การเปรียบเทียบประสิทธิภาพของแบบจำลองลักษณะเฉพาะ S-CURVE และ LUT สำหรับแอลซีดี

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PERFORMANCE COMPARISONS OF S-CURVE AND LUT CHARACTERIZATION MODELS FOR LCDS

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งานวิจัยนี้ทำการหาแบบจำลองลักษณะเฉพาะที่เหมาะสมสำหรับจอแอลซีดี โดยใช้เครื่องสเปกโทรเรดิโอมิเตอร์ ในการวัดค่าสีและทำการทดลองในห้องมืด ซึ่งก่อนการหาแบบจำลองลักษณะเฉพาะได้มีการทำการทดสอบสมบัติของจอแอลซีดีที่ใช้ได้แก่ สมบัติ Spatial independence, สมบัติ Channel independence, สมบัติ Chromaticity constancy, สมบัติ Spatial uniformity, และสมบัติ Temporal stability หลังทำการทดสอบพบว่าจอแอลซีดีมีสมบัติดังกล่าวที่ดี จากนั้นจึงทำการหาแบบจำลองลักษณะเฉพาะด้วย LUT (Look-up table) และ S-curve โดยวัดค่า chromaticities และ luminance ของตัวอย่างสีจำนวน 729 สีสำหรับการสร้างแบบจำลองลักษณะเฉพาะ 3D LUT และตัวอย่างสีเทากลาง 36 สีสำหรับสร้างแบบจำลองลักษณะเฉพาะ S-curve แล้วนำแบบจำลองลักษณะเฉพาะทั้ง 2 ที่ได้ไปทำนายชุดสีแบบสุ่มจำนวน 200 สี และหาค่าความแตกต่างสี (ΔE^*_{ab}) ระหว่างค่าสีที่ได้จากการทำนายกับค่าสีที่ได้จากเครื่องวัด ซึ่งผลที่ได้จากการทดลองพบว่า 3D LUT มีค่าความแตกต่างสี (ΔE^*_{ab}) เฉลี่ยเท่ากับ 1.8 ส่วนแบบจำลองลักษณะเฉพาะ S-curve มีค่าความแตกต่างสี (ΔE^*_{ab}) เฉลี่ยเท่ากับ 1.3 จากผลการทดลองที่ได้แสดงให้เห็นว่าแบบจำลองลักษณะเฉพาะ S-curve สามารถทำนายค่าสีของจอแอลซีดีได้ถูกต้อง และแม่นยำกว่าแบบจำลองลักษณะเฉพาะ LUT

ภาควิชา วิทยาศาสตร์ทางภาพถ่ายและเทคโนโลยีทางการพิมพ์ ลายมือชื่อนิสิต..........
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This research aimed to evaluate performance of two characterization methods: 3D LUT and S-curve model, for LCD characterization. In the experiment, the colorimetric values were measured with a spectroradiometer in a dark room. Before characterization, the characteristics of LCD monitor were tested, which were spectral characteristics, channel independence, chromaticity constancy, spatial independence, spatial uniformity, temporal stability. It was found that this LCD had good performance for all properties. In the characterization process, two training sets were used: one had 729 sample data for creating 3D LUT and the other had a 36-step neutral ramp for creating the S-curve model. The performance of the characterization models was tested using a test set, which contained 200 random colors. The average color difference (ΔE^*_{ab}) between measured colors and predicted colors from 3D LUT was 1.8. The average color difference (ΔE^*_{ab}) between measured colors and predicted colors from S-curve was 1.3. Thus the S-curve model could predict colorimetric values more accurate than 3D LUT.

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CHAPTER I

INTRODUCTION

At present, a flat-panel LCD monitor is increasingly popular as part of multimedia systems due to its little power consumption and easy-to-handle nature. It has recently gained preference over the use of CRT displays for creating, viewing, reproducing and presenting color images. However, without careful management of data transformation multimedia users would fail to see colors consistency across media. A color that appears on one LCD monitor could appear different on another LCD monitor or on other types of media. Therefore, in order to ensure the consistency of color appearance across media, the use of color management system (CMS) is required. One of the most important elements in CMS is a process of characterization, thereby device-dependent color data are transformed to colorimetric specifications, which are device-independent color data. Accurate colorimetric characterization of display devices has an essential role for achieving device-independent color reproduction. Since characteristics of LCDs are different from CRT monitors, using the same method for characterizing LCDs as that use for CRT would be inappropriate. This was recognized by Fairchild and Wyble [1]. In their study, it was found that the GOG model, a typical model for characterizing CRT, did not fit well with the electro-optical transfer function of the LCD. A number of researches has been carried out to investigate and model the characteristics and colorimetry of LCDs [1-6]. This included the work by Kwak and MacDonald [2-3], in which S-curve type models were developed. In 2002, Tamura et al. [4] proposed a method for LCD characterization called Masking model. In their study, the Masking model had a prediction error of 2.73 ΔE^*_{94} on average. Day et al. [5] studied the accuracy of a 3x4 transformation matrix used in the two-stage process of characterization. They found that characterization would be required at multiple positions and angles so as to achieve sufficient accuracy. The performances of characterization methods were compared in Bastani et al.'s study [6]. This included a 3D LUT, a linear model and a masking model. It was found that a 3D LUT gave that most accurate prediction for LCDs, with the maximum ΔE^*_{94} of 4.2 and the mean ΔE^*_{94} of 0.9. In the study by Kwak and MacDonald [3], S-curve model performed well with the range of CIELAB color difference (ΔE^*_{ab}) of 2.2-3.8. Therefore the 3D LUT and S-curve model seem to be promising methods for LCD characterization. The derivations of the two methods were based on different concepts, resulting in the models having different structure. The performance in predicting colorimetric specifications of LCDs of these two methods should be evaluated and compared. This is because the results from the previous studies could not be directly compared due to the fact that they used different metrics to evaluate models' accuracy and different LCDs for characterization which could have different characteristics and these could greatly affect the performance of the models. The present study thus aimed to evaluate the performance of the 3D LUT and S-curve model in predicting colorimetry of an LCD monitor. The colorimetric characterization was done under controlled conditions, based on measurements at the center of the display and perpendicular to the face. Characteristics of the LCD such as channel, and spatial independence were also investigated. The result of this study would provide useful information for selecting the method of LCD characterization and therefore for the success of color management system.

1.1 Objectives

1. To investigate characteristics of a flat-panel LCD monitor.

2. To evaluate the accuracy of color prediction of S-curve and 3D LUT for LCD characterization.

1.2 Scope of research

This research investigated methods for LCD characterization. Two characterization models, i.e. S-curve model and 3D LUT with linear interpolation, were evaluated with respect to models' accuracy in color prediction. A flat-panel LCD monitor with its white point set to illuminant D65 was used in the experiment. All measurements were made in a complete dark room using a spectroradiometer. The characterization was conducted for the right angle view to the face of LCD panel. The performance of the characterization models was compared in terms of CIELAB color difference between the measured color values and the values predicted from the models. Six characteristics of LCD devices were tested prior to the characterization. These included spectral characteristics, channel independence, spatial independence, spatial uniformity, chromaticity constancy and temporal stability.

1.3 Expected outcomes

An appropriate characterization model for a flat-panel LCD monitor that provides accurate transformation between RGB digital counts and CIE color specifications, so that accurate color reproduction could be achieved.

Content of thesis

Chapter 1 describes background of the present study, objectives, scope of research, and expected outcomes.

Chapter 2 explains the theoretical considerations behind the study and literature reviews that involve in this research.

Chapter 3 contains the experimental set-up and detailed description of experimental methods.

In Chapter 4, the experimental results are presented and discussed.

Finally, conclusions and suggestion of the thesis are given in Chapter 5.

CHAPTER II

THEORETICAL CONSIDERATIONS AND LITERATURE REVIEW

2.1 Theoretical considerations

This chapter has some theories involving this research. First, the mechanism of LCD needs to be addressed (Sections 2.1.1). Section 2.1.2 describes the electro-optical transfer function. Section 2.1.3 expresses a color space and describes RGB color space, CIEXYZ color space, and CIE uniform color space. In Section 2.1.4, the characterization method consisting of device calibration, device characterization and properties of LCD monitor is explained. The main contributions of this thesis are the LUT, described in Section 2.1.5 and the S-curve model, described in Section 2.1.6.

2.1.1 Mechanism of LCD devices

Currently, an LCD or liquid crystal display is the favorite display of computer because it has many advantages: flat panel, slightly weigh, small shape, high resolution, and high performance. The LCD is composed of a back-light illumination source, diffuser, rear linear polarizer, glass sheets with transparent thin-film, indium-tin-oxide (ITO) electrodes and thin-film transistors (TFT), optically active layer of birefringent LC material, absorbing thin-film color selection filters, and a front polarizer. The operation of the LCD depends mainly on the polarization properties of light. Light from the illumination source is plane polarized by the rear (entrance) polarizer. The light passes through the liquid crystal (LC) layer where its polarization state can be altered. Depending on the polarization state after passing through the LC, the light is either absorbed or transmitted by the front (analyzing) polarizer that shown in Figure 2-1.

Three components have the principle effects on the colorimetric and photometric characteristics of the emitted light: spectral power distribution (SPD) of the illumination source; the spectral transmission of the thin-film color selection filter; and the spectral transmission of the LC cell. The largely clear optical elements, such as the glass containing the ITO electrodes, only modify the spectral composition of the light by a small amount. Along imaging path, prior to reaching the human observer, each optical component must be characterized by its full emission or transmission spectrum. The backlight illumination for most LCDs is either a hot-cathode or cold-cathode fluorescent lamp. Fluorescent lamps have the advantages of high luminous efficiency and the ability to tailor the SPD of the lamp via the selection and mixture individual phosphor components and their proportional contributions to the total phosphor blend. Tri-band phosphor mixtures are typically employed to improve color performance for these lamps. The final emission spectra are the weight sum of the three phosphor emissions plus energy at the mercury mission lines. LCDs typically use thin-film color absorption filters to determine the spectral composition of the three primary lights. Only a limited variety of dyes and pigments compatible with LC materials and the LCD manufacturing process exist. Once the filter materials are selected varying the filter thickness and dye concentration can make some adjustments to their spectral transmission, though the value of these parameters must fall within the limits of the thin-film deposition process. The most complex spectral component of the system is the LC layer. The spectral properties of the LC cell depend on a variety of material parameters and geometry of the LC cell. In addition, the spectral transmission depends on the display voltage (i.e. luminance or gray level) and the direction of light propagation.

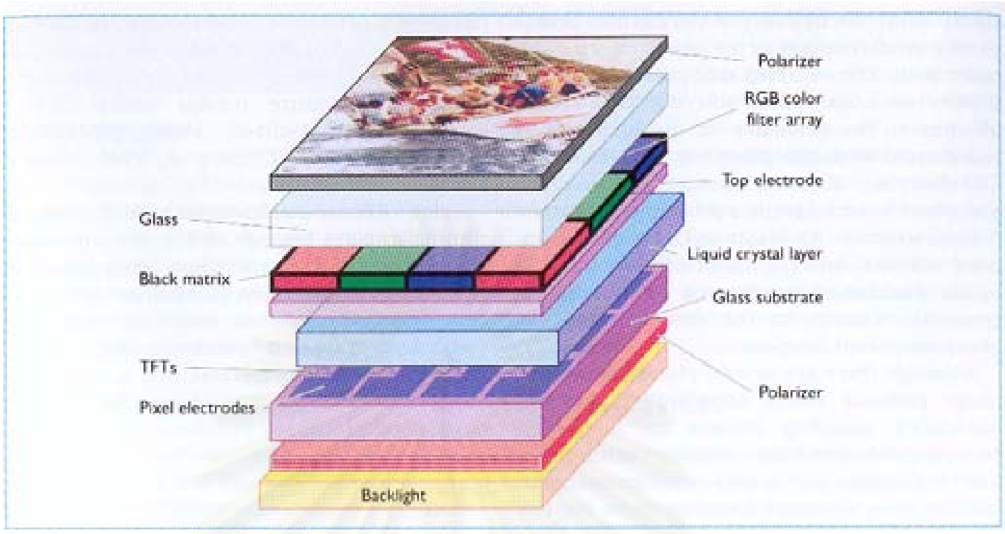


Figure 2-1: The architecture of a transmissive color LC display employing active-matrix addressing [7].

Liquid crystals (LCs) are complex, anisomeric organic molecules that, under certain temperature conditions, exhibit the fluid characteristics of a liquid and the molecular orientational order characteristics of a solid. A consequence of the ordering of anisomeric molecules is that LCs exhibit mechanical, electric, magnetic, and optical anisotropy. Most Lc materials are uniaxial and birefringent. Uniaxial materials possess one unique axis, the optic axis, which is parallel to the liquid crystal director (i.e., the long axis of the molecules). The anisotropic nature of LC materials gives them the optical property of birefringence, which refers to the phenomenon of light traveling with different velocities in crystalline materials depending on the propagation direction and the orientation of the light polarization relative to the crystalline axe. For a uniaxial LC, this implies different dielectric constants and refractive indices for the unique or 'extraordinary' direction and for other 'ordinary' directions in the LC material.

As mentioned above, the predominant LC cell configuration for high-performance color LCDs is the twisted nematic (TN) cell, whose basic principles of operation are illustrated in Figure 2-2. An entrance polarizer linearly polarizes the source light. In the field-off state (panel A), with no voltage applied, the LC layer optically rotates the axis of polarization of the incoming light. The typical twist or rotation angle used for most TN LCDs is 90°, although other twist angles may be used to achieve certain desired optical characteristics. In the field on state (panel B), the dielectric anisotropy of the LC material enables the applied electric field to deform the LC Layer, destroying the twisted structure and eliminating the LC birefringence for normally incident incoming light. The LC layer does not rotate the axis of polarization of the incoming light. The difference in polarization state is the key variable for determining the display output.

After passage through the LC layer, the exit polarizer or ‘analyzer’ analyzes the polarization state of light exiting the LC layer. Light polarized parallel to the analyzer polarization vector is transmitted, light polarized perpendicular to the analyzer polarization director is extinguished, and light polarized at intermediate angles follows Malus′ Law; $I' = \cos^2 \theta$, where (I) is the intensity of polarized incident light from a first linear polarizer, (I′) is the intensity of light output and (θ) is the relative angle between the orientations of the to linear polarizers. Two configurations of TN (twisted nematic) cell entrance and exit polarizers are used. LCDs that use crossed rear and front polarizers operate in the normally white (NW) mode. LCDs with parallel polarizers operate in normally black (NB) mode. The TN cell of Figure 2-2 operates in the NW mode.

The precise polarization state of light exiting the LC cell depends on several liquid cell parameters, including the LC birefringence, LC layer thickness, twist angle, and importantly for us, the wavelength of the light. As a consequence of this dependence, the transmitted spectrum (and thus color appearance) of the display can vary with viewing angle. This variation is an important consideration in the ultimate color performance of LCDs and models of the influence of these parameters are an important element in LCD design. Various methods for compensating for this wavelength-dependence have been developed [7].

