70.2: Virtual Display: A Platform for Evaluating Display Color Calibration Kits

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Abstract

We propose a method of evaluating the performance of color calibration kits for LCD monitors. Routine color calibration is imperative for critical applications that rely on color fidelity such as digital pathology and professional graphics. However, the commercially available products vary greatly in price and performance with no available evaluation standard. We propose the concept of Virtual Display, a universal display platform that emulates tone reproduction curves. A field programmable gate array board was used to process the video signals based on a pre-programmed look-up table, which contains the tone reproduction curves of the target display. A spectroradiometer-based and a colorimeter-based color calibration kits were challenged by 8 virtual displays that have problematic tone reproduction curves. The results show that both color calibration kits offer only one-dimensional lookup tables for each channel, which might be insufficient. We also spectrally characterized three real displays of different grades and derived spectral models for them. By using the virtual display and spectral models, evaluation of color calibration kits can be greatly simplified and standardized without the burden of optical measurement on target displays.

1. Introduction

To faithfully reproduce colors on the display is a critical requirement for professional users such as radiologists, pathologists, and graphics designers. Before colors can be reproduced, a clear definition is necessary for different devices, programs, or users to communicate. The *sRGB* is the standard color space for displays. The *CIEXYZ* is a device-independent color space, which is calculated by the spectral power distribution of the color and a set of *color matching functions*, which define a standard observer. The coordinates in the CIEXYZ are usually normalized to x, y, and z, where $x+y+z=1$, by eliminating the amplitude or luminance information. Then (x, y) can be plotted on a two-dimensional *chromaticity diagram* to indicate its chroma and hue. The CIEXYZ can be transformed into *CIELAB*, which is a more uniform color space. Uniformity means that the perceivable difference between two colors can be accurately predicted by the Euclidean distance between them, the ΔE [1].

The color reproduction of modern displays is governed by the color management framework. The ICC-based color management system consists of four components. The *profile connection space* (PCS) is an unambiguous color space, usually defined by CIEXYZ or CIELAB, for identifying the color of interest. The *profile* is a file that describes the mapping between the display digital count and the PCS. The *color management module* (CMM) is an OS-level program that performs the conversion between PCS and the display digital count according to a profile. The *rendering intent* is a parameter that specifies which of the 4 possible mappings, defined in a profile, to use when converting colors between two devices with different gamuts [2].

The color calibration process includes two steps: measuring the display with hardware instruments and creating the profile with software programs.

The commercially available color calibration kits vary greatly in price and performance. Sharma and Fleming conducted a study on the performance of such products [3]. In their work, a single LCD was used to test 8 color calibration kits. Adobe PhotoShop was used as the CMM to convert images. Besides the measurements performed by the hardware bundled with the color calibration kits, most evaluation was done in the software domain without considering the effects of the operating system and device driver. Their methodology can screen the color calibration kits that fail to calibrate a good display, which however is not representative.

In this paper we propose the concept of *virtual display*. The basic idea is to build a display platform which can emulate any tone response curve for challenging the color calibration kits. The tone reproduction curves are altered by inserting a color processor between the computer and the display for processing the DVI signals. The color processor was implemented by a programmable circuit such that the tone reproduction curves can be programmed in the circuit as lookup tables. The display color is processed in real-time by the hardware circuit so the modification is transparent to the color calibration kits. In addition, the interception of the DVI signals allows us to examine the transmitted data in the digital domain, which is very useful for determining the behavior of the color manager, the ICC profile, and the graphics card.

The virtual display consists of a computer system, a well-calibrated high-end display and a color processor as shown in Figure 1.

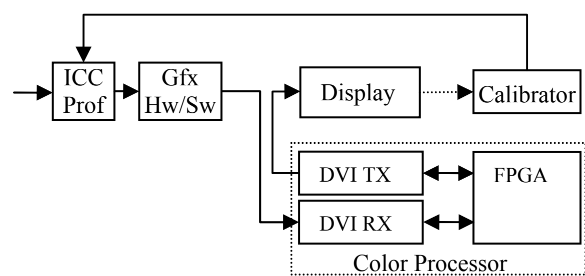

Figure 1: Block diagram of the virtual display.

