國 立 交 通 大 學

顯示科技研究所

碩 士 論 文

即時運算處理適應性背光

於色序法顯示器抑制色分離現象

Color Breakup Suppression Using Adaptive Backlight for

Field-Sequential-Color Liquid Crystal Displays

in a Real-Time Process

研 究 生：簡世勛

指導教授：謝漢萍 教授

黃乙白 副教授

中 華 民 國 九十九 年 六月

即時運算處理適應性背光於色序法顯示器抑制色分離現象

Color Breakup Suppression Using Adaptive Backlight for Field-Sequential-Color Liquid Crystal Displays in a Real-Time Process

研 究 生： 簡世勛　　Student：Shih-Hsun Chien

指導教授： 謝漢萍　　Advisor：Han-Ping D. Shieh

黃乙白　　Yi-Pai Huang

國 立 交 通 大 學

顯 示 科 技 研 究 所

碩 士 論 文

A Thesis

Submitted to Institute of Display Technology

College of Electrical and Computer Engineering

National Chiao Tung University

in partial Fulfillment of the Requirements

for the Degree of Master

in

Display Institute

June 2010

Hsinchu, Taiwan, Republic of China

中華民國 九十九 年 六 月

即時運算處理適應性背光
於色序法顯示器抑制色分離現象

碩士研究生：簡世勛　指導教授：謝漢萍教授
黃乙白副教授

國立交通大學電機學院　　顯示科技研究所

摘　要

近年來環保意識興起，各顯示器廠商及各研究單位都在積極開發節省能源消耗的顯示器，期望能夠減緩全球暖化現象。然而，在傳統的顯示器上，是用白色背光與彩色濾波片搭配，經由空間混色達到全彩的影像，因為背光穿透彩色率玻片的光效率不佳，要達到高亮度的影像，就得要提高背光的亮度，隨之即會產生過高的能量消耗。隨著高效率的發光二極體的發展，背光不再是用冷陰極射線管，而發光二極體可以產生的紅、綠、藍，三種基本的光顏色，利用這三種光顏色，可以混成各個顏色。因此，有人提出了色序法顯示器，將彩色濾波片移除，利用多彩的發光二極體，利用高頻率的時間混色，使人眼可以觀賞到彩色的影像，又使光效率上升。

然而色分離現象會伴隨著色序法顯示器，因此提出了四個畫面形成一個彩色畫面，將主要影像資訊集中在一個畫面，其餘的三個畫面就可以減少亮度，色分離現象就可以被抑制。為了要將此概念實現在硬體上，需要做一些簡化，在找出最具代表的背光顏色，需將畫面分割成三等份，每一等份去做背光逼近的計算，當畫面資訊全部給入硬體後，即可即時運算背光顏色，並將其餘三個場的畫面計算出，使色序法顯示器能夠即時呈現畫面。

Color Breakup Suppression Using Adaptive Backlight for Field-Sequential-Color Liquid Crystal Displays in a Real-Time Process

Student: Shih-Hsun Chien **Advisor: Dr. Han-Ping D. Shieh**
Dr. Yi-Pai Huang

Institute of Display Technology
National Chiao Tung University

Abstract

In conventional liquid crystal display, using CCFL backlight and color filters to generate a full color image. However, the optical throughput is lowered owning to the color filters. The backlight needs to give more power to generate a high luminance image. Accompany with the highly improved LED technology, the power and life time of LED can substitute the CCFL backlight. Because multi-color LEDs can mix color using red, green, and blue colors, the color filters can be removed. Therefore, a new liquid crystal display is proposed called Field Sequential Color LCD.

However, the color breakup happens when there is a relative motion during eye movement. We proposed four fields to combine a full color image. Let most information detail to display in specific field and rest of fields decrease its intensities. Then the color breakup is less observed. In order to implement on hardware with the concept, some simplification is needed. When finding the majority color of input image, we separate the image into three parts. Each part does the backlight convergence approach. Therefore, after image information is loaded into hardware, the adaptive backlight color is determined at the same time. Other three field images is re-calculated in the following. FSC LCD displays the image in a real-time process.