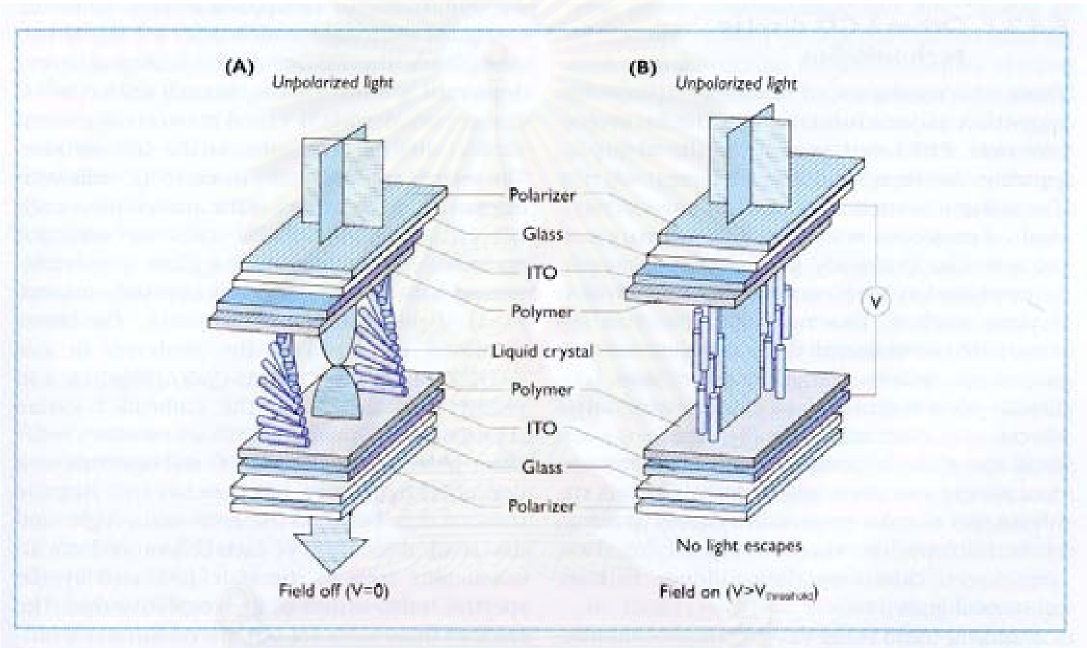


Figure 2-2: The composition of a twisted nematic liquid crystal cell in LCD [7].

2.1.2 Electro-optical transfer function

The electro-optical transfer function is used to describe the relationship between the signal used to drive a given display channel and the luminance produced by that channel. For CRT displays, this function is sometimes referred to as "gamma" and it is the aspect of the display characterization described by the gain-offset-gamma (GOG) portion of the traditional CRT-characterization model. The GOG model properly describes the physics and circuitry of a CRT display and has therefore performed exceptionally well in their characterization. There is no a priori reason to believe that the same function would be appropriate to describe the electro-optical transfer functions of an LCD monitor. Figure 2-3, that has shown the transfer function for an LCD is very different from that of a CRT [1].

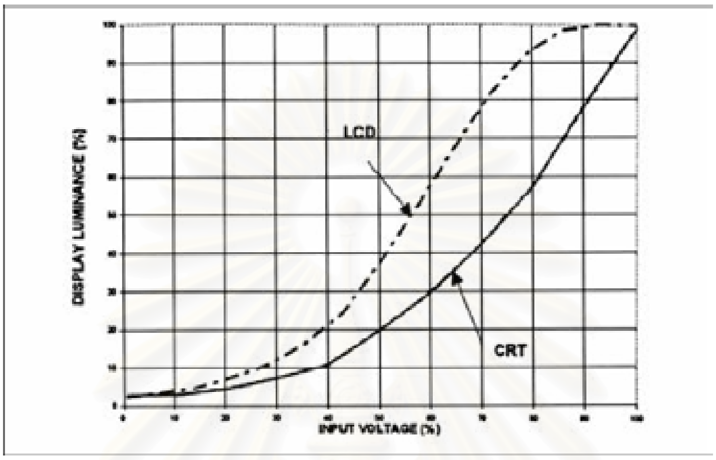


Figure 2-3: Typical electro-optical response functions for a CRT and LCD [1].

2.1.3 Color Space

A color space is a method by which we can specify, create and visualize color. As humans, we may define a color by its attributes of brightness, hue and colorfulness. A computer may describe a color using the amounts of red, green and blue phosphor emission required to match a color. A printing press may produce a specific color in terms of the reflectance and absorbance of cyan, magenta, yellow and black inks on the printing paper. A color is thus usually specified using three co-ordinates, or parameters. These parameters describe the position of the color within the color space being used. They do not tell us what the color is, that depends on what color space is being used. Different color spaces are better for different applications, for example some equipment has limiting factors that dictate the size and type of color space that can be used. Some color spaces are perceptually linear, i.e. a 10 unit change in stimulus will produce the same change in perception wherever it is applied. Many color spaces, particularly in computer graphics, are not linear in this way. Some color spaces are intuitive to use, i.e. it is easy for the user to navigate within them and creating desired coolers is relatively easy. Other spaces are confusing for the user with parameters with abstract relationships to the perceived color. Finally, some color spaces are tied to a specific piece of equipment (i.e. are device dependent) while others are equally valid on whatever device they are used [8].

2.1.3.1 RGB color space

This is an additive color system based on the RGB color space. RGB is shorthand for Red, Green and Blue. Often found in systems that use a display to show images. This color space is easy to implement but non–linear with visual perception. RGB color space defines colors within a unit cube by the additive-color mixing model. This model provides a color stimulus for which the radiant power in any wavelength interval, small or large, in any part of the spectrum, is equal to the sum of the powers in the same interval of the constituents of the mixture, constituents that are assumed to be optically incoherent. Red, green, and blue are additive primaries represented by the three axes of the cube; all other colors within the cube can be represents as the triplet (R, G, B), where values for R, G, and B are assigned in the range from 0 to 1. In an ideal case, the mixture of two additive primaries produces a subtractive primary; thus, the mixture of the red (1, 0, 0) and green (0, 1, 0) is yellow (1, 1, 0), the mixture of the red (1, 0, 0) and blue (0, 0, 1) is magenta (1, 0, 1), and the mixture of the green (0, 1, 0) and blue (0, 0, 1) is cyan (0, 1, 1). White (1, 1, 1) is obtained when all three primaries are added together, and black (0, 0, 0) is located at the origin of the cube. Shades of gray are located along the diagonal line that connects the black and white points. An important characteristic of the additive system is that the object itself is a light emitter such a television. Scanner and computer monitors also use RGB space [9].

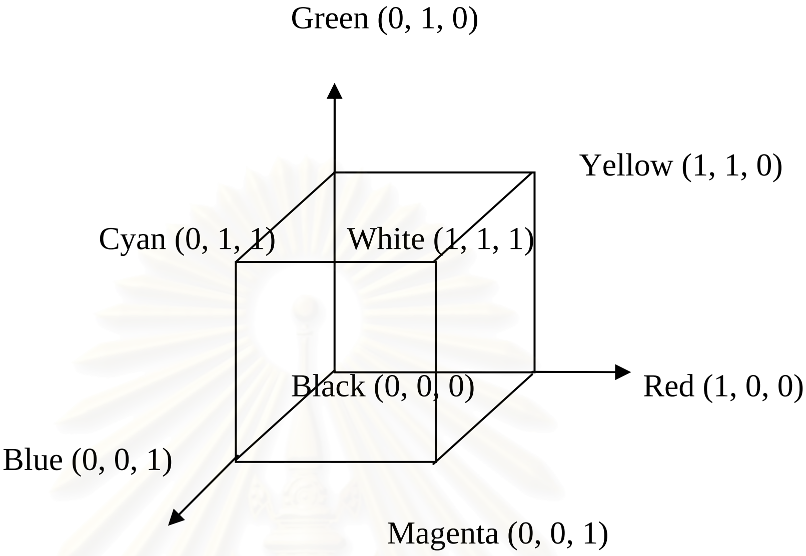


Figure 2-4: The Red-Green-Blue color space [9].

2.1.3.2 CIE XYZ color space

In the study of the perception of color, one of the first mathematically defined color spaces was the CIE XYZ color space (also known as CIE 1931 color space), created by the International Commission on Illumination (CIE) in 1931. The color matching functions in the RGB system has some negative values. In earlier times, when tristimulus had to be calculated manually, the presence of both negative and positive values made the calculations complicated. The color matching function for a different set of reference stimuli can be obtained by a simple conversion of primaries. This allowed the CIE to introduce the 1931 XYZ color system in addition to the RGB color system by establishing reference stimuli [X], [Y], and [Z] in such a manner that the color matching functions have all positive values. Because the XYZ system is based on the 1931 RGB system and thus on color matching experiments at a viewing angle of 2°, it is called the CIE 1931 Standard Colorimetric System or, alternatively, the CIE 2° Colorimetric Observer.

Another characteristic of the XYZ color system is that, in accordance with a proposal of Judd, $\bar{y}(\lambda)$ is set so that it is identical to the spectral luminous efficiency function V (λ). This is convenient because it means that the tristimulus value Y directly expresses a photometric quantity. Another feature of the XYZ system is that the straight line connecting the reference stimuli [X] and [Y] in the chromaticity diagram is tangential to the spectrum locus at the long wavelength end with $\lambda \geq 650$ nm. Because of this, $\bar{z}(\lambda)$ is zero for $\lambda \geq 650$ nm, and the tristimulus value Z can be obtained with the fewer steps of calculation. Moreover, another advantage is that $\bar{z}(\lambda)$ matches approximately one of the basic spectral responsivities of the human color vision system. The CIE XYZ tristimulus values can be calculated by Equation 2.1 [11].

$$
\begin{aligned}
X &= k\int_{vis} \phi(\lambda)\bar{x}(\lambda)d\lambda \\
Y &= k\int_{vis} \phi(\lambda)\bar{y}(\lambda)d\lambda \\
Z &= k\int_{vis} \phi(\lambda)\bar{z}(\lambda)d\lambda
\end{aligned}
\qquad (2.1)
$$

$\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ are the color matching function

k is a constant

For a reflecting object, the color stimulus is $\phi(\lambda)$ that are $R(\lambda)P(\lambda)$, and for a transparent object $\phi(\lambda)$ is $T(\lambda)P(\lambda)$, where $P(\lambda)$ is the spectral distribution of the illuminating light, $R(\lambda)$ is the spectral reflectance of the reflecting object, and $T(\lambda)$ is the spectral transmittance of the transmitting object. For example, the tristimulus values X, Y, and Z of a reflecting object can be express by Equation 2.2 [11].

$$
\begin{aligned}
X &= k\int_{vis} R(\lambda)P(\lambda)\bar{x}(\lambda)d\lambda \\
Y &= k\int_{vis} R(\lambda)P(\lambda)\bar{y}(\lambda)d\lambda \\
Z &= k\int_{vis} R(\lambda)P(\lambda)\bar{z}(\lambda)d\lambda \\
k &= 100/\int_{vis} P(\lambda)\bar{y}(\lambda)d\lambda
\end{aligned}
\tag{2.2}
$$

The constant k is selected such that the tristimulus value Y yields a value of 100 for a perfect reflecting object (R(λ) = 1 for all λ). In general, R(λ) < 1 for any real object color, and Y is therefore < 100. The tristimulus value Y of a reflecting (transmitting) object is called the luminous reflectance (transmittance), is roughly correlated with the lightness of the object color [11].

The three-dimensional nature of color suggests plotting the value of each tristimulus component along orthogonal axes. The result is called tristimulus color space. The two-dimensional X and Y plane of this space can be converted to the chromaticity diagram by Equation 2.3 [12] where x, y and z are chromaticity coordinates, the normalization of the tristimulus value.

$$
\begin{aligned}
x &= \frac{X}{(X+Y+Z)} \\
y &= \frac{Y}{(X+Y+Z)} \\
z &= \frac{Z}{(X+Y+Z)} \\
x+y+z &= 1
\end{aligned}
\tag{2.3}
$$

x, y, z are the chromaticity coordinates

The chromaticity coordinates represent the relative amounts of three stimuli X, Y, and Z required obtaining any color. However, they do not indicate the luminance of the resulting color. The luminance is incorporated in to Y value. Thus a complete description of a color is given by the triplet (x, y, Y) [12].

The 1931 CIE chromaticity diagram is shown in Figure 2-5; the boundary of the color locus is the plot of the color matching functions (the spectral colors). The chromaticity diagram provides useful information such as the dominant wavelength, complementary color, and purity of a color. The dominant wavelength for a color is obtained by extending the line connecting the color and the illuminant to spectrum locus.

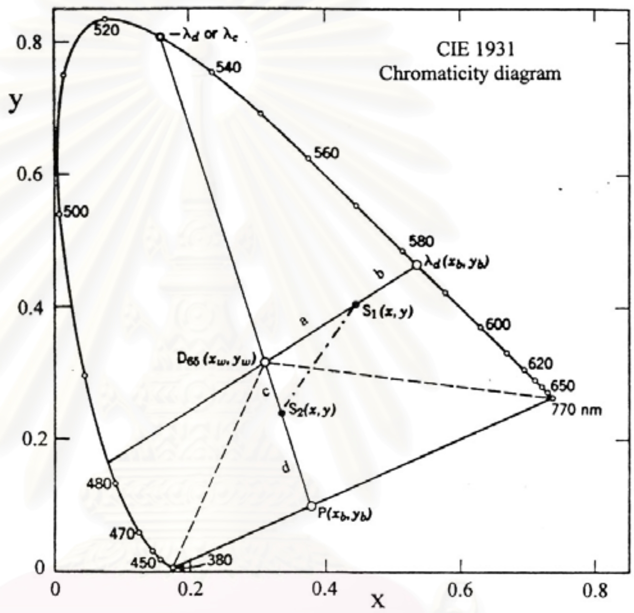


Figure 2-5: xy chromaticity diagram [12].

For example, the dominant wavelength for color s_1 in Figure 2-5 is 584 nm. The complement of a spectral color is on the opposite side of the line connecting the color and the illuminant used. Thus, the complement of the color s_1 is 483 nm under the illuminance D65. A color and its complement when added together in proper proportion yield white. If the extend line for obtaining the dominant wavelength intersects the "purple line," the straight line that connects to extreme spectral color (usually 380 to 780 nm), then the color will have no dominant wavelength in the visible spectrum. In this case, the dominant wavelength is specified by complementary spectral color with a suffix c. The value is obtained by extending a line “backward” through the luminance to spectrum locus. For example, the dominant wavelength for color at point s_2 in Figure2-5 is 530c nm. Pure spectral colors lie on the spectrum locus that indicates a fully saturated 100% purity. The illuminant represents a fully diluted color with purity of 0%. The purity of intermediate colors is given by the ratio of two distances: the distance from the illuminant to the color and the distance from the illuminant through the color to the spectrum locus or the purple line. In Figure 2-5, the purity of color s_1 is a/(a+b) and s_2 is c/(c+d) expressed as a percentage [12]. The X, Y, and Z tristimulus values can be calculated from the chromaticity xy and the luminance Y value by Equation 2.4 [13].

$$\begin{aligned} X &= \frac{xY}{y} \\ Y &= Y \\ Z &= \frac{zY}{y} \\ z &= 1 - x - y \end{aligned} \qquad (2.4)$$

2.1.3.3 CIE LAB color space

The CIE colorimetric system includes computational methods designed to aid in the prediction of the magnitude of the perceived color difference between two given object-color stimuli that are found to mismatch in color. The development of a satisfactory color-difference formula has been recognized as an urgent industrial problem. However, none of the many color-difference formulae that have been proposed in the literature over the past several decades is considered a sufficiently adequate solution of the problem.