2. Method

2.1. Color Processor

The color processor was implemented by a field programmable gate array board (Cyclone III QB3, Altera) with a DVI daughter board. A circuit for processing the DVI signals was designed in the Verilog hardware description language. The circuit was compiled by Quartus II V9 and used 3K logic elements, 500 registers, 1K memory, and 2 PLLs.

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The circuit implements three functions: (1) By pressing a button, it can switch between 8 lookup tables for emulating various tone reproduction curves. The details will be described in Section 4. (2) It shows the RGB values of a target pixel in the center for the last 4 frames, which was carried out by drawing the bitmap of the 12 decimal digits in the corresponding positions. This information is required for checking the digital counts sent by the computer and for studying the behavior of the color calibration kits. The target pixel is located near but not on the center such that during a calibration session it will not be covered by the sensor while it is still inside the color patch so that we can peek at its digital count. (3) The color processor writes the 256-byte EDID information into the DVI receiver such that the computer can retrieve the display information of available resolutions. The details of DVI signaling can be found in [4].

2.2. Characterization Method

As the ground truth, a spectroradiometer (PR730 with MS75 lens, Photo Research) was used to measure the spectra of color samples of the displays. A Matlab program was written to generate the color samples, to trigger the spectroradiometer, and to record the measured spectra. The ICC profile was removed such that the raw RGB signals can be delivered to the display without alternation. The display was driven by an nVidia GeForce GTX260 graphics card and device driver 260.99 via a dual-link DVI cable. The measurement was conducted inside a lightproof tabletop enclosure on an air-cushioned optical table.

Four criteria must be tested when examining the gamut charts: white point, gray balance, stability of primaries, and gamut size [5].

(1) White point is the color of the brightest graylevel <255,255,255>. It determines the adaptation level and chromatic adaptation, which are the most important factors for the color appearance. It is also the reference white used to convert to the other color spaces such as the CIELab and CIELuv.
(2) Gray balance represents whether the gray remains in the same chromaticity when the luminance changes.
(3) A stable primary means the chroma and hue of RGB will not change as the digital count reduces. This criterion is almost impossible for LCD displays due to the light leakage and birefringence nature of liquid crystals. However, the hue of a high-quality LCD should not deviate too much.
(4) The gamut size indicates the range of different colors can be displayed. In this paper, the gamut size of a certain digital count is represented by a triangle defined by the primaries on the CIEXYZ 1931 chromaticity diagram. The trend of the triangles shrinking as the digital count decreasing is an indicator of how stable the primaries are. Also note that it is not appropriate to compare the gamut areas with a single number because the CIEXYZ color space is not perceptually uniform as described in Section 1. For example, a display having a larger area in the green region does not necessarily mean that it can reproduce more colors, because the human eye has less resolving capability in the green region.

3. Color Calibration Kits

Two color calibration kits were investigated – X-Rite i1XTreme UVcut and DataColor Spyder3 Elite. We will refer to them as *EyeOne* and *Spyder3* hereafter.

The EyeOne is a spectroradiometer-based kit. The sensor is capable of reading spectra between 380 and 730nm at 10nm resolution. The spectral data can be exported for external analysis or color space conversion. With different attachments, the sensor can be used to measure LCD/CRT displays, light sources, projectors, cameras, printers, and cameras. It came with a standard white patch for self-calibration before each measurement session.

The Spyder3 is a colorimeter-based kit dedicated to flat-panel displays only. The colorimeter (Chroma-5) has 4 color-filtered (transparent, red, green and blue) sensors for measuring the response of the color matching functions. It also has a secondary sensor for measuring the ambient light, which can be used to adjust the brightness automatically when this feature is enabled.

