-up test using gray patch (left) and white patch (right) for Acer display.*

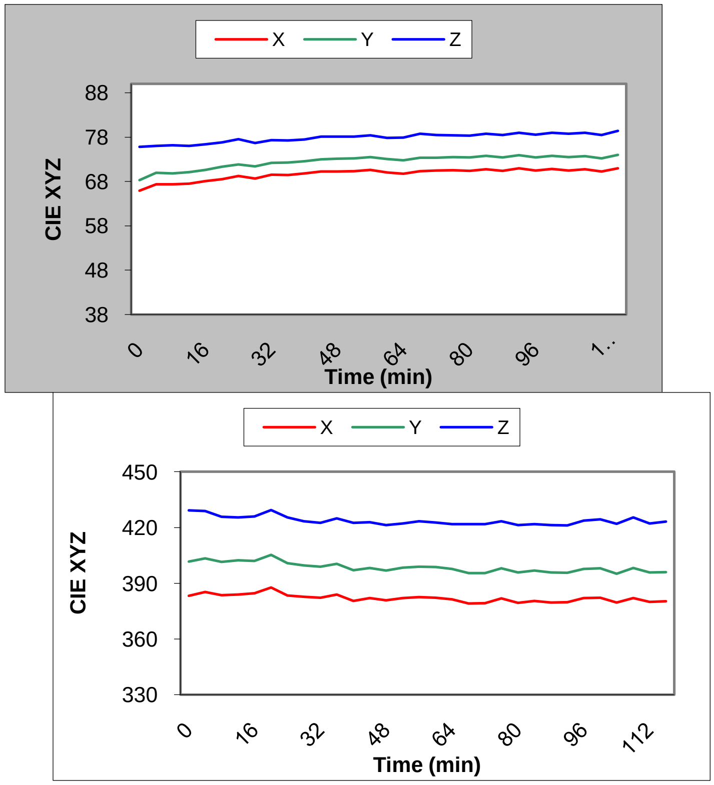

Figure 3. *Warm-up test using gray patch (left) and white patch (right) for Apple cinema display.*

Overall, the measured XYZ for both gray and white patches on the Apple cinema display record higher values than those measured on the Acer display. For the LED backlight monitor, the output levels of the white patch were mostly stable for the whole 2-hour test period and the same results were obtained for the gray patch under all tested profiles (matrix-based and LUT-based). On the other hand, in the case of the fluorescent backlight monitor, the output levels for the white patch were decreased with the passage of the 2-hour time test, where the output levels for the gray patch under profiles that were constructed by ProfileMaker software had a different behavior than those that were constructed by MonacoProfiler. There, the measured XYZ values for gray level under profiles constructed by MonacoProfiler were more correlated to each other than those constructed by ProfileMaker, where the Z values were significant higher.

Next, the average value of the correlated color temperature (CCT) was calculated for the white and gray patches of the whole warm-up test interval for each display, using the measured XYZ values of both patches. Figure (4) shows the CCT of the displayed white and gray patches on the Acer monitor under different native profiles.

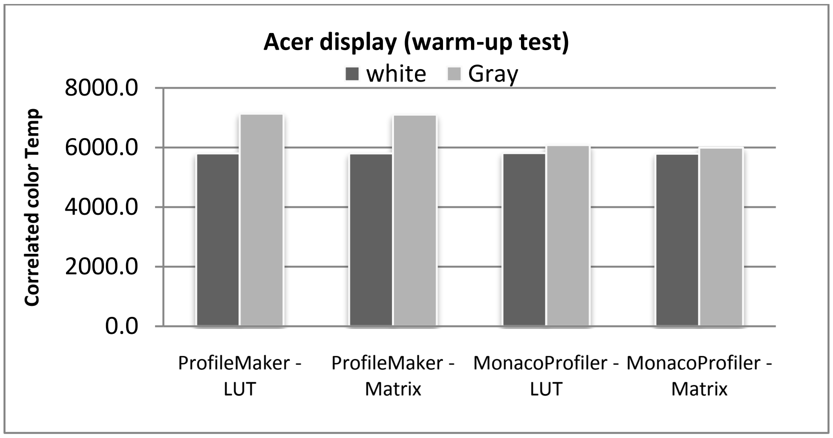

Figure 4. *The CCT (in Kelvin) of the displayed white and gray patches on the Acer monitor under different native profiles.*