The determination of a quantity that suitably describes the color difference an observer may perceive between two given color stimuli rests on the ability of the observer to judge the relative magnitude of two color differences possibly perceivable when viewing two pairs of stimuli. The observer's judgment varies greatly with the conditions of observation and the kind of stimuli presented. Sizes, shapes, luminances, and relative spectral radiant power distributions of the test stimuli and the stimuli surrounding them and making up the display situation, are important factors affecting the observer's judgment. There are a great deal of experimental data available on color discrimination and uniform color scaling, that help to appreciate the complexity of the problem, and that have led many investigators to propose empirical formulae designed to predict observed color differences under certain experimental conditions. Attempts have also been made to develop appropriate mathematical models of the visual processes that govern color discrimination, and then predict, by means of such models, a variety of experimental data. A model of this kind takes on the form of a line element, a measure of distance in a postulated space in which perceived colors are represented by points or vectors.

Thus the CIE recommends the CIELAB color spaces and associated color-difference formulae that were chosen from amongst several of similar merit to promote uniformity of practice, pending the development of a space and formula giving substantially better correlation with visual judgments. The following recommendations are all given in terms of the CIE 1931 Standard Colorimetric Observer and Coordinate System, but also apply to the CIE 1964 Supplementary standard Colorimetric Observer and Coordinate System; in the latter case, the appropriate tristimulus values and chromaticity coordinates must be used.

LAB refer to the coefficients or coordinates of this space, L*, a*, and b*. While L*, a* and b* are not linear transformation of the CIE. This is obvious in the following transformations of CIE XYZ space to CIELAB by Equation 2.5 [14].

$$L^* = 116(Y/Y_n)^{\frac{1}{3}} - 16$$
$$a^* = 500\left[(X/X_n)^{\frac{1}{3}} - (Y/Y_n)^{\frac{1}{3}}\right] \qquad (2.5)$$
$$b^* = 200\left[(Y/Y_n)^{\frac{1}{3}} - (Z/Z_n)^{\frac{1}{3}}\right]$$

with the constraint that X / X_n, Y / Y_n, $Z / Z_n > 0.008856$

In calculating L*, a*, and b*, values of X / X_n, Y / Y_n, Z / Z_n less than 0.008856 may be included if the normal formulae are replaced by Equations 2.6, 2.7, and 2.8 [14].

$$L^* = 903.3(Y/Y_n) \quad \text{for} \quad Y/Y_n \le 0.008856 \qquad (2.6)$$

and

$$a^* = 500[f(X/X_n) - f(Y/Y_n)]$$
$$b^* = 200[f(Y/Y_n) - f(Z/Z_n)] \qquad (2.7)$$

where

$$f(X/X_n) = (X/X_n)^{\frac{1}{3}} \qquad (X/X_n) > 0.008856$$
$$f(X/X_n) = 7.787(X/X_n) + \frac{16}{116} \qquad (X/X_n) \le 0.008856$$
$$f(Y/Y_n) = (Y/Y_n)^{\frac{1}{3}} \qquad (Y/Y_n) > 0.008856$$
$$f(Y/Y_n) = 7.787(Y/Y_n) + \frac{16}{116} \quad \text{where} \quad (Y/Y_n) \le 0.008856 \qquad (2.8)$$
$$f(Z/Z_n) = (Z/Z_n)^{\frac{1}{3}} \qquad (Z/Z_n) > 0.008856$$
$$f(Z/Z_n) = 7.787(Z/Z_n) + \frac{16}{116} \qquad (Z/Z_n) \le 0.008856$$

The tristimulus values X_n, Y_n, Z_n are those of the nominally white object-color stimulus. Usually, the white object-color stimulus is given by the spectral radiant power of one of the CIE standard illuminants, for example, D_{65} or A, reflected into the observer's eye by the perfect reflecting diffuser. Under these conditions, X_n, Y_n, Z_n are the tristimulus values of the standard illuminant with Y_n equal to 100.

The total color difference ΔE^*_{ab} between two color stimuli, each given in terms of L*, a*, and b* is calculated from Equation 2.9 [14].

$$\Delta E^*_{ab} = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\right]^{\frac{1}{2}} \qquad (2.9)$$

The values of the coefficients of the equations defining the CIE 1976 (L*a*b*) space and its associated color difference formula are intended to apply to the observing conditions normally found in practice. However, there is evidence that, in certain situations, different values for the coefficients may be more appropriate. In particular, the weight of the perceived lightness difference between two given color stimuli relative to the perceived chromatic difference between the same two stimuli may, under certain observing conditions, require different coefficients.

The color space defined by Equation 2.5 is called the CIE 1976 (L*a*b*) space. The color-difference formula, defined by Equation 2.9, is called the CIE 1976 (L*a*b*) color-difference formula. The letters CIELAB are used as an abbreviation.

When color-difference formulae are used in practice, it is often desirable to identify the components of color differences in terms of correlates of the perceived lightness, chroma, and hue. It is also often desirable to express color specifications in terms of such correlates. Either one of the two CIE 1976 uniform color spaces and associated color-difference formulae can be used to define appropriate correlates.

The quantity L*, given in Equation 2.4 serves as the correlate of lightness. The quantities C^*_{ab} defined by Equation 2.10 [14] that serve as correlates of chroma and the quantities h_{ab} can be calculated from Equation 2.11 [14].

$$C*_{ab} = \left[(a*)^2 + (b*)^2\right]^{\frac{1}{2}} \qquad (2.10)$$

$$h_{ab} = \arctan\left(\frac{b*}{a*}\right) \qquad (2.11)$$

h_{ab} are hue angles

Hue angles are useful quantities in specifying hue numerically. The angles are given in degrees using the following conventions [14]:

$0° < h_{ab} < 90°$	if	$a* > 0, b* > 0$
$90° < h_{ab} < 180°$	if	$a* > 0, b* > 0$
$180° < h_{ab} < 270°$	if	$a* > 0, b* > 0$
$270° < h_{ab} < 360°$	if	$a* > 0, b* > 0$

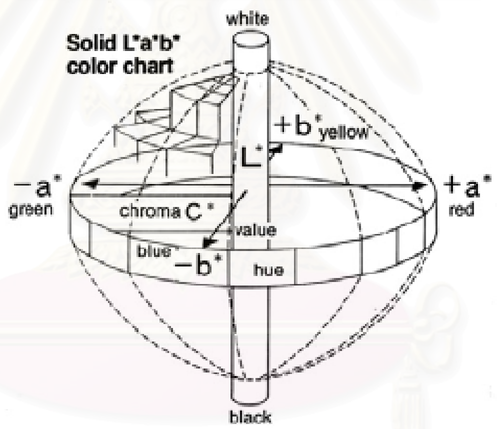


Figure 2-6: CIELAB color space [15].

Figure 2-6 shows the L*, a*, b* color space. The derived quantities saturation (chroma) C* and h (hue) are also indicated. L* is the Lightness that may have values between 0 and 100. a* and b* may have values between around -80 and +80. Colors with no chroma always have the values a* = b* = 0. Because the opponent color theory is used to develop the transformation, one of the coordinate (a*) show the redness or the greenness of the color the other coordinate (b*) shows the yellowness or the blueness. The blueness and greenness are given with the negative sign. In this color space the lightness is perpendicular to the plane of the a*, b* diagram. The a*, b* diagram differs from the CIE chromaticity diagram in an important quality. The colors with no chroma are to be found, for every illuminant, at the zero point of the plane (intersection of two axes). This is achieved by dividing the tristimulus values by the tristimulus values of the ideal white [16].

2.1.4 Characterization method

Achieving consistent and high-quality color reproduction in a color imaging system necessitates a comprehensive understanding of the color characteristics of the various devices in the system. This understanding is achieved through a process of device characterization. One approach for doing this is known as closed-loop characterization, where a specific input device is optimized for rendering images to a specific output device. An alternative approach that is increasingly embraced by the digital color imaging community is the device-independent paradigm, where translations among different device color representations are accomplished via an intermediary device-independent color representation. This approach is more efficient and easily managed than the closed-loop model. The device-independent color space is usually based on a colorimetric standard such as CIE XYZ or CIELAB. Hence, the visual system is explicitly introduced into the color imaging path. A device dependent color space is a color space where the color produced depends both the parameters used and on the equipment used for display. A device independent color space is one where a set of parameters will produce the same color on whatever equipment they are used. The characterization techniques describe to the device-independent paradigm and involve deriving transformations between device-dependent and colorimetric representation. Many of device characterization techniques have been reported. The optimal approach depends on several factors, including the physical color characteristics of the device, the desired quality of the characterization, and the cost and effort that one is willing to bear to perform the characterization [17].

2.1.4.1 Device calibration

Device calibration is the process of maintaining the device with a fixed known characteristic color response and is a precursor to characterization. Calibration can involve simply ensuring that the controls internal to the device are kept at fixed nominal settings (as is often the case with scanners and digital cameras). Often, if a specific color characteristic is desired, this typically requires making color measurements and deriving correction functions to ensure that the device maintains that desired characteristic [17].

2.1.4.2 Device characterization

The characterization process derives the relationship between device-dependent and device-independent color representation for a calibrated device. For input devices, the captured device signal is first processed through a calibration function while output devices are addressed through a final calibration function. In typical color management workflows, device characterization is a painstaking process that is done infrequently, while the simpler calibration process is carried out relatively frequently to compensate for temporal changes in the device's response and maintain it in a fixed known state. It is thus assumed that a calibrated device maintains the validity of the characterization function at all times. Samples of color set for characterization are training set and test set. Training set is a set of color data which is used to create the Characterization model. This data set should cover scope of color on the screen. Another is Test set that is a set of color data used to examine the accuracy of predicted color value of Characterization model. This data set should be different from the Training set. Note that calibration and characterization form a pair, so that if a new calibration alters the characteristic color response of the device, the characterization must also be re-derived [17].

2.1.4.3 Characteristics of LCD

a) Spatial independence

A major assumption of the models is that the luminance and chromaticity at one pixel is stable and not dependent on the setting of other pixels in the display. In reality this is selfdom the case. There are many reasons for spatial interdependence and instability but the most common is power supply overload. A spatial interdependency problem is easy to evaluate and a variety of images can be used. [18] Monitors with poor spatial independence are not reliable since stimuli displayed in one region might affect the color of stimuli in another region. This error of this property that should be below is $1\Delta E^*_{ab}$ when using the monitor's peak white as an estimate of X_n, Y_n, and Z_n in order to calculate CIELAB coordinates [19].

b) Channel independence

Channel independence is the important assumption. The output of one channel at a given pixel is not dependent on the other channel at that pixel. For example, color value from red signal should not be affected by color from both green and blue signal. The influence of one channel on the output of the others was tested by selecting a set of red, green, and blue value compare with white values. Display and measurement tristimulus values of each channel's maximum output and the system's peak white. If the system exhibits channel independence, the sum of the three channels should equal the measured peak white that based on principle of additive imaging [19]. The tristimulus values were transformed to CIELAB using each measured peak white as X_n, Y_n, and Z_n. Color difference were calculated between the white image measurements and the sum of red, green, and blue image. These color difference should be below 1 (ΔE^*_{ab}). Lack of channel independence would correspond to failure of the assumption of additivity in the linear transformation matrix. This could dramatically reduce colorimetric characterization accuracy. Thus overdriving the display in order to improve luminance has many detrimental consequences. Lack of channel independence affects hue, lightness, and chroma [18].

c) Spatial uniformity

Most of the analyses performed have been concerned with a single portion of the display. For images, the entire display area is important. All displays exhibit a lack of uniformity in term of their measured radiant exitance of resulting in varying luminance and chromaticity. This is due to difficulties in compensating for an increased path length toward the edges of a screen for nonradial screens, nonuniformities in applying the phosphors onto the faceplate, and external effects such as local temperature differences and magnetic fields. The nonuniformity affects both luminance and chromaticity of display and the model parameters were affected. In the case of correcting the entire screen when display images, do not make any corrections but use the transformation matrix derived from measuring the center of the display. For the most displays, the lack of uniformity is below the visual system's contrast threshold to low spatial frequencies and, as a consequence, it is reasonable to ignore this problem [18].

d) Chromaticity constancy

Chromaticity changes of primary colors depend on the drive signal level of each channel were evaluate. In chromaticity diagram, the chromaticities of each channel varied with the input level and approach that of black as the input level approach zero because the chromaticity of black arises from the leaked light through LC (liquid crystal) cells and this leak light is always added to any color. Therefore the chromaticities could be corrected by subtracting the black values.

If the chromaticities of primaries were constant, the chromaticities should vary along straight line from maximum point to black point and after black correction the chromaticities from each channel should fall on the same points [2]. A good screen should have a constant chromaticity which is independent from the different luminance level. This is an important characteristic for positive color mixture prediction. If chromaticity of primaries in the display vary with display level, a simple 3x3 matrix transform could be used to convert RGB tristimulus values to CIEXYZ tristimulus values [1].

e) Temporal stability

There are two common causes of temporal variations in many types of display: those caused by warm-up and lifetime decay. CRTs and LCD panels (as a result of their backlight) take a significant time to warm up after being turned on. This can be long as 45 to 60 minutes during which time the luminance of a uniform patch will gradually increase by as much as 20%. There may also be significant color changes during this period. The magnitude of this effect is proportional to the total light that has ever been emitted from the tube. Thus, presenting very bright stimuli for long periods will cause it to happen faster. Typical magnitudes of this phenomenon can be a 50% decrease in luminance across a few thousand hours [20].

2.1.5 Look-up Table (LUT)

The three-dimensional (3D) look-up table with interpolation is a relatively in color space transformation. It consists of three parts that are packing (or partition), extraction (or find), and interpolation (or computation). Packing is a process that divides the domain of the source space and populates it with sample points to build the lookup table. In general, the table is built by an equal-step sampling along each axis of the source space as show in Figure 2.6. This will give $(n-1)^3$ cubes and n^3 lattice points where n is the number of levels. The advantage of this arrangement is that it implicitly supplies the information about which cell is next to which. Thus, one needs only to store the starting point and the spacing for each axis. Generally, a matrix of n^3color patches at the lattice point of the source space is made, and the destination color specifications of these patches are measured. The corresponding values from the source and destination spaces are tabulated into a lookup table. Nonlattice points are interpolated by using the nearest lattice points. This is the step where the extraction performs a search to select the lattice points necessary for computing the destination specification of the input point. A well-packed space can make the search simpler. For nonequally spaced packing, a series of comparison will be needed to locate the nearest lattice point s. Further selection within the cubic lattice points is required. Depending on the interpolation technique employed to compute the color values of non lattice points that are the geometrical method and cellular regression. There are four geometrical interpolations - trilinear, prism, pyramid, tetrahedral and many variations. All geometric interpolations except the linear approach require a search mechanism to find the subdivided structure where the point resides. These search mechanism are inequality. The last step is the interpolation where the input signals and the extracted lattice points are used to calculate the destination color specification for the input point [21].

2.1.5.1 Packing

Packing is the step to divide color space into uniform tiny cubes such as 5x5x5, 7x7x7 and 9x9x9. The smaller size of cubic the more accuracy of the model. However, dividing color space into many tiny pieces of cubic will consume a lot of time and resources to investigate. Figure 2-7 shows a segregation of RGB color space into 5x5x5 cubic.

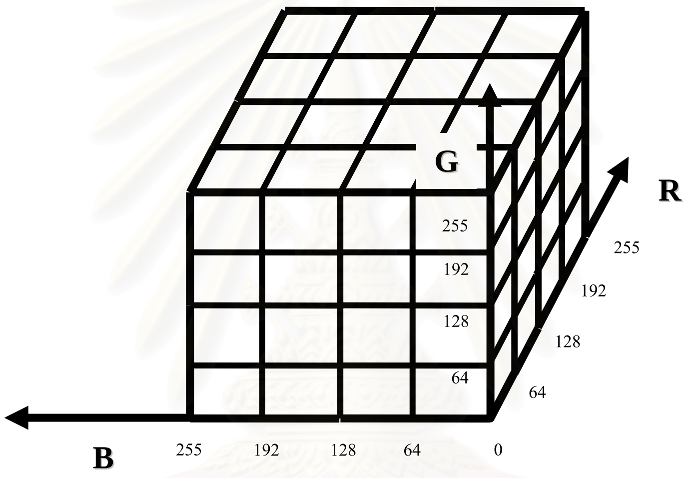


Figure 2-7: Example of 5x5x5 color space segregation.