誌　謝

首先誠摯的感謝指導老師謝漢萍教授和黃乙白副教授，在這碩士兩年的求學中對於研究態度及英文能力的教導，不僅提供豐富的資源與完善研究環境，使我得以在碩士生涯提升了專業及英文的能力，並且順利完成此論文。此外，也感謝各位口試委員所提供的寶貴意見，使本論文更加的完備。

在此特別感謝陳均合學長、林芳正學長在研究上的指導，吳政育學長對於論文的指導，其細心的指導方式，嚴謹的研究態度，讓我不僅只在研究上的學習成長，更在做人處世上受益良多。此外我要感謝中華映管諸位合作同仁，戴文智博士、邱顯鈞先生提供我寶貴的意見及實作的協助，讓整個研究進展的更順利。

在實驗室的日子裡，感謝有鄭榮安、許精益、王國振、廖凌嶢、陳致維、張育誠等學長們提供各方面的指導與協助，也感謝宗緯、浩彣、宜伶、靖堯、博文、佑禎、拓江、宜如、俊賢、高銘、益興等學長姊們讓我的生活更加精彩。同時感謝壁丞、毅翰、裕閔、怡菁、景文、期竹、甫奕、姚順、耆賢、泳材等同學們在課業、研究、生活上的幫助與分享，並伴我一起度過兩年碩士班的日子。我也感謝實驗室的學弟妹們與助理小姐，感謝你/妳們的幫忙及讓實驗室充滿歡愉的氣氛。

感謝我在清華大學時的同學、跟來交大認識的朋友，在不同研究所的生活中，還能夠保持聯絡，用運動串連起來，一股熱血，互相打氣、揶揄，都是研究所中最好的回憶。

最後，對於我的家人，我要感謝你們多年來的支持與鼓勵以及生活上的細心照顧，使我能無後顧之憂的研究與學習，並順利完成碩士學位。這份喜悅與榮耀我將跟所有我所認識的各位分享。

Table of Contents

Figure Captions

Chapter 1

Introduction

Recently, liquid crystal displays (LCDs) have become a mature product in the display field. Because research in the light emitting diode (LED) is developing too the original backlight source, Cold Cathode Fluorescent Lamp (CCFL), in LCDs will be soon or later replaced. So, new driving methods for controlling LEDs were proposed. Field-sequential-color LCD (FSC-LCD) technology is one of these proposed methods [1][2]. In the following, the pros and cons of FSC-LCD will be introduced. Then the motivation and objective of this thesis will be given.

1.1 Field Sequential Color Liquid Crystal Displays (FSC-LCDS)

Conventional LCDs are composed of CCFL backlight, thin film transistor (TFT) arrays, liquid crystal (LC) and color filters (CF). The structure of conventional LCDs is shown in Fig. 1-1 TFT arrays control the LC and block light emitted from the CCFL [3]. The light is continually transmitted into color filters, and then a full color image is yielded. This is called the spatial color mixing method and is illustrated on Fig. 1-2.

As light is transmitted through one element optical throughput is weakened. Finally, total optical throughput is only 7% of original light source. The color filter is a key element in absorbing light. Thus, the concept of field-sequential-color liquid crystal displays (FSC-LCDs) removes the color filters and use high power multi-colored LEDs as a backlight source. So FSC-LCDs have higher optical throughput than conventional LCDs does while giving the same backlight power, and the color gamut is widened by using LED backlight.