The output of both EyeOne and Spyder3 is an ICC profile, which is the "*display*" class with perceptual rendering intent. The profile contains the CIEXYZ measurements of the white-point and red/green/blue primaries. Each of the RGB tone reproduction curves was modeled by a single gamma value, which was stored in a byte. A "*Video Card Gamma Tags*" (vcgt) section was also generated by both kits. The data structure of vcgt is defined in the ColorSync Manager Reference, Mac OS X Reference Library. It defines the lookup table for each color channel. With limited information, we tried to retrieve these lookup tables from the ICC profiles. The EyeOne stores 3 lookup tables for the RGB channels. Each lookup table has 256 entries. Each entry is represented by 2 bytes in the format of $x1+x2/255$. The Spyder3 also stores 3 lookup tables but each entry uses only one byte. In Section 4, these lookup tables are shown as curves. The results are identical to those shown by using the ColorSync Utility in Mac OSX.

It is well known that changing the default ICC profile is tricky and sticky in Windows XP -- changing the ICC profile in the Display Properties will not be executed immediately. The Spyder3 offers a ProfileChooser utility to solve this problem, but interestingly it does not recognize the ICC profiles generated by the EyeOne. Otherwise, without the digital feedback from our color processor, it is very difficult to confirm the current ICC profile in use. In our experiments, we rebooted the computer whenever a different ICC profile was assigned followed by checking the digital counts of a color ramp.

The calibration process starts with characterization, which was done by measuring a series of color samples. To understand the approaches of the two color calibration kits, we used our color processor described in Section 2.1 to read the digital counts of the color samples used during the calibration process. The calibration target is 6500K and 2.2 gamma in easy mode. The results are shown as follows.

The EyeOne used about 50 color samples. In the beginning, a ramp of 10 gray shades was measured. Then another ramp of calibrated gray shades was measured and fine-tuned. In the second phase, all combinations of 138 and 255 of RGB channels were measured. In the final phase, ramps of the calibrated RGB channels were measured and fine-tuned.

The Spyder3 used about 75 color samples. Four ramps of 16 shades of red, green, blue, and white were measured. Then another ramp of 8 calibrated gray shades was measured and fine-tuned. The cyan, magenta, and yellow shades were not used. The traces of both kits are shown in Figure 2.

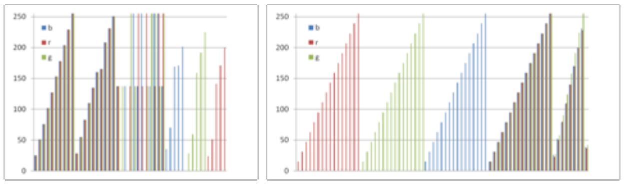


Figure 2: Sequences of color samples used by the EyeOne (left) and Spyder3.

4. Experimental Results

To test the calibration capability of the color calibration kits, eight functions were designed to emulate the common problems of the tone reproduction curve (gamma) found in un-calibrated LCDs. As shown in Figure 3, the abnormal cases in consideration include low (f1) and high (f2) gamma, reverse (f3), discontinuity (f4), and different types of clipping (f5-f8). These curves were programmed into the color processor in a lookup table for the green channel only while the red and blue signals were intact. The manipulation is transparent to the computer and color calibration kit as well as the display.

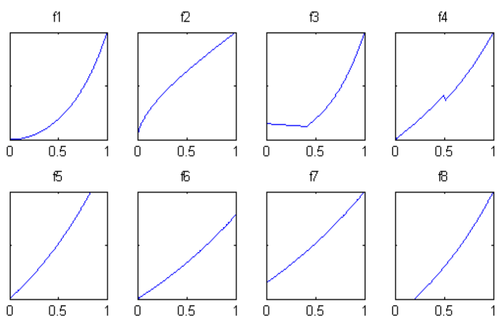


Figure 3: The 8 tone reproduction curves for the green channel used to test the color calibration kits.

The color processor was attached to the Eizo R31 monitor to constitute the virtual display. The measured gamut charts before calibration are shown in Figure 4. Apparently, virtual display 1, 2, 3, and 7 are unacceptable because of the pronounced color shift.