2.1.5.2 Extraction

Extraction is the step to calculate the predicted color value in specific Color space cubic. The peak of all necessary cubes for specific predicted color value calculation must be found. If the color space is segregated properly, this peak can be easily found.

2.1.5.3 Interpolation

If the required color does not belong to any specific peak of cubic, the interpolation is required for color value average within the cubic. One of the geometrical interpolations is tetrahedral interpolation that is used in this research. The advantage of this interpolation is used only four points to calculate and when used to predict value of training set, the color difference between measured data and predicted data is 0. Descriptions for each step tetrahedral interpolation are:

a) This interpolation divides a cube of color to six parts that had a triangle base, as showed in Figure 2-7[21]. The relationships and coefficient are given in Table 2-1[21].

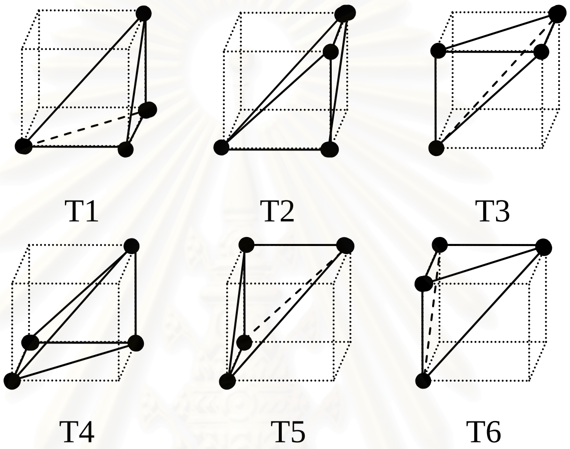


Figure 2-8: Tetrahedral interpolation [21].

b) Find the location of part in cube that can find from Table 2-1. After that, when find the four point of a part of cubic, a color value can be calculated.

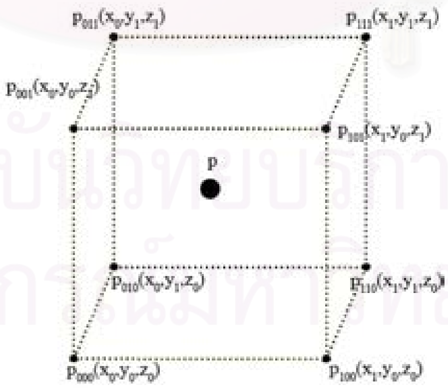


Figure 2-9: Point and cube of color after extraction [21].

c) The predicted color value of 3D LUT with tetrahedral interpolation can be calculated from Equation 2.12 [21].

$$P(x,y,z) = p_{000} + c_1 * x/(x_1 - x_0) + c_2 * y/(y_1 - y_0) + c_3 * z/(z_1 - z_0) \quad (2.12)$$

Table 2-1: The inequality relationships and the coefficients for tetrahedral interpolation.

Tetrahedral	Test	c_1	c_2	c_3
T1	Δx>Δy>Δz	p_{100}-p_{000}	p_{110}-p_{100}	p_{111}-p_{110}
T2	Δx>Δz>Δy	p_{100}-p_{000}	p_{111}-p_{101}	p_{101}-p_{100}
T3	Δz>Δx>Δy	p_{101}-p_{001}	p_{111}-p_{101}	p_{001}-p_{000}
T4	Δy>Δx>Δz	p_{110}-p_{010}	p_{010}-p_{000}	p_{111}-p_{110}
T5	Δy>Δz>Δx	p_{111}-p_{011}	p_{010}-p_{000}	p_{011}-p_{010}
T6	Δz>Δy>Δx	p_{111}-p_{011}	p_{111}-p_{001}	p_{001}-p_{000}

2.1.6 S-curve model

S-curve model was developed from S-shaped characteristics of the electro-optical transfer function of liquid crystal display. The LCD typically has an S-shaped curve, as shown in Figure 2-3. S-curve model has two steps in calculation and uses hyperbolic function that is a mathematical construction, suggested by analogy with Hunt's use of a similar function for retina cone responses. First step is a linear transformation matrix where the R, G, B luminance are transformed to CIE X, Y, Z tristimulus values. This step is calculated by Equation 2.13. The linear transformation in S-curve model assumes constancy of the channel chromaticity for any input level. Step two is non-linear relationship between DAC signal values and monitor R, G, B luminance levels. This step uses hyperbolic function to calculate the luminance values of the display by Equation 2.15 [2-3].

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_{flare} \\ Y_{flare} \\ Z_{flare} \end{bmatrix}_{ambientflare} + \begin{bmatrix} X_{R,\max} & X_{G,\max} & X_{B,\max} \\ Y_{R,\max} & Y_{G,\max} & Y_{B,\max} \\ Z_{R,\max} & Z_{G,\max} & Z_{B,\max} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \qquad (2.13)$$

X, Y, Z	is Sample of XYZ color value obtained from the measurement
X_{flare}, Y_{flare}, Z_{flare}	is XYZ value at minimum digital signal (d_r, d_g, d_b is zero)
$X_{r,max}$, $Y_{r,max}$, $Z_{r,max}$	is XYZ value of red color at maximum digital signal.
$X_{g,max}$, $Y_{g,max}$, $Z_{g,max}$	is XYZ value of green color at maximum digital signal.
$X_{b,max}$, $Y_{b,max}$, $Z_{b,max}$	is XYZ value of blue color at maximum digital signal.
R, G, B	is luminance level of red, green and blue, respectively

$$R_{normlized} = \frac{R}{R_{\max}}$$
$$G_{normalized} = \frac{G}{G_{\max}} \qquad (2.14)$$
$$B_{normalized} = \frac{B}{B_{\max}}$$

The most direct method used to determine the elements of the linear transformation matrix in Equation 2.13, most direct method is to measure the tristimulus values of the red, green, and blue channels at the maximum digital count values. This method depends on a monitor exhibiting excellent channel independence and chromaticity constancy. There is some leakage of light from the LCD. So to calculate the parameters, the tristimulus values of black are subtracted from all measurement data and then added back again to calculate the final output values. The measured XYZ tristimulus values are converted to monitor radiometric scalar RGB values by inverse of 3 x 3 matrix transformation in Equation 2.13. After that the monitor radiometric scalar RGB values are normalized by dividing their respective maximum values (see Equation 2.14). These normalized values are used to calculate parameters for the nonlinear transformation from digital counts to luminance levels of RGB channels using Equation 2.15 [2-3]. The optimum values for A, α, β and C can be obtained by some software optimization programs such as Solver function in Microsoft Excel. It is important to used reasonable starting values and repeats the optimizations using different starting values.

$$
\begin{aligned}
R_{normalized} &= A_r \frac{d_r^{\alpha_r}}{d_r^{\beta_r} + C_r} \\
G_{normalized} &= A_g \frac{d_g^{\alpha_g}}{d_g^{\beta_g} + C_g} \\
B_{normalized} &= A_b \frac{d_b^{\alpha_b}}{d_b^{\beta_r} + C_b}
\end{aligned}
\qquad (2.15)
$$

$R_{normalized}$	is the normalized luminance level of red channel.
$G_{normalized}$	is the normalized luminance level of green channel.
$G_{normalized}$	is the normalized luminance level of blue channel.
d_r, d_g, d_b	is digital count value for red, green and blue, respectively.

2.2 Literature review

There have been a number of researches investigating methods for characterization of LCD. This includes the study by Fairchild and Wyble [1], whereby a flat-panel LCD monitor was characterized using the gain-offset-gamma (GOG) model (a typical characterization model for CRT monitor) and one-dimensional lookup table. The model with LUT followed by a 3 x 3 matrix was included to test the assumption that the prediction errors came from the poor fit of the GOG model to electro-optical transfer characteristics of the LCD. The LUT model performed excellently with CIE94 color differences between measured and predicted colors of approximately 1.0. The result indicated that the typical CRT characterization model, GOG, was inadequate and a different model was needed for accurate characterization of LCD.

Kwak and Macdonald [2] described the characterization of a desktop LCD projector. In their research, measurements were made with a spectroradiometer to establish the additivity of primaries, inter-channel dependence, color gamut, tone scale, contrast spatial non-uniformity, temporal stability, and viewing angle variation. The LCD projector was characterized by four mathematical methods, i.e. PLCC, GOG, S-curve model I and S-curve model II, that were compared for their accuracy in predicting the colors generated by LCD display for arbitrary inputs. S-curve models were newly developed for the S-shaped electro-optical transfer function of the LCD device. The result showed that the PLCC and S-curve model II performed better and the GOG model performed worst. Since the LCD projector lacked the property of chromaticity constancy, S-curve model I, assuming constancy of the channel chromaticity for any input level did not perform well in this study. However, the S-curve type models performed better than the GOG model and had potential for characterizing LCD monitors. Kwak and MacDonald [3] further investigated the performance of the S-curve type characterization models for LCD flat panels and LCD projectors. The results from their study showed that all LC-based displays had similar characteristics, including an S-shaped tone characteristics curve and poor chromaticity constancy. S-curve characterization models based on the hyperbolic function fitted the tone curve very accurately. It was found that the S-curve type models gave more accurate color prediction than the GOG model for all types of LC-based displays, with CIELAB color difference of approximately 2 units.

Bastani, et al. [6] characterized seven different display devices including two CRT monitors, three LCD monitors, and two LCD projectors. In their experiment, the display devices were characterized by a 3D look-up table (LUT) , a linear model, and the masking model. The 3D LUT method mapped color data between RGB digital counts and XYZ tristimulus values directly, while the linear model had two steps in the characterization process: linearising digital inputs with a non-linear function and transforming the luminance outputs to XYZ. Note that for the forward LUT (mapping RGB to XYZ) 3D spline interpolation was used for intermediate values and tetrahedral interpolation was used for backward LUT (mapping XYZ to RGB). The masking model applied the concept of under color removal (UCR) in printing. It was found that the 3D LUT gave the best prediction for LCD devices with the average CIE 1994 color difference of 0.9.

An appropriate characterization model requires not only an accurate prediction of colors but also efficiency in terms of time and storage space in the characterization process. From the previous studies, it was evident that a different method from CRT characterization was needed for LCD devices. Thus, the GOG model is inappropriate. The S-curve model could provide reasonable predictions with small numbers of the training set. Its accuracy depends upon how well the hyperbolic function fits the electro-optical transfer function of the LCD. Moreover, the model was derived based on certain assumptions of LCD characteristics such as channel independence and chromaticity constancy. Consequently, if the LCD lacks some property, the model would give poor performance. The 3D LUT seems to perform best in terms of accurate prediction; however, it requires a large number of measurements, leading to time-consuming process. Its accuracy depends upon the number of colors constructing the look-up table and the method of interpolation. Since the S-curve model and 3D LUT have dissimilar structure, the performance of these two models for LCD characterization is of interest. This study thus investigated the performance of the S-curve and the 3D LUT with linear interpolation for characterizing an LCD monitor. Some characteristics of the LCD monitor were tested to evaluate the performance of the characterization models.

CHAPTER III

EXPERIMENT

3.1 Apparatus

3.1.1 LCD Monitor

Model: EIZO Height Adjustable Stand for Flexscan L767

Size: 19” TFT color LCD panel

Resolution: 1024 x 768 pixels True color

Color: Color quality Highest 32 bit

Pixel pitch: 0.294 x 0.294 mm

Viewing angles (H, V): 170°, 170°

Brightness: 250 cd/m^2 Maximum luminance

Contrast ratio: 500:1

Response time: 25 ms (typical)

3.1.2 Laptop computer:

Model: Intel Core Duo T2300E (1.66GHz, 667MHz FSB)

3.1.3 Display card for controlling LCD: ATI RADEON X1400 with 128MB

3.1.4 Spectroradiometer

Model: Konica Minolta CS-1000A

Wavelength range: 380-780 nm

Spectral bandwidth: 5 nm

Wavelength resolution: 0.9 nm/pixel

Display wavelength bandwidth: 1 nm

Wavelength precision: ± 0.3 nm (median wavelength: 546.1 nm)

Luminance accuracy: ± 2 %, ± 1 digit

Chromaticity accuracy: ± 0.0015x, ± 0.001y

Luminance repeatability: ± 0.1 %, ± 1digit

Chromaticity xy repeatability: ± 0.0002

Polarization error: Less than 5% (400-780 nm)

3.1.5 Software

ACDSee Version 8.0

Adobe Photoshop Version 7.0

MATLAB Version R2006a

Microsoft Office 2003

3.2 Experimental procedure

In this research, the experiments can be divided into three steps. The flow chart of these three steps is shown in Figure 3-1. The first step is the experimental preparations, which include processes of creating experimental images and testing the characteristics of LCD. Step Two is the characterization method, whereby the relationship between RGB digital counts and XYZ tristimulus values is defined by the selected characterization model. Step Three involves the method of testing the performance of the characterization models and the comparison between a 3D LUT and S-curve model. The detailed descriptions for each step are given in Sections 3.2.1, 3.2.2, and 3.2.3, for the steps of experimental preparation, LCD characterization, and models' performance test, respectively.

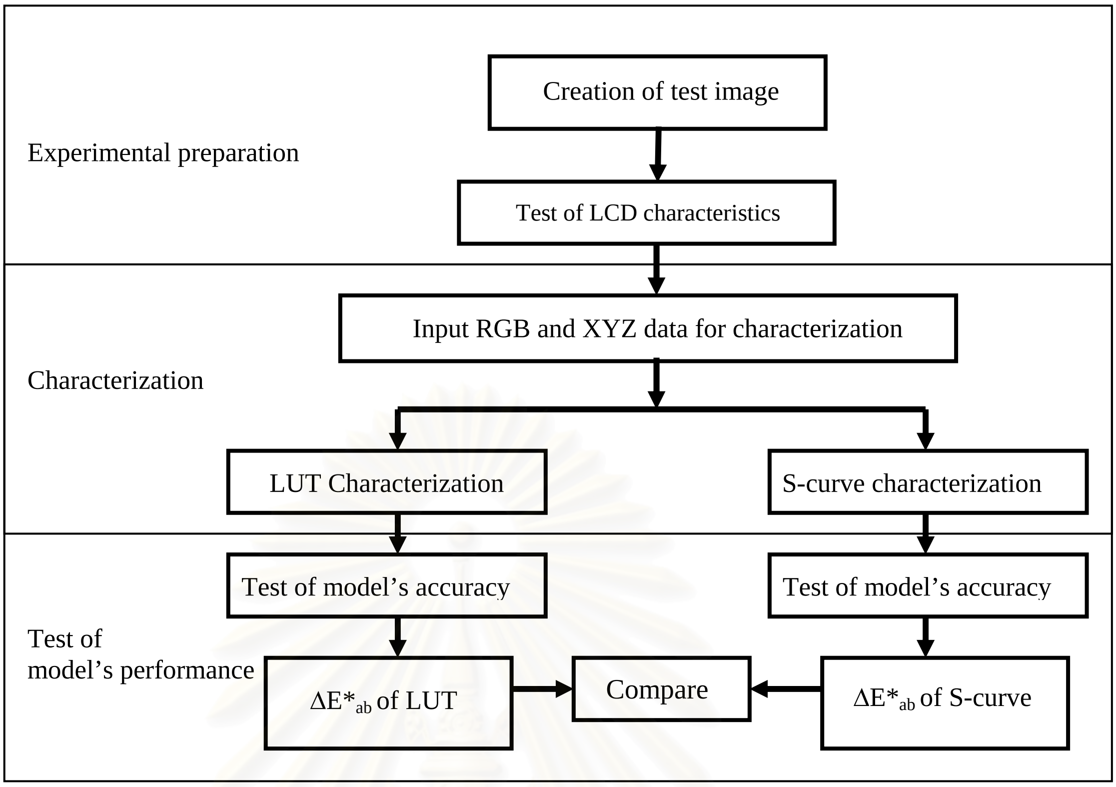


Figure 3-1: A flow chart of experimental procedure.