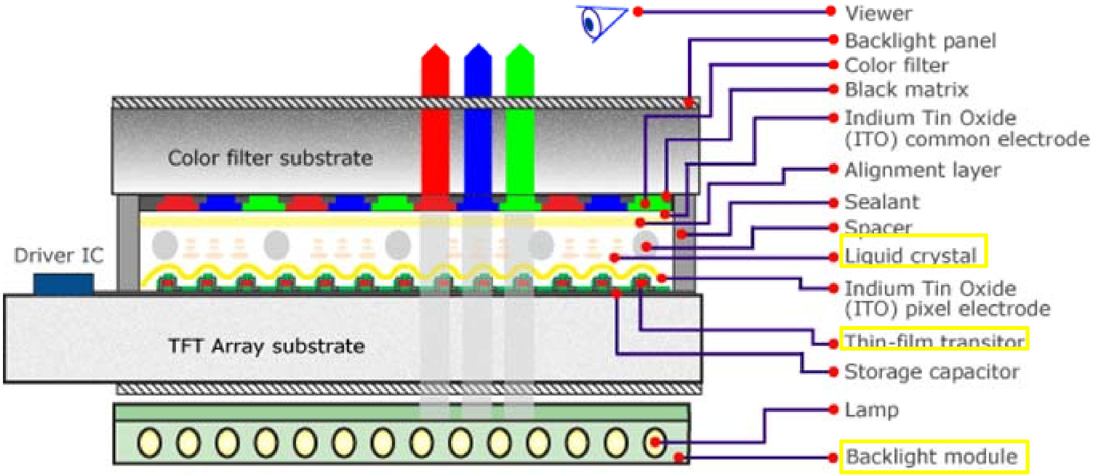


Fig. 1-1 Detail elements of conventional LCD [3]

Without color filters, three sub-pixels for red, green and blue are no longer required, and increase the panel resolution. FSC-LCDs use LEDs to flash three primary colors (red, green and blue) sequentially at 180Hz and utilize liquid crystal to determine which color light will transmit at 1/180 second. Through temporal integration of different color lights at 1/60 second, human eyes will perceive a full color image. This is called the temporal color mixing method and is illustrated in Fig. 1-3.