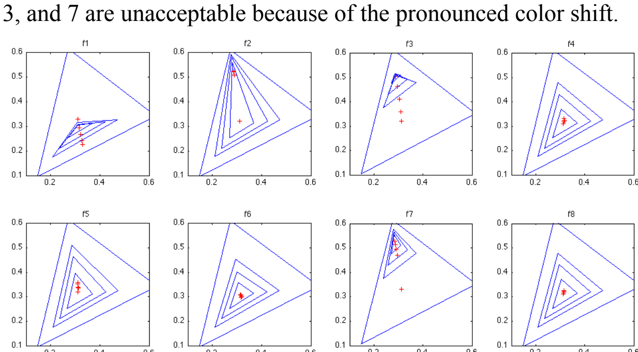


Figure 4: The measured gamut of virtual displays before calibration.

Both color calibration kits went through the calibration process for each virtual display and generated corresponding ICC profiles. Then we used the spectroradiometer to measure the 24 GretagMacBeth color samples on each virtual display with its corresponding ICC profile. Figure 5 shows the measurement results after the calibration by EyeOne. Compared with Figure 4, the color shift of virtual display 1 and 2 was improved significantly.

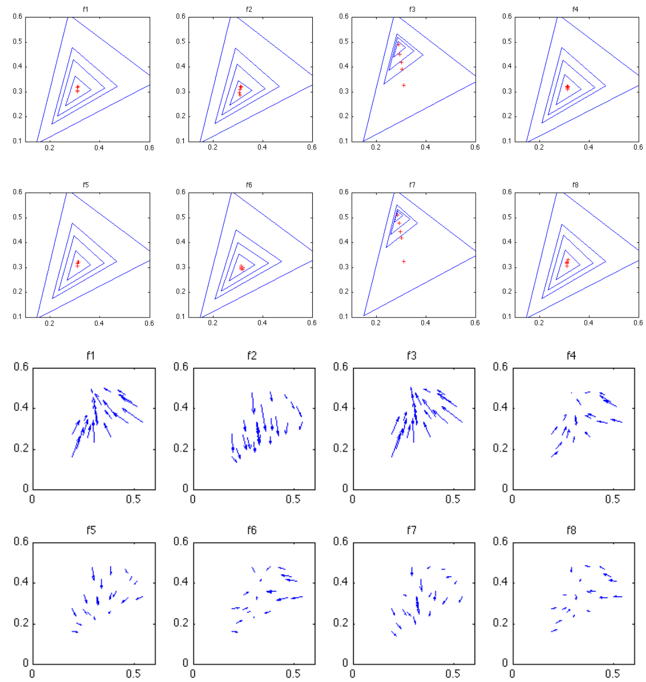
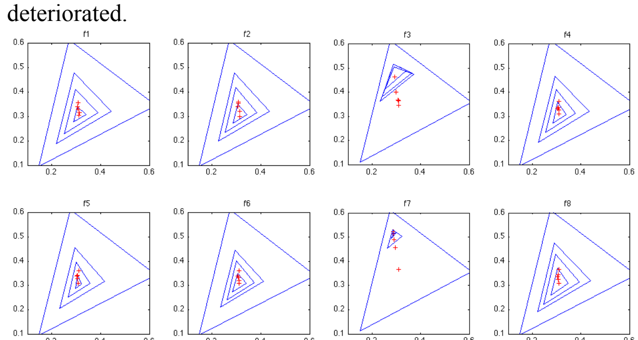


Figure 5: The gamut and color differences of 24 color samples after calibration with EyeOne shown on the CIEXYZ chromaticity diagram.

Figure 6 shows the measurement results after the calibration by Spyder3. Color shift of virtual display 1 and was improved too but the white points of 4, 6, and 8 were deteriorated.



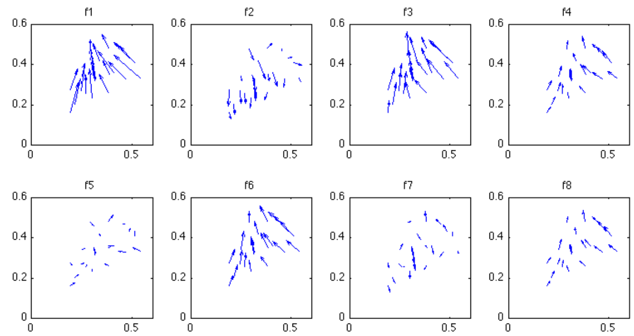


Figure 6: The color differences of 24 color samples after calibration with Spyder3 shown on the CIEXYZ chromaticity diagram.