3.2.1 Experimental preparation

3.2.1.1 Experimental images

The experimental images were classified into seven sets according to the usage of each set. All images were generated using Adobe Photoshop and saved in TIFF file format. A typical experimental image was as illustrated in Figure 3-2. The center color patch was 2” x 2” in size when displayed at 72 dpi; its background was set to black (RGB digital counts equal zero), unless stated otherwise. When displayed for measurements, the image covered the whole LCD screen.

Set 1: For spatial independence test.

There were three images in this set. A white square was presented in the center against neutral backgrounds: white, gray and black (255, 128 and 0 RGB digital counts, respectively).

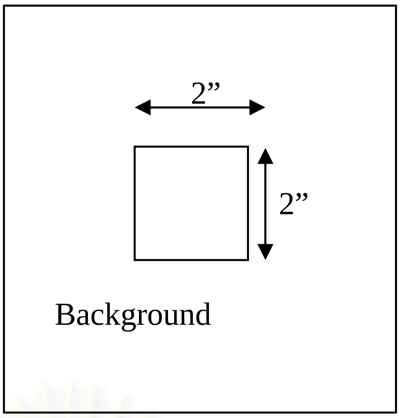


Figure 3-2: Experimental image.

The details of each of the seven image sets are as follows:

Set 2: For channel independence test.

This set included four images; each of them had a gray background (128 digital counts). The color patches were red, green, blue and white (digital counts of 255 for each corresponding channel with the others set to zero for creating the relevant colors).

Set 3: For tests of spatial uniformity and temporal stability.

This set contained only one image. It was a plain white image covering the whole screen.

Set 4: For chromaticity constancy test.

In this set, 16-step ramps of red, green and blue were generated by equally spacing the range of 0-255 digital count (16 units apart) of the red, green and blue channels, respectively. Thus, there were 48 images in total.

Set 5: For establishing a look-up table.

This set was comprised of 729 colors, which generated from a 9 x 9 x 9 color cube with equal steps of RGB digital counts, i.e. 32 units apart.

Set 6: For deriving an S-curve function.

In this set, a 36-step ramp of neutral colors was created. Toward both ends of the ramp, digital counts were sampled at smaller units apart. This was done to serve the purpose of defining the electro-optical transfer function more closely. From 0-50 and 200-255, the colors were created at 5 units apart, and from 50-200, were at 10 units apart.

Set 7: For performance test.

To test the performance of characterization models, the image set other than the set used to derive the model is preferred. Thus, Set 7 was generated with randomly selected colors. There were 200 colors in this set.

3.2.1.2 Measuring condition

Before making color measurements, a 60-minute warm-up time was allowed for LCD to stabilize (except for temporal stability test). The white point of LCD was set to illuminant D65 with the maximum brightness. All measurements were made in a complete dark room with a Konica Minolta CS-1000A spectroradiometer at the distance of 1 m from the LCD screen. The measurement position was at the center of the displayed image (except for spatial uniformity test) and the right angle view of the screen. The colors of displayed images were measured in terms of xy chromaticity coordinates and luminance Y in cd/m^2, unless otherwise stated. These xyY values for 2° observers were transformed to XYZ tristimulus values and L*a*b* values when needed. The experimental images were displayed at 72 dpi using ACDSee software. Figure 3-3 shows the set-up of color measurements.

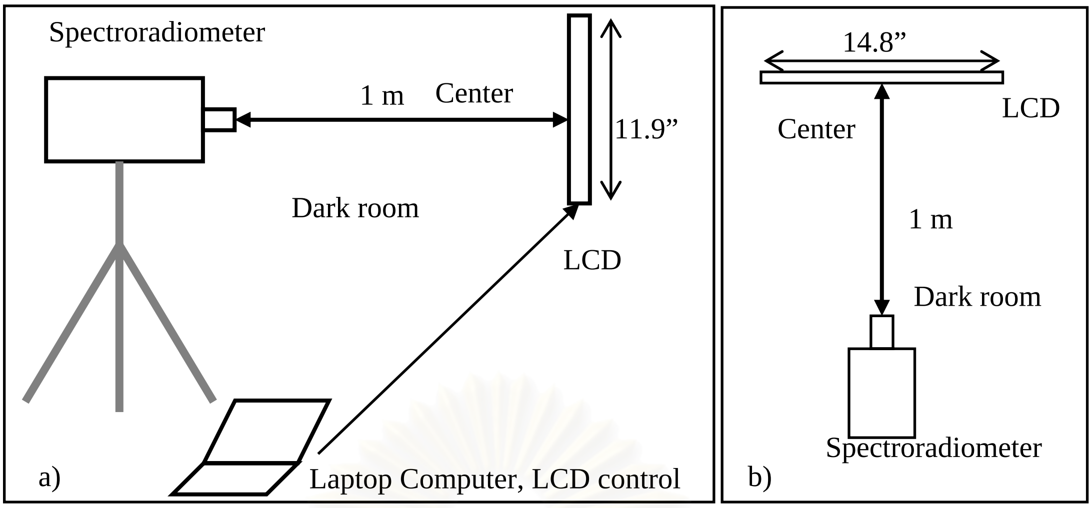


Figure 3-3: Image geometry for measurements a) side view b) top view.

3.2.1.3 Test of LCD characteristics.

The characteristics of display are normally investigated before the characterization procedure is taken place. This is because they have an impact on performance of characterization models. Six tests were included in this study. They were tests of spectral characteristics, spatial independence, channel independence, spatial uniformity, chromaticity constancy and temporal stability. The explanations of each test are given below.

a) Spectral characteristics

This was to investigate spectral distributions for three primaries, a white and a black of the LCD monitor. The spectral radiance characteristics were measured for peak outputs of each individual channel, peak white and the minimum output black.

b) Channel independence test

Channel independence test was carried out to determine whether the color of a particular channel is independent of the other channels. Colors seen on the monitor result from additive color mixing of the colors of red, green and blue channels. The experimental image Set 2 was used for this test. The difference between the display white and the sum of the red, green and blue primaries was investigated in terms of CIELAB color difference (ΔE^*_{ab}).

c) Chromaticity constancy test

The chromaticities of the red, green and blue primaries should be constant at different luminance levels. This was tested by comparing xy chromaticity coordinates of each primary having different steps of display values.

d) Spatial independence test

The aim of this test is to investigate whether a color on one area affects a color on another area. Thus the measurements were done for a white patch displayed against different background colors: white, gray and black (image Set 1). The color values of white on three backgrounds were averaged and CIELAB color difference (ΔE^*_{ab}) were then calculated between the average color and the white color on each background.

e) Spatial uniformity test

For spatial uniformity test, white color was displayed at full screen. The screen was divided into 25 areas, as shown in Figure 3-4. The colors of 25 areas across the entire screen were measured at the center of each area. The CIELAB color difference (ΔE^*_{ab}) between the values averaged from all 25 areas and the values in each area were calculated. In addition, the luminances of each area on the entire screen were compared in terms of percentage with the maximum luminance measured set to 100%.

1	2	3	4	5
6	7	8	9	10
11	12	13	14	15
16	17	18	19	20
21	22	23	24	25

Figure 3-4: Measurement points for spatial uniformity.

f) Temporal stability test

The test of temporal stability was done to find the appropriate warm-up time and the time span of stable period. These characteristics are important for the application of a characterization model, as its performance depends upon them. In this experiment, a white image was displayed on the entire screen once the LCD started up. For the first 45 minutes, measurements of luminance were made every 3 minutes. After that, the measurements were made every 15 minutes up until completion of 4 hours.

3.2.2 LCD characterization

To characterize the LCD monitor in this study, two characterization models were employed. They were a 3D LUT (look-up table) with linear interpolation and S-curve model. The implementation of each model is described in the following sections.

3.2.2.1 LUT with linear interpolation

a) A look-up table was built from a 9 x 9 x 9 training set (images Set 5) to convert color values from RGB digital counts to XYZ tristimulus values.

b) Black correction was done by subtracting the XYZ values of black from the XYZ values of each color, so that XYZ corresponding to minimum RGB digital counts equaled zero.

c) A 3D LUT was then established and for the intermediate values the method of tetrahedral interpolation was employed. This process was done via MATLAB programming (see source code in Appendix A).

d) After obtaining the relevant XYZ values from LUT and the process of interpolation where applicable, the resultant XYZ values were obtained by adding black correction to the values.

3.2.2.2 S-curve model

a) As described in Section 2.1.6, S-curve model is comprised of two stages. First, a 3 x 3 matrix was formed from the measured XYZ values of maximum outputs of red, green and blue channels (see Equation 2.13). Note that all measured XYZ had been corrected for black level before further calculation.

b) Calculated RGB luminances from the inverse of 3 x 3 matrix and measured XYZ of each color of Set 6 image set.

c) Determine the parameters in S-curve function for RGB luminances and RGB digital counts relationship, see Equation 2.15. Note that the parameters were optimized for 36 training colors using the Solver function in Microsoft Excel.

3.2.3 Test of models' performance.

a) The electro-optical transfer function (the relationship between the signal used to drive a display channel, e.g. RGB digital counts, and the luminance produced by that channel) was established for red, green and blue channels. For each channel, the function was formed from output luminances of the 36-step ramp of neutral colors (test image Set 6)

b) The errors between S-curve function fits and the data points plotted were evaluated.

c) To investigate the accuracy of models' prediction, the relevant XYZ values were calculated via LUT and S-curve for RGB inputs of experimental image Set 7.

d) The difference between the XYZ values predicted from characterization models and the measured values was investigated in terms of CIELAB color difference (ΔE^*_{ab}).

CHAPTER IV

RESULTS AND DISCUSSIONS

4.1 Characteristics of LCD

Before carrying out a characterization process, some characteristics of a display should be tested. This is because some characteristics have an impact on the performance of some characterization models and therefore would limit the effectiveness of the models if the display lacks of some properties. Six characteristics were tested in this study and the results are presented in the following sections.

4.1.1 Spectral characteristics

Spectral radiance measurements were taken with the Minolta CS-1000A spectroradiometer for white, black, red, green, and blue having RGB digital counts of (255, 255, 255), (0, 0, 0), (255, 0, 0), (0, 255, 0), and (0, 0, 255), respectively. Spectral radiance characteristics of the display are shown in Figures 4-1, 4-2, and 4-3 for white, black and the three primaries, respectively. The spectral radiance of white illustrates the basic characteristics of the fluorescent backlight utilized in this display. The fluorescent source has a three-narrow band distribution that maximizes emission in three relatively narrow regions of the spectrum. The peak spectral radiance of the white point is about 0.024 W / m^2sr at 545 nm.

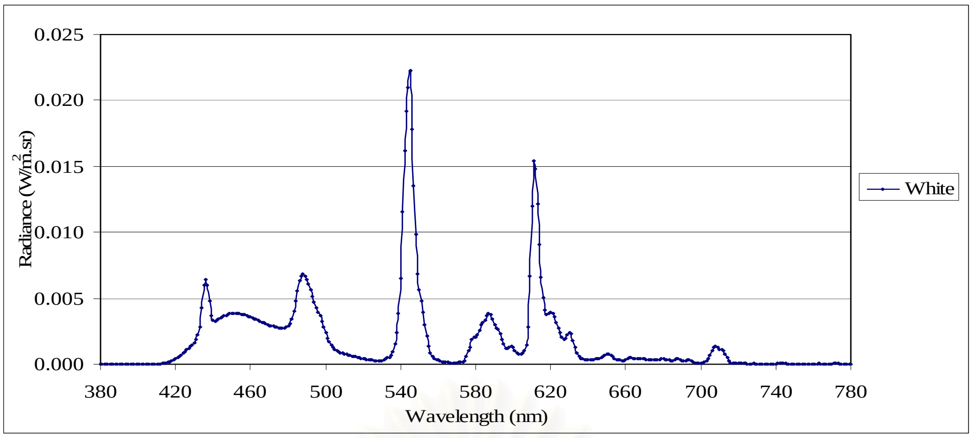


Figure 4-1: Spectral radiance distribution of the monitor white.

As can be seen in Figure 4-2, the spectral distribution of black, the displayed black does not have spectral radiance values of zero. The spectral distribution of the black is similar to that of the white. However, a slight difference can be observed in the blue region of the spectrum, where a bit more amount of energy is emitted for black. The non-zero black radiances are due to a minimal amount of energy that always leaks through the LCD filters. These results agree with those found in Fairchild and Wyble [1]. The peak spectral radiance of the black is approximately 0.000016 W/ m^2sr at 611 nm, or about 0.07 percent of the white.

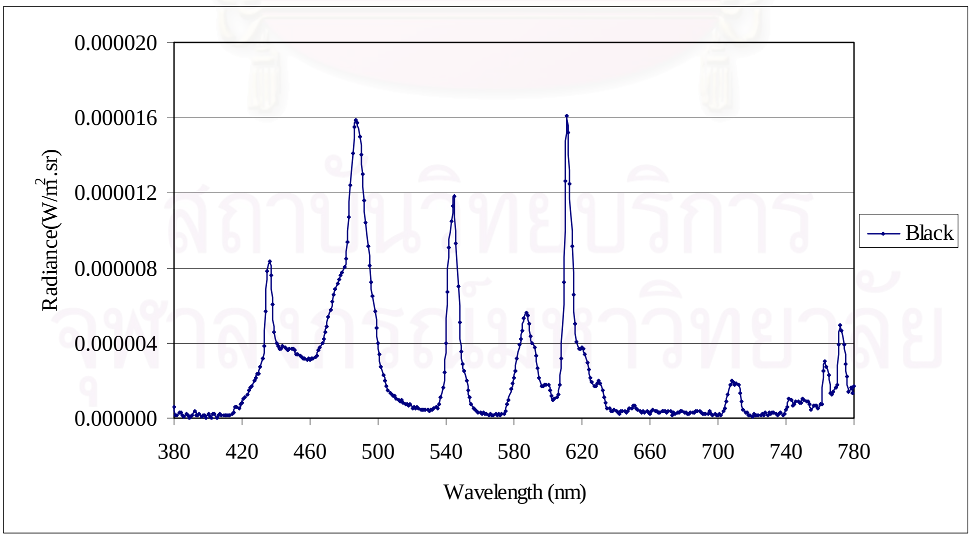


Figure 4-2: Spectral radiance distribution of the monitor black.