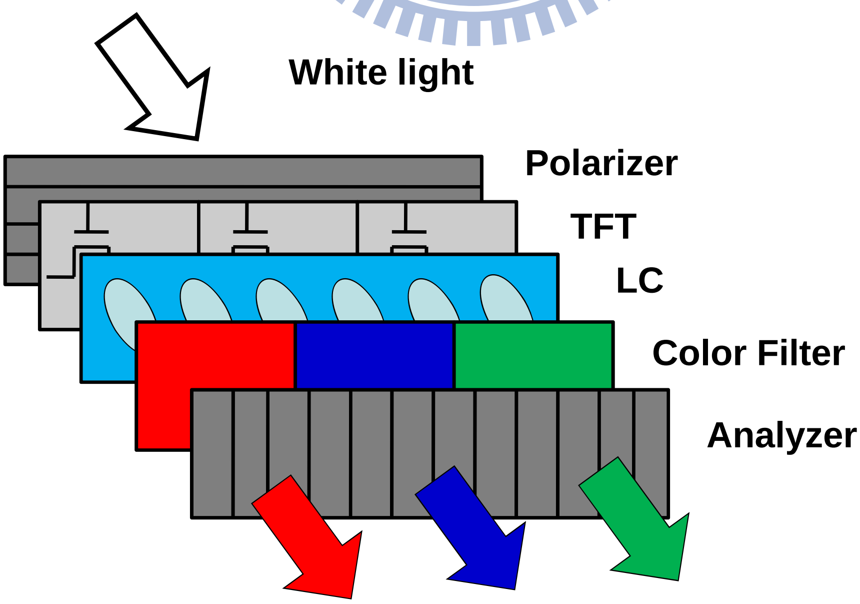


Fig. 1-2 Spatial color mixing with color filters

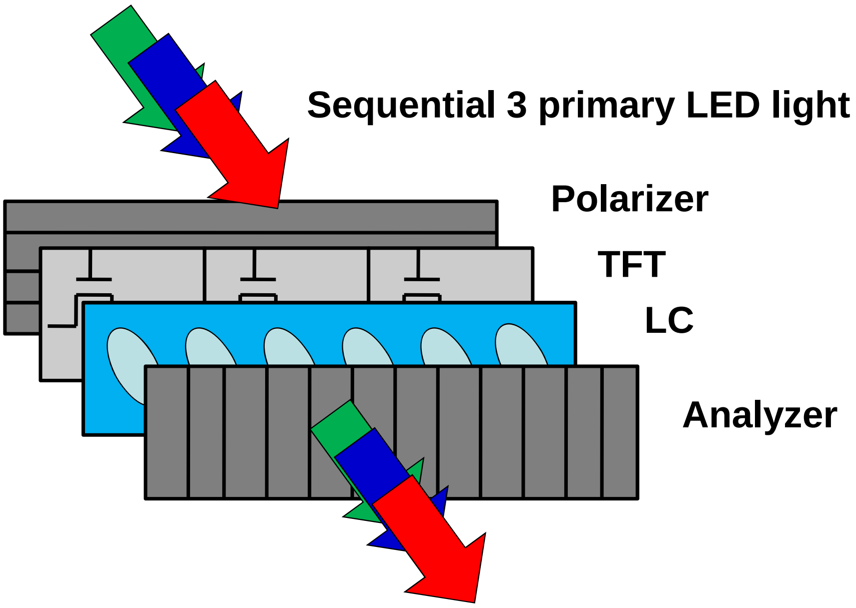


Fig. 1-3 Temporal color mixing without color filters

1.2 Color Breakup Phenomenon

FSC-LCDs use the temporal color mixing method to make a full color image. However, when the LEDs keep flashing and human eyes have a relative velocity with the image, human eyes will perceive a rainbow-like edge after temporal integration. This is the color breakup (CBU) phenomenon [4][5][6], also called the rainbow effect as shown in Fig. 1-4. This CBU phenomenon degrades image quality and will cause humans headache and dizzy.

Fig. 1-4 Color breakup image with temporal color mixing during eye movement

1.3 Color Shift Phenomenon

The image frame time is separated into at least three intervals for red, green and blue as shown in Fig. 1-5. Each interval is for the rotation of LC and backlight emission. FSC-LCDs can then display a field image correctly at each field. Therefore, FSC-LCDs need a fast liquid crystal response time to rotate to the target value in a field time, which is about 1/3 frame time if there are three fields in one frame. If the response time of liquid crystal is not fast enough, the blocked volume of light will be not correct [7]. After human eye integration, the hue, saturation, intensity of color might be different when compared to the input image. This phenomenon is called color shift. Although LEDs have a very wide color gamut, a slower liquid crystal will shrink the color gamut and display the incorrect color.