For an accurate gray level display, the CCT of the white and the gray patch need to be near to each other. This is not the case for the Acer display. These results might be due the lack of equal gamma in the RGB channels, where equal RGB values should produce a natural gray level.

For the second phase of this study ProfileMaker was the only profiling software that was used to construct the new set of the monitor profiles using a gamma value of 1 due to lack of ability to set the same gamma value in Monaco Profiler software. Figure 5 illustrates one example of fit gamma graph to red channel obtained in Minitab software using matrix-based profile for the Acer display. The axes of the graph represent the log red channel values from the vcgt tag against the log range values.

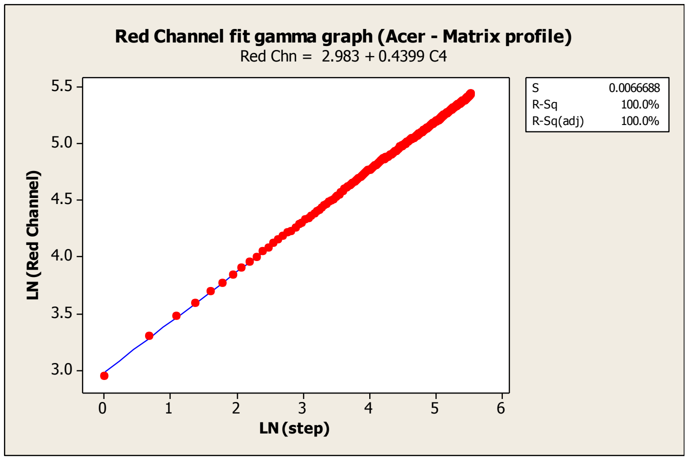

Figure 5. *Fit gamma graph of red vcgt channel in Acer display matrix-based profile.*

The inverse value of the graph slope represents the actual displayed gamma, and in our experiment it would be considered as the native gamma of the display. The calculated gamma value for both displays was very close to 2.2. For accurate behavior of a monitor profile with proper gamma setting, the effective vcgt gamma value should be 1. Thus, the vcgt contents of the matrix-based profiles set that had a 2.2 gamma were read again using the C++ program code and were plotted in Minitab. The result values of the affective vcgt gamma value for both displays were 1, which indicates an accurate behavior of the new set of matrix-based profiles.

The local transformation matrix would be constructed from the contents of the RGB primaries, which can be obtained from the contents of the XYZ matrix data tags (rXYZ, gXYZ, and bXYZ) from the monitor profiles (refer to Appendix – matrix 1 and 2 for both displays). To evaluate the accuracy of this matrix the XYZ values of RGB primaries along with white and black colors were calculated using the obtained matrices based on the following formula:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix} \begin{bmatrix} (R/255)^\gamma \\ (G/255)^\gamma \\ (B/255)^\gamma \end{bmatrix}$$

where γ is the display “gamma” value. Since the output values from this matrix are normalized, the input values (in this case they are RGB color values) were also normalized by dividing them by the maximum color intensity, which is 255. In addition the tested profiles had a gamma value of 2.2, which indicates that the color transformation wouldn’t be linear unless the input values were raised to the gamma power. The same primaries set were displayed in Measure Tool software and measured, and also the measured XYZ values were compared with the calculated XYZ values from the matrix.

Based on the compared XYZ values for the white color, the measured XYZ values gave approximately D_{65} white point values, while the calculated XYZ values from the matrix gave D_{50} white point values. In addition, looking at the white point tag inside all the constructed profiles for both displays, the calculated white point gave a D_{50} white point value (Figure 6).