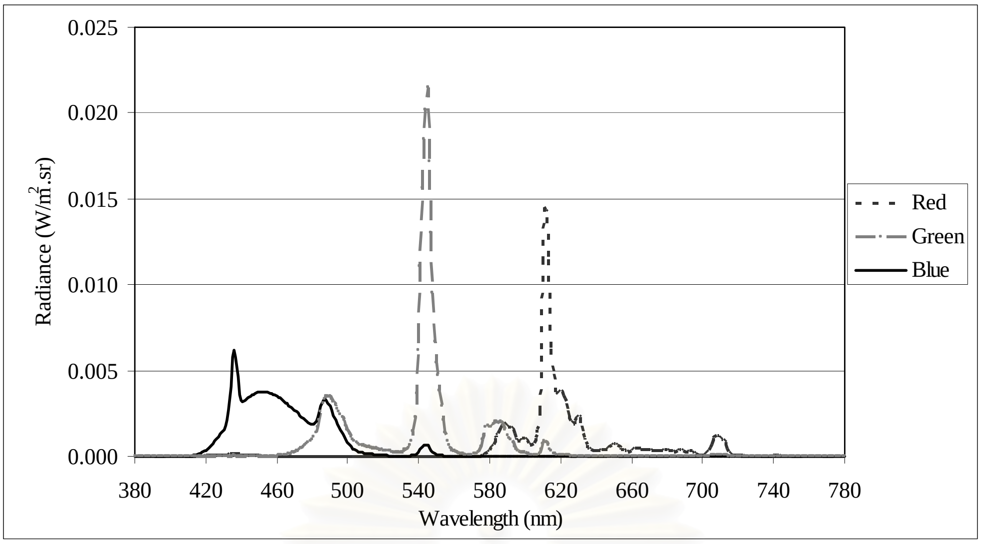


Figure 4-3: Spectral radiance distributions of the RGB primaries.

Figure 4-3 shows the spectral radiance distributions of the separate RGB primaries of the display. This indicates the efficient combination of the broadband RGB filter of the LCD and the narrow-band emissions of the fluorescent backlight. It is apparent that the combination of the spectral distributions of the three primaries does not resemble the spectral distribution of illuminant D65, which is the white point to which the monitor is set. By examining the XYZ values of the measured white point, it was found to be 95.80, 100, and 104.50, which were very close to the nominal values of D65 with its XYZ of 95.05, 100, and 108.88. The measured white point had a correlated color temperature (CCT) of 6123K.

It can also be observed from Figure 4-3 that there is some overlapping between wavelengths of three primaries. This could cause a lack of channel independence characteristic of the monitor. The channel independence characteristic is further investigated in the next section.

4.1.2 Channel independence

The channel independence, sometimes called additivity, of the display was tested by comparing the tristimulus values for white with the sum of the tristimulus values of the individual red, green, and blue primaries. If the display exhibits channel independence, i.e. output from one channel is independent of the other channels, the equivalence between white and the sum should be present. Table 4-1 shows the results of this test. It is clear that the differences were negligible, showing preservation of additivity along the three colorimetric dimensions. Thus the display colors on the display result from the additive mixing of the three primaries. The ΔE^*_{ab} of 0.24 indicated the good performance of the LCD regarding the channel independence.

Table 4-1: Channel independence test results.

<table>
<tr><th>Value</th><th>White</th><th>Sum
(R+G+B)</th><th>% difference</th><th>ΔE^*_{ab}</th></tr>
<tr><td>X</td><td>212.07</td><td>212.06</td><td>0</td><td rowspan="3">0.24</td></tr>
<tr><td>Y</td><td>221.42</td><td>221.12</td><td>0.14</td></tr>
<tr><td>Z</td><td>229.84</td><td>229.78</td><td>0.03</td></tr>
</table>

4.1.3 Chromaticity constancy

Chromaticities of each primary should be constant regardless of input level of each primary. This property was tested by measuring a 16-step ramp from 0-255 of each primary. If the chromaticities of the primaries are constant, the chromaticities with different luminance levels shall fall on the same points in the xy chromaticity diagram. The chromaticity coordinates are plotted in Figure 4-4.

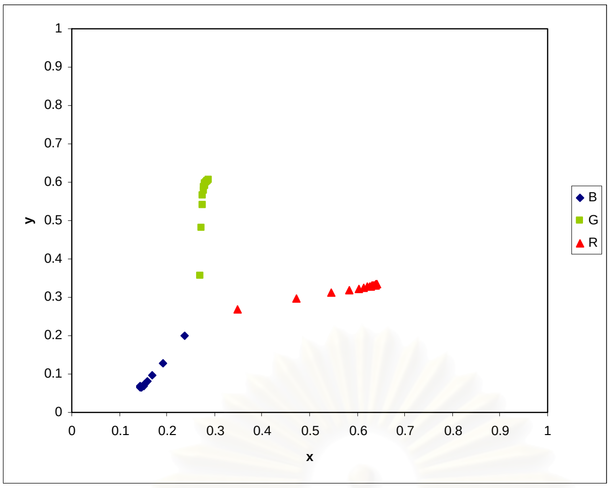


Figure 4-4: Measured chromaticities of red, green, and blue primary ramps.

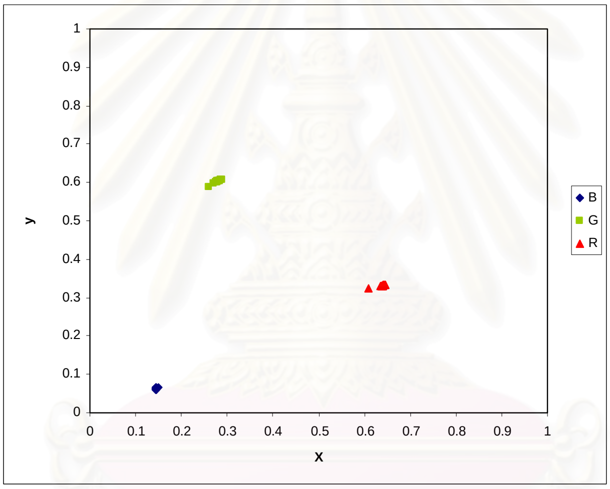


Figure 4-5: Chromaticities of red, green, and blue primary ramps after black correction.

From Figure 4-4, it can be seen that the chromaticities vary along a straight line towards a single point in the center of the diagram. This shows that the chromaticities varied as functions of the luminance levels of primary lights. As displayed level approached zero, the primary chromaticities approached those of the measured display black. This was due to the leaked light through the LCD filters, as discovered in Section 4.1.1. This leaked light is always added to a displayed color. Thus this additive flare should be removed from all of the measurements. This was done by subtracting all measurements by the XYZ tristimulus values of the display black. This method is called black correction. Chromaticity coordinates after black corrections are plotted in Figure 4-5. After black correction, the display clearly showed the characteristics of chromaticity constancy. Quantitative analysis was carried out by calculating average differences in xy chromaticities of primary ramps. The results are given in Table 4-2. It was found that all the differences were less than 0.05, indicating the good performance of the LCD in terms of chromaticity constancy.

From the results found in Sections 4.1.2 and 4.1.3, a 3 x 3 transform matrix for converting from RGB luminances to XYZ tristimulus values could be applied successfully. This is due to the fact that the use of this technique is based on the assumption that the display exhibits channel independence and chromaticity constancy. Note that the matrix can be used effectively after the black correction is done.

Table 4-2: Average differences in xy chromaticities of three primaries.

	Red Average	Green Average	Blue Average
x	0.0045	0.0047	0.0045
y	0.0017	0.0028	0.0017

4.1.4 Spatial independence

A display with poor spatial independence cannot produce reliable color stimuli since colors displayed on one area of the screen affect color stimuli on another area. Spatial independence was examined by measuring color patches presented in a way that its background was alternated. In this study, a white patch was measured on a white, a gray, and a black background. CIELAB color difference was calculated for the white colors measured on different backgrounds. It was found that ΔE^*_{ab} for white on white and on black backgrounds was 0.24, and for white on white and on gray backgrounds

0.19. The average ΔE^*_{ab} across all backgrounds was 0.21. These results showed that there was very little spatial dependence for this display. Thus the spatial independence of the LCD display was very good and not a limiting factor for colorimetric characterization.

4.1.5 Spatial uniformity

Colors, particularly luminances, of the display should be uniform across the entire area, so that the same characterization can be applied to the different spatial locations. The spatial uniformity was evaluated by measuring XYZ values of 25 points of white and calculating the percentage of luminance in each area (Figure 4-6). The percentages of luminance in each area were calculated by taking the maximum value as a reference set to 100% and the other areas were scaled accordingly. Figure 4-6 illustrates the relative luminance across the display area. The results showed that this display had the range of relative luminance between 80%-100%.

Further investigation on spatial uniformity was carried out by calculating CIELAB color difference between the color values averaged from all 25 areas and each of the 25 measured areas across the display. The results are given in Table 4-3. It was found that the ΔE^*_{ab} values were in a reasonable range, 0.66-4.23, with the average ΔE^*_{ab} of 2.12. Thus this display is considered to be fairly uniform and the spatial non-uniformity could be neglected.

Table 4-3: ΔE^*_{ab} distribution across the display.

$\Delta^* E_{ab}$		Horizontal position				
		1	2	3	4	5
Vertical position	1	3.30	1.41	0.66	0.66	2.15
	2	2.46	1.43	2.15	1.27	3.35
	3	2.49	1.78	4.23	2.18	1.65
	4	1.87	2.28	1.84	1.12	0.86
	5	1.62	2.71	2.57	3.34	3.62

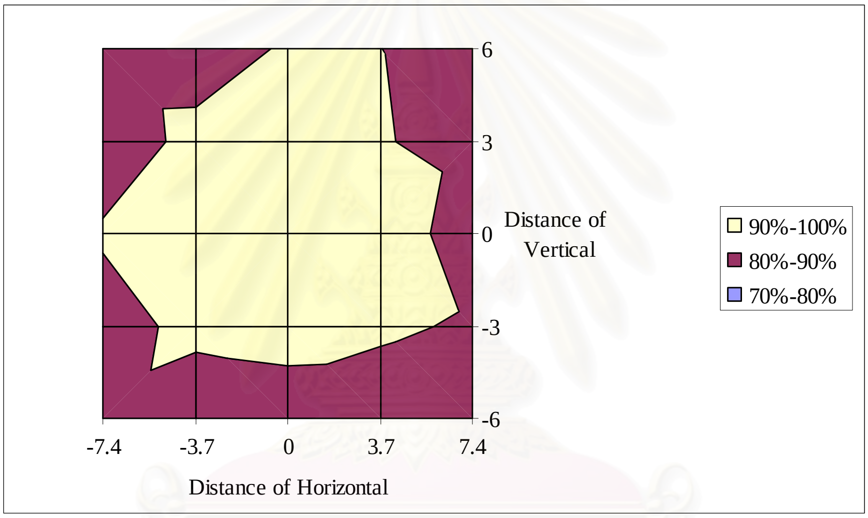


Figure 4-6: The Percentage of luminance in each area of display.

4.1.6 Temporal stability

An LCD has a fluorescent back light that requires warm up time in order to reach stable output. The relationship between luminance of display and time was determined to find the warm up time. A full white (255,255,255) was measured every three minutes for the first 45 minutes, then every 15 minutes up until four hours. Figure 4-7 shows the XYZ values of the display white over the 4-hour period.

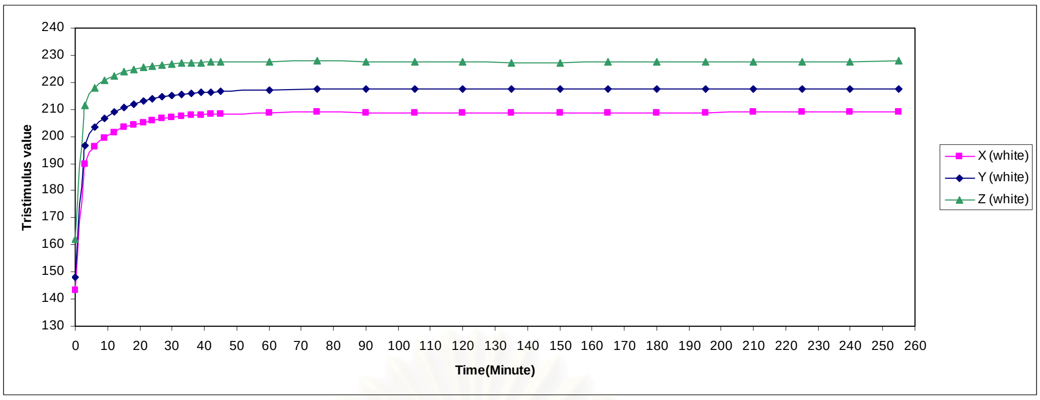


Figure 4-7: XYZ tristimulus values over a 4-hour period for a white color.

The results showed that the XYZ values were stable when the time was over 40 minutes. The output XYZ values increased quickly initially for the first 10 minutes and then slowly increased until reaching the stable level. After 40-minute warm-up period, the XYZ values were at the stable level until the end of 4-hour evaluation. Thus the characterization of this LCD should be carried out after 40-minute warm-up period and the characterization would be valid for up to 4 hours, based on the results of this test.

4.2 Performance of characterization models

Tone characterization means establishing the electro-optical transfer function, which describes the relationship between signal used to drive a display channel and the luminance produced by that channel. Any characterization model that describes this function robustly would perform well in transformation between color data. For CRT displays, the GOG model describes this function very well and therefore gives good performance in the characterization. However, it has been well known that the electro-optical transfer function of a CRT differs from that of an LCD monitor. Thus, to understand the performance of the characterization models tested in this study, the electro-optical transfer functions for red, green and blue channels were evaluated. For each channel, normalized output luminances of 36 steps were measured from digital counts 0-50 and 200-255 with increments 5, and 50-200 with increments 10. The electro-optical transfer functions of the LCD are shown in Figure 4-8.

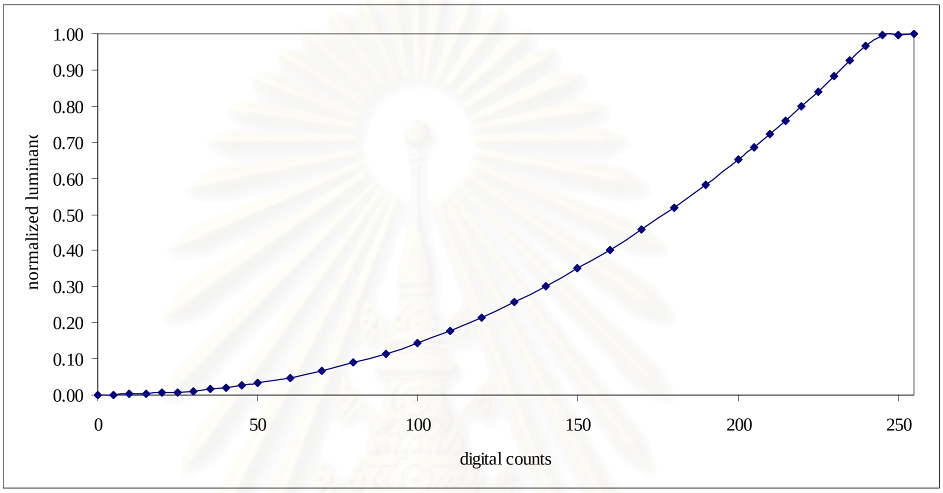


Figure 4-8: Electro-optical transfer functions of three channels of LCD.

It can be seen from the figure that the electro-optical transfer functions for each channel were nearly identical, revealing the monotonicity of the display. It can also be observed that the relationship between digital counts and output luminances was non-linear. Thus for a look-up table to perform well in the characterization, either it is constructed by a large number of data with employment of linear interpolation for intermediate values or it utilizes some forms of non-linear interpolation.

In S-curve, the S-shaped function is applied to describe the electro-optical transfer function between the digital inputs and the RGB scalars. Thus the performance of the model depends on agreement between the derived function and the relationship of these data. Figures 4-9 to 4-11 present how well the S-shaped functions derived fit the training data points for the red, green and blue channels, respectively. Note that the RGB scalars were obtained via the inverse of the 3x3 matrix (after black correction).