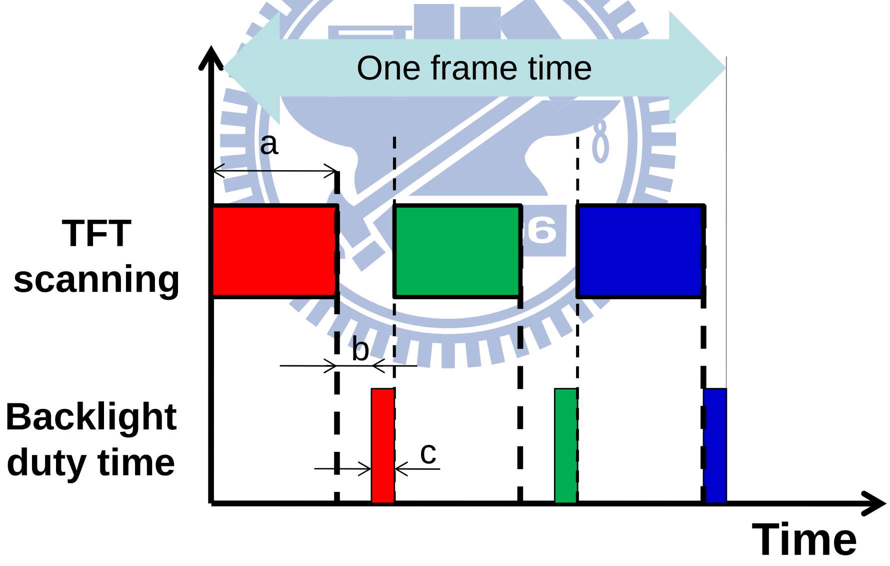


Fig. 1-5 Three intervals for red, green and blue fields

a: TFT addressing time; b: time of LC rotating; c: backlight flashing time

1.4 Motivation and Objective

FSC-LCDs have higher optical throughput without color filter requirement which saves more power and creates a wider color gamut using multi-colored high power LEDs. However, FSC-LCDs still suffer from the color breakup artifact when human's eyes follow saccade or smooth pursuit movement across the screen. Our group had proposed a Dominant-Field plus Three Primary Fields called DRGB to effectively suppress the CBU artifact [8]. However, the concept of DRGB method needs a precise and complicated calculation process. FSC-LCDs use DRGB method without frame buffers is hard to implement in hardware. Therefore, the objective of this thesis is to propose a modified DRGB method (called Fast-DRGB [9]) to simplify the calculation process and implement the Fast-DRGB method in hardware without any frame buffers.

1.5 Organization of This Thesis

This thesis is organized as follows. In **Chapter 2**, some prior arts to suppress CBU and characterize color shift phenomenon in FSC-LCDs are presented. In **Chapter 3**, the concept of the Fast-DRGB method is proposed to implement on field programmable gate arrays (FPGA) with a 15.4" panel. In **Chapter 4**, simulation of the Fast-DRGB will be discussed. In **Chapter 5**, the hardware implementation of the Fast-DRGB and panel characterization with modified color model will be demonstrated. Finally, conclusions and future works will be given in **Chapter 6**.

Chapter 2

Prior Arts in Field-Sequential-Color LCDs

FSC-LCDs have advantages of higher optical throughput, lower material cost without color filters requirement, a wider color gamut, higher resolution without subpixels. However, the mechanism of eye movement on FSC-LCDs degrades the image quality because of CBU artifact. The LC response time is not fast enough to cause color shift phenomenon. Many researches on CBU artifact suppression and color shift characterization in FSC-LCDs have been discussed in recently years.

2.1 Mechanism of Color Breakup (CBU)

2.1.1 Human Eye Structure and Eye Movement

In the beginning, we should discuss the human color vision. The image use light to be transmitted and refracted by the lens, finally projected onto the retina. The structure of eye ball is depicted in Fig. 2-1 [10]. The retina is composed of photosensitive cells, rods and cones and is shown in Fig. 2-2 [11]. These cells transducer the image information to optic nerve and then brain receives the signals to decode signals into a color full image. The retina contains two kinds of photoreceptor for receiving the image details.

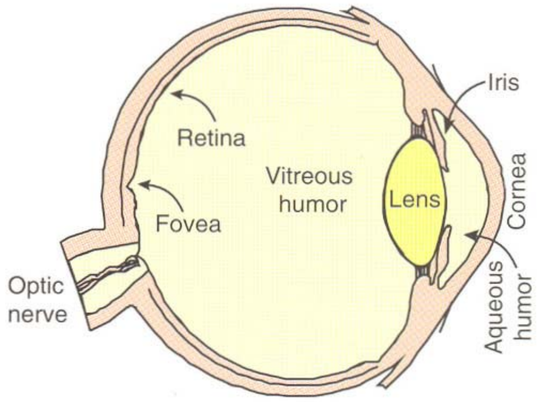


Fig. 2-1 The cross section of eye ball

The rods are in charge of achromatic color at low luminance (scotopic vision) while the cones are in charge of chromatic color at high luminance (photopic vision). And both cells work in the intermediate luminance environment (mesopic vision).