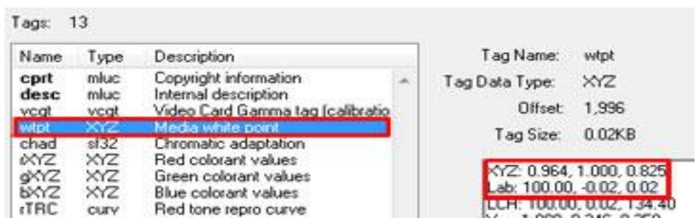

Figure 6. *White point tag value inside matrix-based profile for Acer display.*

Looking for a more correct matrix, the measured XYZ values for the RGB primaries were used as new entries for the newly constructed transformation matrix for each display (Acer and Apple cinema) (refer to Appendix – matrices 3 and 4 for both displays). The same RGB primaries set along with white and black color were used again to calculate their equivalent XYZ values for each display, with the newly constructed matrices. This time, the calculated XYZ values for the white point give approximate D_{65} white point values, which is consistent with the previously measured XYZ value of the displayed white patch. Therefore, these inconsistent results indicate that there is some deficiency in either the ICC profile file itself or the measuring instrument. This requires more investigations.

Another evaluation test for the newly constructed matrix involves constructing a gray scale ramp consisting of a series of gray patches, where its values starts with (0,0,0), (15,15,15) and ends with (255,255,255). The patches were displayed and measured and also were used to calculate their equivalent XYZ values using the newly constructed matrix. The compared XYZ values for all the gray patches in the scale ramps were nearly identical, which indicates good behavior of the constructed matrix.

Omitting the luminance information, the chromaticity of the primaries should remain the same. Thus, the chromaticities (Yxy) of the RGB primaries along with the white patch were calculated using their measured XYZ values and the following equation:

$$x = \frac{X}{X+Y+Z} \qquad y = \frac{X}{X+Y+Z}$$

The calculated chromaticity values were then compared with their equivalents that are recorded in the ICC profiles for both displays. For both displays the compared values were close but not identical, which reflects a well-calibrated display.

Conclusions

Since the evaluation tests verify the accuracy of the new matrix, and based on previous calculations, we were able to determine the native gamma value of a display. Both of these results could be used as an input for a newly constructed matrix-based profile, where a C++ program code would be used to build this new profile. This procedure would overcome the noise or the errors that could have occurred from the profiling software or the instrument itself. If the new matrix-based profiles improved its accuracy, the transformation matrix would then be used to construct the LUT-based profiles, which is the main focus of this study.

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Appendix

Matrix constructed from XYZ matrix data tags of the native white point profiles with 2.2 gamma value for Apple cinema display. The profile was build using ProfileMaker software.	$\begin{bmatrix} 0.43 & 0.39 & 0.14 \\ 0.21 & 0.73 & 0.06 \\ 0.01 & 0.08 & 0.74 \end{bmatrix}$
Matrix constructed from XYZ matrix data tags of the native white point profiles with 2.2 gamma value for Acer display. The profile was build using ProfileMaker software.	$\begin{bmatrix} 0.49 & 0.34 & 0.14 \\ 0.29 & 0.63 & 0.09 \\ 0.03 & 0.12 & 0.68 \end{bmatrix}$
Matrix constructed from measured Primaries for native white point profiles with 2.2 gamma value for Apple cinema display	$\begin{bmatrix} 0.41 & 0.37 & 0.17 \\ 0.21 & 0.73 & 0.07 \\ 0.01 & 0.09 & 0.95 \end{bmatrix}$
Matrix constructed from measured Primaries for native white point profiles with 2.2 gamma value for Acer display	$\begin{bmatrix} 0.49 & 0.31 & 0.17 \\ 0.27 & 0.64 & 0.10 \\ 0.01 & 0.09 & 0.90 \end{bmatrix}$