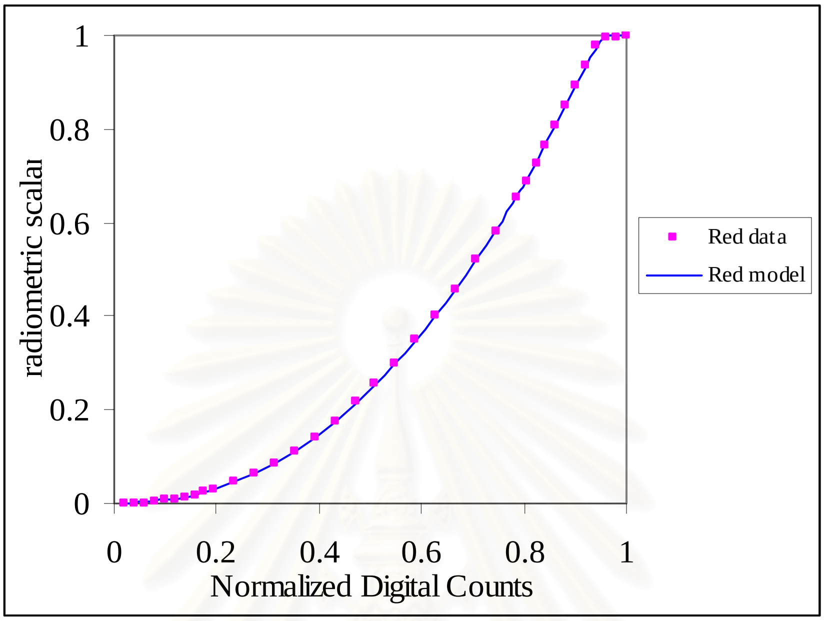


Figure 4-9: Measured data and fitted S-curve model for the red channel electro-optical transfer function.

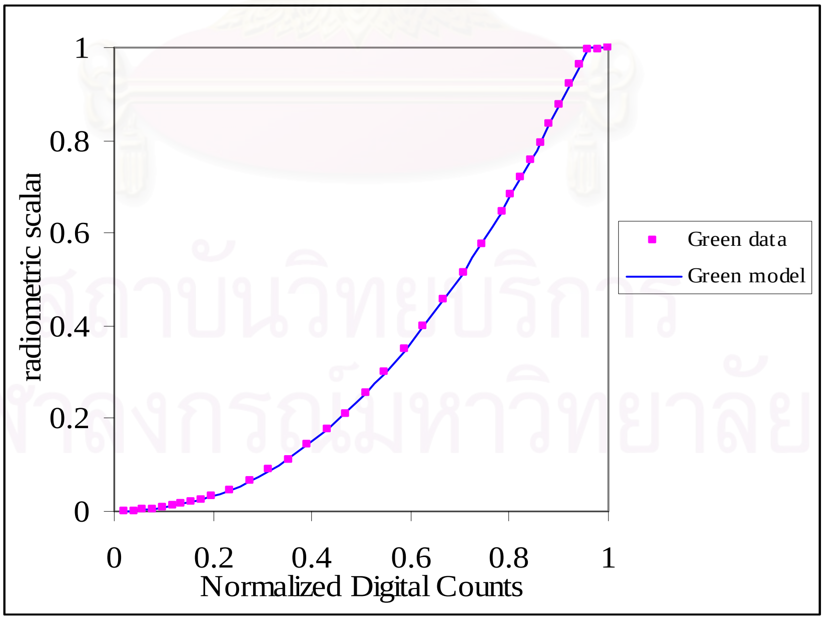


Figure 4-10: Measured data and fitted S-curve model for the green channel electro-optical transfer function.

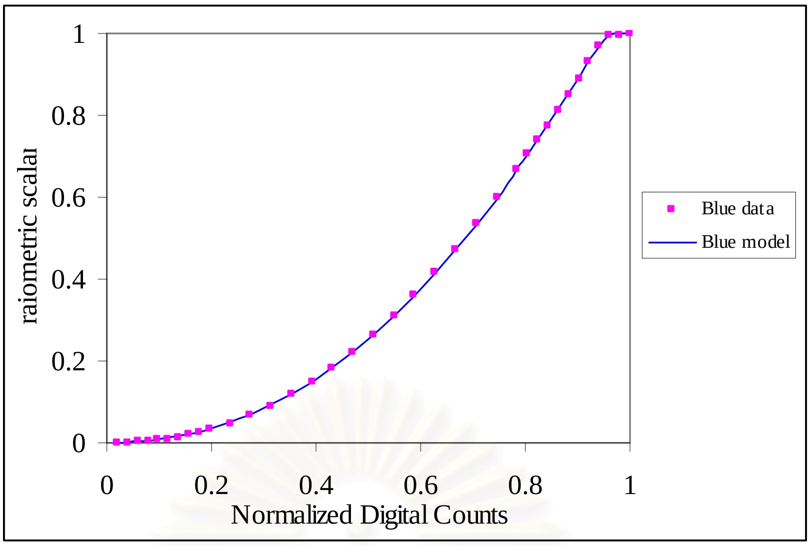


Figure 4-11: Measured data and fitted S-curve model for the blue channel electro-optical transfer function.

In Figures 4-9 to 4-11, the solid lines represent the best fitting S-curve models for each of the three functions. The results clearly showed that the S-curve models fitted the data excellently well for all three channels. Table 4-4 contains the fitted parameters for S-curve functions together with the R^2 goodness-of-fit metric. The R^2 value of 1 indicates the perfect fit between the training data and the function. Nevertheless, to test the overall colorimetric performance of the characterization model the separate data set is required.

Table 4-4: Fitted S-curve model parameters and R^2 values.

Channel	A	alpha	beta	C	R^2
R	9.2140	2.2067	37.4410	8.2140	0.9999
G	11.1758	2.1735	59.6052	10.1758	1.0000
B	9.2140	2.1443	30.8695	8.2140	1.0000

4.2.2 Comparison between 3D LUT and S-curve

The overall performance of the two models tested in this study was evaluated by measuring a set of 200 color stimuli that were generated using random combination of RGB digital counts. This test set gave a good coverage and distribution of colors within the LCD gamut. The characterization models then predicted the XYZ values for each of the 200 colors in the test set and the predictions were compared with the actual measurements by means of CIELAB color difference. The results are summarized in Table 4-5 and illustrated in the histograms of Figure 4-12.

Table 4-5: Color difference (ΔE^*_{ab}) between the measured and predicted stimuli using S-curve and LUT.

	ΔE^*_{ab}	
	S-curve	LUT
Average	1.30	1.80
SD	0.74	1.11
Max	3.56	5.70
Min	0.21	0.27

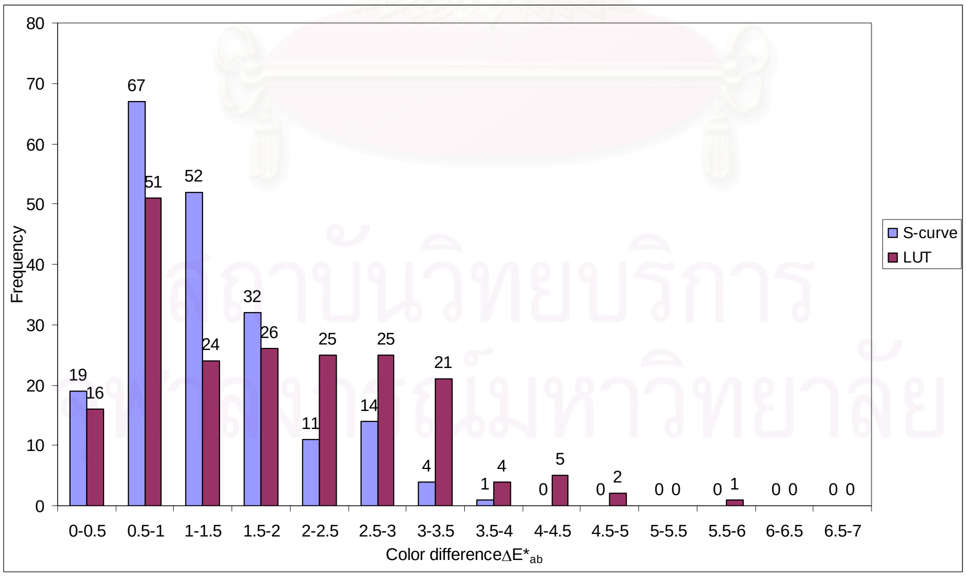
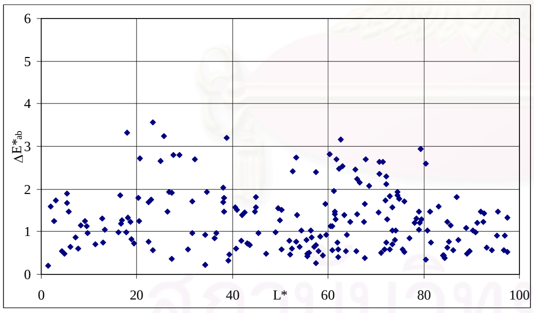
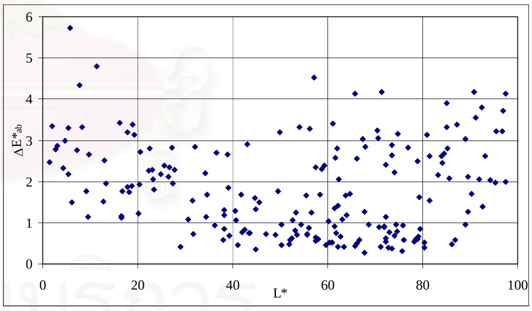


Figure 4-12: Histogram of color difference (ΔE^*_{ab}) between model predictions and measurements for 200 randomly generated colors using S-curve and LUT.

It was found that S-curve gave slightly better performance than the 3D LUT with tetrahedral interpolation. As described earlier, the accuracy of the LUT method depends upon the number of data used to construct the look-up table and the method of interpolation employed. Since the electro-optical transfer function of the LCD under study was non-linear, the method of non-linear interpolation, rather than tetrahedral interpolation, would be more appropriate. The accuracy of S-curve depends not only on the fitted S-shaped function but also on the 3x3 transform matrix. The results in Day et al. [5] showed that by using the optimization of the matrix coefficients the performance of the characterization could improve by a factor of two compared with the use of direct measurements as the matrix coefficients. This is probably due to the fact that the monitor exhibited some inter-channel dependence. The performance of the models was further investigated by plotting color difference against L*, C^*_{ab}, and hue-angle of the measured colors (Figures 4-13, 4-14, and 4-15, respectively).

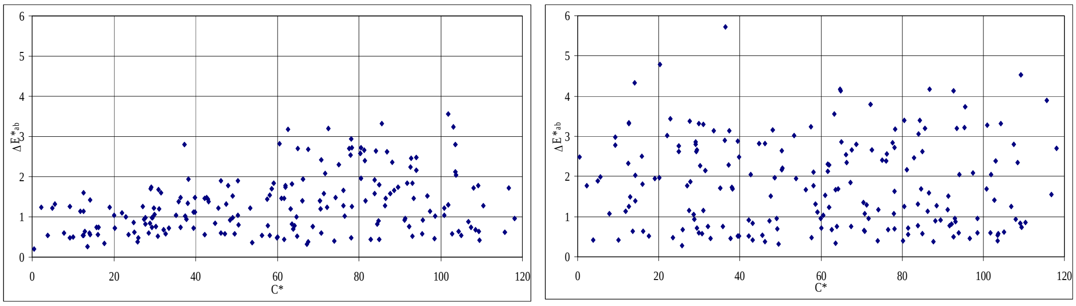


a) S-curve



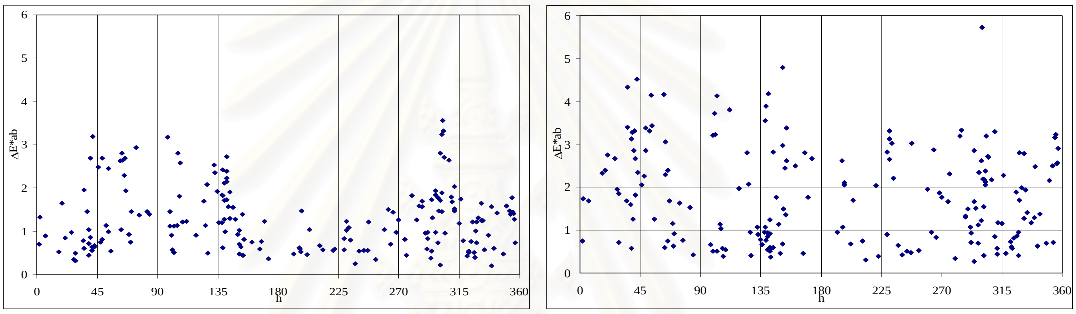
b) LUT

Figure 4-13: Distributions of color difference in relation to L for a) S-curve model and b) LUT.*



a) S-curve *b) LUT*

Figure 4-14: Distributions of color difference in relation to C^*_{ab} for a) S-curve model and b) LUT.



a) S-Curve *b) LUT*

Figure 4-15: Distributions of color difference in relation to h_{ab} for a) S-curve model and b) LUT.

Regarding lightness, no particular prediction error was found for S-curve, while LUT seemed to give poor predictions for low and high lightness colors. This confirms the inadequacy of the method of linear interpolation used with the LUT. As can be observed in Figure 4-8, the slopes at the low and high levels of the digital inputs were critical, determining the shape of the electro-optical transfer function. In the case of chroma, both methods did not show any particular prediction errors. Some trends of prediction errors were found in Figure 4-15. S-curve tended to give poor predictions for yellowish and purplish colors. The LUT did not show any clear trend of prediction errors for any color.

CHAPTER V

CONCLUSIONS

5.1 Conclusions

In order to achieve successful cross-media color reproduction, in which color of images appear consistency across media, an accurate transformation of color data from one medium to another is essential. The accurate color transformation can be obtained through a process of device characterization, thereby the relationship between the device color space and the CIE system of color measurement is defined. For a display device, the characterization normally defines the relationship between digital signals and the CIE measurements of the color displayed. The characterization may be defined as a mathematical model or a look-up table. A method for characterizing CRT monitors has been well established, with high accuracy in color transformation. Unfortunately, the same method is not suitable for LCD monitors due to differences in a fundamental property of LCDs and CRTs. The aim of this study was thus to investigate methods for LCD characterization, so as to find an appropriate method with accurate color prediction. A flat-panel LCD monitor EIZO Flexscan L767 was characterized in this study. The accuracy in transforming RGB digital counts to CIE colorimetric specification of two characterization models: S-curve model and 3D LUT with tetrahedral interpolation, was evaluated in terms of CIELAB color difference (ΔE^*_{ab}) between the measured colors and the predicted colors. The characterization was carried out in a dark room, based on measurements at the center of the display and perpendicular to the face, with a Minolta CS-1000A spectroradiometer. Six characteristics of the LCD monitor, i.e. spectral distributions, spatial independence, channel independence, chromaticity constancy, spatial uniformity and temporal stability, were tested and the results are summarized as follows:

- The spectral radiance of the display white showed that the LCD fluorescent source had a three-narrow band distribution that maximized emission in three relatively narrow regions of the spectrum, providing the XYZ values close to those of illuminant D65 with its CCT of 6123K.
- The non-zero spectral radiance of the display black indicated that there was the minimal leaked energy from the LCD monitor. The leaked light affected displayed colors, which was confirmed by the inconstancy of the three primaries' chromaticities.
- The chromaticities of each primary varied with input levels and approached those of black as the input levels approached zero. After black correction, subtraction of black values from all measurements, the chromaticities of the primaries were constant.
- The LCD under study exhibited channel independence (each channel operates independently). The ΔE^*_{ab} between the tristimulus values for white and the sum of the tristimulus values of the individual red, green, and blue primaries was 0.24.
- The LCD monitor exhibited the good spatial independence, no impact of a color on one area on colors on another area. The average color difference (ΔE^*_{ab}) between white stimuli on different backgrounds was 0.21 ΔE^*_{ab}.