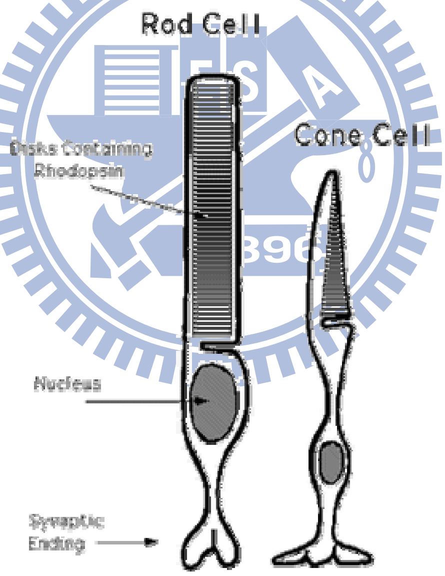


Fig. 2-2 A schematic drawing of rods and cones cell

After discussing the human vision system, two kinds of eye movement are related to color breakup issue, saccade and smooth pursuit [13][14][15]. Saccade is human eyes jump from one position to another position and the velocity, direction of eyes is voluntary.

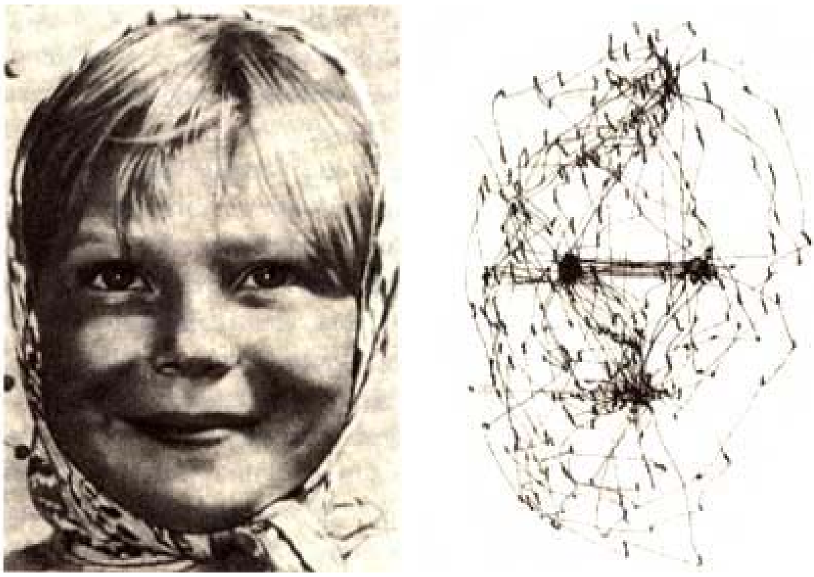


Fig. 2-3 (a) Perceived image, (b) trajectory of saccadic movement

Fig. 2-3(b) shows that lines are the trajectory of saccadic eye movement. After several cycles of movement, the clear image will be perceived and is shown in Fig. 2-3(a) [12]. Smooth pursuit is human eyes follow the moving object at the same velocity, so that the image is clearly when eyes are doing smooth pursuit.

2.1.2 Two Types of Color Breakup

There are at least three fields (Red, Green and Blue) needed to make a correct full color image in FSC-LCDs. Because of the temporal color mixing, the frequency of alternation between three fields should be quicker enough so that different field images are projected in the same position of retina. The brain will receive a correct image. If the projected images are not in the same position of retina, human eyes perceive color breakup (CBU) phenomenon. CBU is strongly dependent on two types of eye movement: saccade and smooth pursuit movement. Therefore, two kinds of CBU phenomenon are discussed, static and dynamic.

2.1.2(a) Static Color Breakup

When a static image is perceived during saccadic eye movement, the CBU happens along the eye movement direction and is illustrated in Fig. 2-4. The left dash block means image is still and only eyes are moving. Other three blocks show three primary field images locate on different positions of retina cause static CBU phenomenon.