For each ICC profile, we used the method described in Section 2 to retrieve their vcgt lookup tables as shown in Figure 7. By comparing the curves, one can deduce how the 24 color samples were shifted in Figure 5 and Figure 6. For example, the green channel of virtual display 1 was intensified. Therefore, in Figure 5 the 24 color samples were moved toward green after calibration.

To confirm whether the vcgt data was used to perform the color management, we wrote a Matlab program to remove the vcgt section from the ICC profiles and compared their results. The results showed that color calibration without the vcgt data leads to inferior outcomes. It proves that the vcgt is the key component of both color calibration kits.

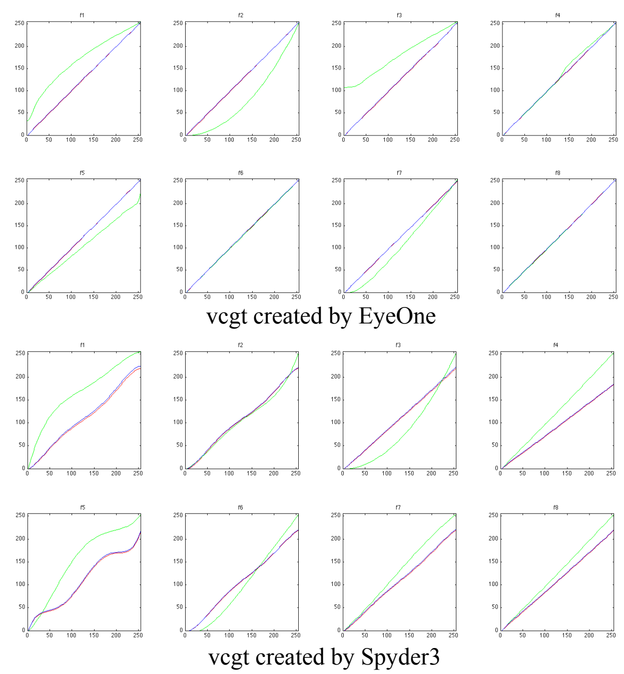


Figure 7: The lookup tables created by EyeOne and Spyder3.

5. Discussion

The gamut size of the virtual display is determined by the gamut size of the real display used and the tone reproduction curves in the lookup tables. The gamut size of the virtual display can be reduced by adding opponent colors, but cannot be enlarged without modifying the display. Therefore, using a wide-gamut real display enables the virtual display to emulate a wider range of gamut sizes.

The resolution of the virtual display is determined by the speed (i.e., circuit timing) of the FPGA in the color processor. Since the FPGA needs to process each pixel sequentially, its processing speed has to be greater than the bit-rate of the display, which is proportional to the product of resolution and frame-rate. For example, 22ns is the timing budget for processing a pixel for the 1024x768x60Hz format. However, this time constrain will be compressed to 4ns for the 2560x1600x60Hz format, meaning that the circuit has to be 4 times faster. In our study, our circuit can support up to 1024x768x60Hz with an entry-level FPGA board, which costs less than US$500. A higher resolution is achievable by using a faster board, more aggressive compiler optimization, and a more efficient design, which will be done in our future work.

The bit-depth of the virtual display is determined by the real display and the DVI transmitter/receiver, so only 8-bit depth is available in the present implementation. However, the bit-depth can be expanded by using temporal dithering.

6. Conclusions

The proposed virtual display is a fast and economical method for evaluating the performance of color calibration kits. Our color processor is not only the key component of the virtual display, but also a powerful tool for examining the behavior of ICC profiles, CMM, and color calibration kits.

In our experiments of virtual displays, the EyeOne performs slightly better than the Spyder3. However, both failed to correct all problematic displays.

The vcgt lookup tables generated by both color calibration kits provide better profiling of the displays but are not defined in the ICC standard tags. Therefore, its utilization depends on the operating system and applications. The Mac OSX computers do take advantage of these lookup tables.

7. Acknowledgements

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