- The relative luminance across the display area of the LCD was found to be between 80-100%. The average color difference (ΔE^*_{ab}) in all area was 2.12. It was considered that the LCD was reasonably spatial uniform.
- The results of temporal stability test showed that the LCD reached the stable state after 40 minutes and were at the stable level until the end of 4-hour evaluation.

The two characterization models investigated in this study were successfully implemented by the use of MATLAB programming software and the Solver function in Microsoft Excel. The two models are different in structure and therefore used different training data for implementation. S-curve model, a mathematical model containing a set of equations, has two stages: transformations from digital signals to luminance and from luminance to CIE XYZ. It used a 36-step ramp of neutral colors as a training set. The 3D LUT with tetrahedral interpolation mapped color data from digital signals to CIE XYZ directly. Its training data contained 729 colors generated from subdividing RGB color space of the display to a 9 x 9 x 9 color cube. The following is the major findings in relation to the performance of these two models.

- The electro-optical transfer function of the LCD was found to be non-linear.
- The best fitting S-curve models for each of the three functions fitted the training data excellently well for all three channels, with the R^2 values of approximately 1 for all functions.
- The accuracy of the LUT method depends upon the number of data used to construct the look-up table and the method of interpolation employed. The larger the look-up table, the more accurate the prediction. However, a large look-up table will consume too much computational time and space. For a

small look-up table to perform well, non-linear interpolation should be employed.

- The accuracy of S-curve depends not only on the fitted S-shaped function but also on the 3x3 transform matrix. In order for S-curve to perform well, the LCD monitor has to exhibit good channel independence and chromaticity constancy.
- No particular trend of prediction errors regarding lightness of colors was found for S-curve, while LUT seemed to give poor predictions for colors having low and high lightness values. This confirmed the inadequacy of the method of linear interpolation used with the LUT.
- In the case of chroma, both methods (3D LUT and S-curve model) did not show any particular prediction errors.
- S-curve tended to give poor predictions for yellowish and purplish colors. The LUT did not show any clear trend of prediction errors for any color.
- Overall, S-curve model gave slightly better performance than the 3D LUT with tetrahedral interpolation.

5.2 Suggestions

- LCD characterization in a normal lit room.
- Separate grid of LUT in range of digital counts 0-50 and 200-255 at smaller than 5 units apart.
- Characterization in different angles on vertical or horizontal direction.
- Characterization the other types of displays by S-curve model.
- Characterization by different methods should be implemented using the same set of training data.

- In spatial independence test, the size of stimuli should well cover the measurement area but not too much larger, so that the effect of spatial independence could be clearly observed.
- Before characterization, brightness and contrast of LCD should be set up such that the non-clipping of electro-optical transfer function curve on highlight is present.

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APPENDICES

APPENDIX A

MATLAB source code for LUT with tetrahedral interpolation

```
function p = LUT9XYZ(x,y,z,table_XYZ_R)

%receive RGB digital count value and load table of XYZ stimulus value%

if( 0 <= x & x < 256 & 0 <= y & y < 256 & 0 <= z & z < 256 )

%check input data%


    a = [ 0 ; 32 ; 64 ; 96 ; 128 ; 160 ; 192 ; 224 ; 255 ; 256];

   %9 value of RGB data plus one over maximum%


    i = 1;

    while x >= a(i)

        x0 = a(i);

        x1 = a(i+1);

        i = i+1;

    end

    if x == 255

        i = i - 1;

        x0 = a(i-1);

        x1 = a(i);

    else

        i = i;
```

```
end
L = 9*(i-2);
 %R value change every 9 rows, and first "i" returned 2 so have to -2
%because "i" can be zero.%


j = 1;
while y >= a(j)
    y0 = a(j);
    y1 = a(j+1);
    j = j+1;
end
if y == 255
    j = j - 1;
    y0 = a(j-1);
    y1 = a(j);
else
    j = j;
end
M = (j-2);
%G value change every single row, and first "k" returned 2 so have to
-2 because "k" can be zero.%


k = 1;
while z >= a(k)
    z0 = a(k);
```

```
    z1 = a(k+1);
    k = k+1;
  end
  if z == 255
    k = k - 1;
    z0 = a(k-1);
    z1 = a(k);
  else
    k = k;
  end
  N = 81*(k-2);
 %B value change every 81 rows, and first "j" returned 2 so have to -2
  because "j" can be zero.%

  n = L + M + N + 1;
 %finding started row by using ending point (P111); have to plus 1
  because "n" start at row 1.%

  b = [ n ; n+81 ; n+1 ; n+82 ; n+9 ; n+90 ; n+10 ; n+91 ];
%equation to find rows of table, 8 corners of the box%

  for a = 1:3
 %looping for 3 values; X , Y and Z%

    P000(a) = table_XYZ_R(b(1),a);
```

```
    P001(a) = table_XYZ_R(b(2),a);
    P010(a) = table_XYZ_R(b(3),a);
    P011(a) = table_XYZ_R(b(4),a);
    P100(a) = table_XYZ_R(b(5),a);
    P101(a) = table_XYZ_R(b(6),a);
    P110(a) = table_XYZ_R(b(7),a);
    P111(a) = table_XYZ_R(b(8),a);
  %input datas to each corner%


    dx = x - x0;
    dy = y - y0;
    dz = z - z0;
%calulated for delta r, delta g and delta b%


    if (dx >= dy) & (dy >= dz)
       c1(a) = P100(a) - P000(a);
       c2(a) = P110(a) - P100(a);
       c3(a) = P111(a) - P110(a);
       T = 1;
    elseif (dx >= dz) & (dz >= dy)
       c1(a) = P100(a) - P000(a);
       c2(a) = P111(a) - P101(a);
       c3(a) = P101(a) - P100(a);
       T = 2;
    elseif (dz >= dx) & (dx >= dy)
```

```
    c1(a) = P101(a) - P001(a);
    c2(a) = P111(a) - P101(a);
    c3(a) = P001(a) - P000(a);
    T = 3;
  elseif (dy >= dx) & (dx >= dz)
    c1(a) = P110(a) - P010(a);
    c2(a) = P010(a) - P000(a);
    c3(a) = P111(a) - P110(a);
    T = 4;
  elseif (dy >= dz) & (dz >= dx)
    c1(a) = P111(a) - P011(a);
    c2(a) = P010(a) - P000(a);
    c3(a) = P011(a) - P010(a);
    T = 5;
  else
    c1(a) = P111(a) - P011(a);
    c2(a) = P011(a) - P001(a);
    c3(a) = P001(a) - P000(a);
    T = 6;
  end
%finding which tetrahedron that data was in%

  px = dx./(x1-x0);
  py = dy./(y1-y0);
  pz = dz./(z1-z0);
```

```
    p(a) = P000(a) + c1(a) .* px + c2(a) .* py + c3(a) .* pz;
%calculated the interpolated data X , Y and Z%

  end

  disp(sprintf(' _____________________________________________ '));
  disp(sprintf('|     |     |     |     |     |     |     |'));
  disp(sprintf('|Point|  R  |  G  |  B  |  X  |  Y  |  Z  |'));
  disp(sprintf('|_____|_____|_____|_____|_____|_____|_____|'));
  disp(sprintf('|     |     |     |     |     |     |     |'));
  disp(sprintf('|P000 |%5.0f|%5.0f|%5.0f|%5.2f|%5.2f|%5.2f|',x0  ,y0  ,z0
,P000(1),P000(2),P000(3)));
  disp(sprintf('|P001 | %3.0f | %3.0f | %3.0f |%3.2f |%3.2f |%3.2f
|',x0,y0,z1,P001(1),P001(2),P001(3)));
  disp(sprintf('|P010 | %3.0f | %3.0f | %3.0f |%3.2f |%3.2f |%3.2f
|',x0,y1,z0,P010(1),P010(2),P010(3)));
  disp(sprintf('|P011 | %3.0f | %3.0f | %3.0f |%3.2f |%3.2f |%3.2f
|',x0,y1,z1,P011(1),P011(2),P011(3)));
  disp(sprintf('|P100 | %3.0f | %3.0f | %3.0f |%3.2f |%3.2f |%3.2f
|',x1,y0,z0,P100(1),P100(2),P100(3)));
  disp(sprintf('|P101 | %3.0f | %3.0f | %3.0f |%3.2f |%3.2f |%3.2f
|',x1,y0,z1,P101(1),P101(2),P101(3)));
  disp(sprintf('|P110 | %3.0f | %3.0f | %3.0f |%3.2f |%3.2f |%3.2f
|',x1,y1,z0,P110(1),P110(2),P110(3)));
```

```
    disp(sprintf('|P111 | %3.0f | %3.0f | %3.0f |%3.2f |%3.2f |%3.2f
|',x1,y1,z1,P111(1),P111(2),P111(3)));
    disp(sprintf('|_____|_____|_____|_____|_____|_____|_____|\n'));

    disp(sprintf('\nInput data is in tetrahedral number %d.',T));


    disp(sprintf('\n3D LUT Characterization %d.'));
    disp(sprintf('\nX = %5.2f, Y = %5.2f, Z = %5.2f\n',p(1),p(2),p(3)));
    disp(sprintf('\nX+flare = %5.2f, Y+flare = %5.2f, Z+flare =
%5.2f\n',p(1)+0.2383,p(2)+0.22,p(3)+0.3467));
%show the XYZ tristimulus value%
%add black level flare to XYZ tristimulus and display the predicted value of  XYZ
tristimulus%
else
    disp(sprintf('\n!!! ERROR : wrong input data(s) !!!\n'));
    p = zeros(3,1);
end
```

APPENDIX B

MATLAB source code for S-curve

```
function p = ScurveXYZ(r,g,b);

s = [104.6369 71.2371 36.5925;54.22 150.38 17.07;3.1372 25.9288 201.3018;];

%create 3x3 transformation matrix%

rn=r/255;

gn=g/255;

bn=b/255;

%normalized digital count value%

q=9.21399*(rn^2.20674)/((rn^37.44099) + 8.21399);

w=11.17581*(gn^2.17353)/((gn^59.60523) + 10.17581);

e=9.21395*(bn^2.14430)/((bn^30.86953) + 8.21395);

% radiometric scalar was calculated, q is value of red channel, w is value of green

channel, e is value of blue channel, by S-curve model%

if q > 1;

   q == 1;

else

   q == q;

end

%limit the luminance value of red channel is less than 1 or equal 1%

if w > 1;

   w = 1;

else
```

```
  w = w;
end
%limit the luminance value of green channel is less than 1 or equal 1%
if e > 1;
  e = 1;
else
  e = e;
end
%limit the luminance value of blue channel is less than 1 or equal 1%


n=[q;w;e;]
%create matrix 3 x 1 of luminance levels%
p=s*n;
% calculate XYZ tristimulus values%
disp(sprintf('\n S Curve Characterization %d.'));
disp(sprintf('\nX = %5.1f, Y = %5.1f, Z = %5.1f\n',p(1),p(2),p(3)));
%show the XYZ tristimulus value%
 disp(sprintf('\nX+flare = %5.2f, Y+flare = %5.2f, Z+flare =
%5.2f\n',p(1)+0.2383,p(2)+0.22,p(3)+0.3467));
%add black level flare to XYZ tristimulus and display the predicted value of  XYZ
tristimulus%
```

APPENDIX C

Table C-1: The percentage of luminance in each area for spatial uniformity

Vertical area	Horizontal area				
	1	2	3	4	5
1	0.86	0.87	0.91	0.90	0.85
2	0.86	0.92	0.95	0.90	0.88
3	0.91	0.94	1.00	0.95	0.86
4	0.87	0.92	0.93	0.91	0.89
5	0.88	0.85	0.86	0.86	0.85

Table C-2: The color diference (ΔE^*_{ab}) for spatial independence test

ΔE^*_{ab}	Background		
Stimuli	gray	black	average
White	0.24	0.19	0.21

Table C-3: Measured XYZ tristimulus values for black, red, green, and blue before black correction.

d_r	d_g	d_b	X	Y	Z
0	0	0	0.24	0.22	0.35
255	0	0	104.88	54.44	3.48
0	255	0	71.48	150.60	26.28
0	0	255	36.83	17.29	201.65

Table C-4: normalized radiometric scalar value of S-curve characterization model.

$d_r/d_{r,max}$	$d_g/d_{g,max}$	$d_b/d_{b,max}$	R/R_{max}	G/G_{max}	B/B_{max}
0	0	0	0	0	0
0.0196	0.0196	0.0196	0.0001	0.0002	0.0002
0.0392	0.0392	0.0392	0.0008	0.0010	0.0009
0.0588	0.0588	0.0588	0.0021	0.0023	0.0023
0.0784	0.0784	0.0784	0.0040	0.0045	0.0043
0.0980	0.0980	0.0980	0.0066	0.0071	0.0070
0.1176	0.1176	0.1176	0.0098	0.0104	0.0105
0.1373	0.1373	0.1373	0.0137	0.0147	0.0145
0.1569	0.1569	0.1569	0.0189	0.0197	0.0197
0.1765	0.1765	0.1765	0.0243	0.0253	0.0256
0.1961	0.1961	0.1961	0.0308	0.0321	0.0325
0.2353	0.2353	0.2353	0.0456	0.0465	0.0483
0.2745	0.2745	0.2745	0.0656	0.0661	0.0679
0.3137	0.3137	0.3137	0.0873	0.0886	0.0908
0.3529	0.3529	0.3529	0.1115	0.1131	0.1177
0.3922	0.3922	0.3922	0.1417	0.1425	0.1492
0.4314	0.4314	0.4314	0.1764	0.1761	0.1822
0.4706	0.4706	0.4706	0.2160	0.2116	0.2206
0.5098	0.5098	0.5098	0.2578	0.2562	0.2644
0.5490	0.5490	0.5490	0.3008	0.2999	0.3102
0.5882	0.5882	0.5882	0.3497	0.3483	0.3628
0.6275	0.6275	0.6275	0.4030	0.3990	0.4162
0.6667	0.6667	0.6667	0.4581	0.4553	0.4735
0.7059	0.7059	0.7059	0.5196	0.5155	0.5341
0.7451	0.7451	0.7451	0.5824	0.5780	0.5996
0.7843	0.7843	0.7843	0.6529	0.6481	0.6672
0.8039	0.8039	0.8039	0.6900	0.6836	0.7044
0.8235	0.8235	0.8235	0.7258	0.7199	0.7397
0.8431	0.8431	0.8431	0.7654	0.7566	0.7760
0.8627	0.8627	0.8627	0.8060	0.7944	0.8139
0.8824	0.8824	0.8824	0.8491	0.8357	0.8514
0.9020	0.9020	0.9020	0.8937	0.8767	0.8914
0.9216	0.9216	0.9216	0.9373	0.9210	0.9319
0.9412	0.9412	0.9412	0.9793	0.9638	0.9705
0.9608	0.9608	0.9608	0.9955	0.9959	0.9940
0.9804	0.9804	0.9804	0.9957	0.9961	0.9942
1	1	1	1	1	1

VITA

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