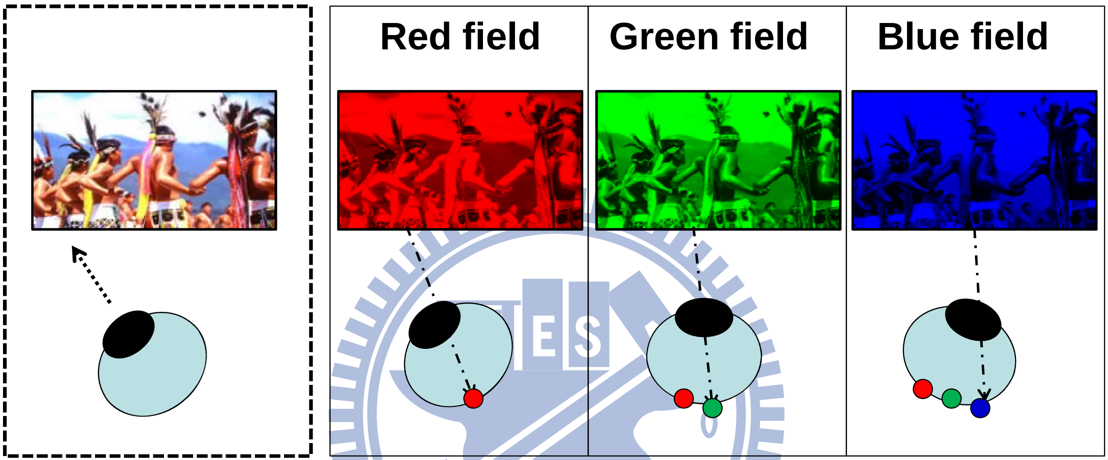


Fig. 2-4 Saccadic eye movement cause static CBU

2.1.2(b) Dynamic Color Breakup

When tracking a dynamic image, the human eye will pursue the moving image as shown in Fig. 2-5. When white bar is moving to specific direction, human eyes will chase white bar through smooth eye pursuit. Human eyes will detect different color fields combination on the edges of white bar after the color temporal mixing integration.

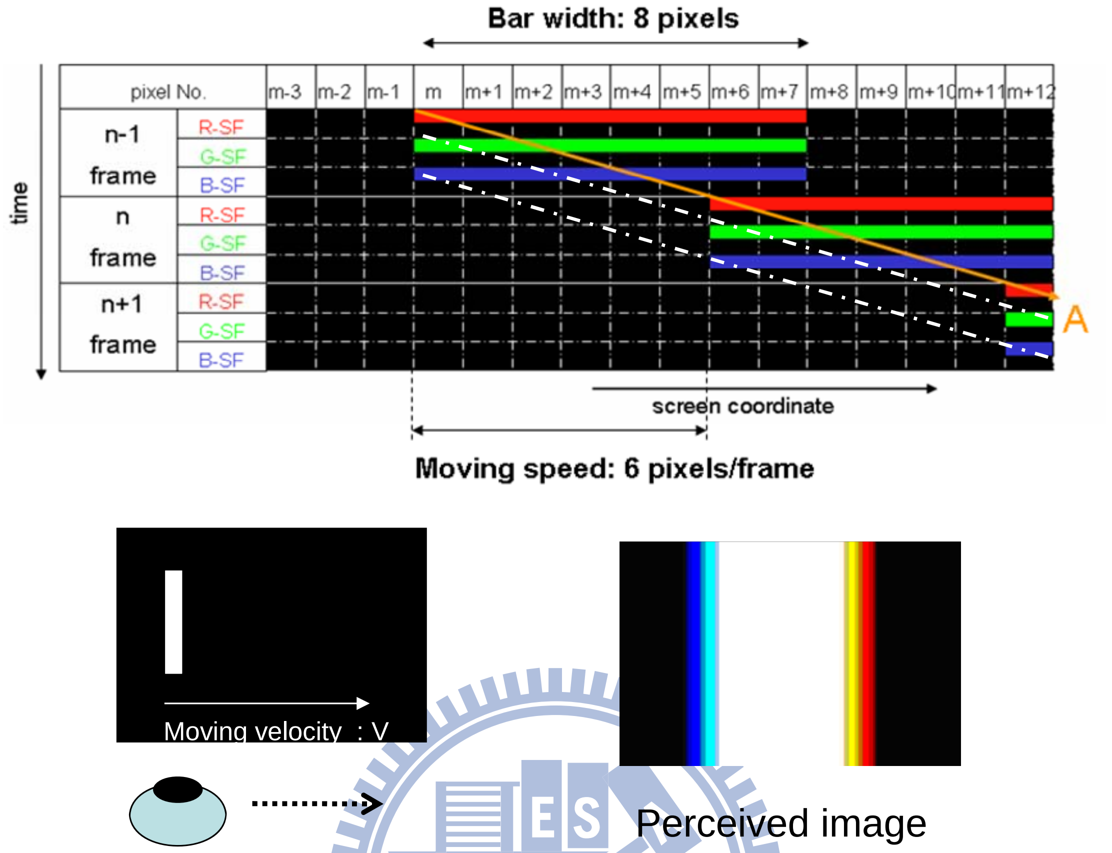


Fig. 2-5 Smooth pursuit movement on moving object causes CBU

2.2 Evaluation of CBU –

Color Difference Equation CIEDE2000 (ΔE_{00})

When describing how human eyes perceived the color, the researches of International Commission on Illumination (CIE) are first published mathematically.

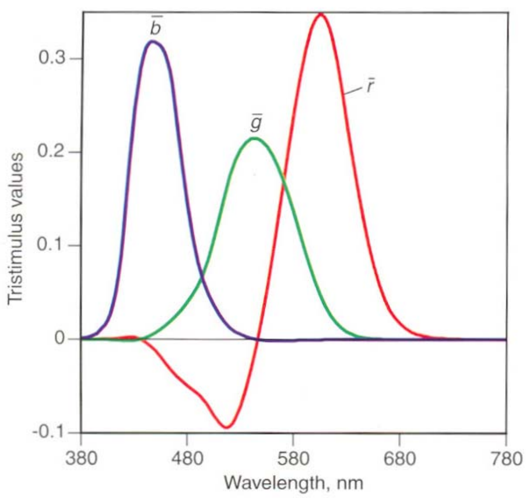
CIE defined color space from a series of psychological experiments. In 1920s, W. David Wright and John Guild designed experiments to measure color matching functions. In 1931, the Colorimetry Committee of CIE selected three primary wavelengths (435.8nm, 546.1nm and 700nm) and 17 standard observers to experiment in color matching functions. These experiments are under specific conditions like a bipartite area subtending a 2 degree viewing angle with dark environment.

However, the measured color matching functions ($\bar{r}(\lambda)$, $\bar{g}(\lambda)$ and $\bar{b}(\lambda)$) are complicated owning to negative values shown in Fig. 2-6(a). After a mathematical transformation, the CIE defined color matching functions ($\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$) are all positive values for simply calculation shown in Fig. 2-6(b) [16]. Using transformed color matching functions, CIE defined a color space with tristimulus values *X*, *Y* and *Z* called *CIE XYZ*. The *CIE XYZ* color space has conditional effect, so the light source (*L*) and reflectance (*R*) factor should be considered to derive *X*, *Y* and *Z* values as shown in Eq. 2-1-1.

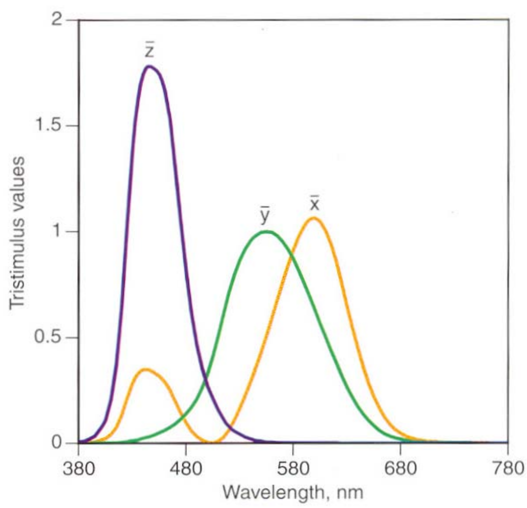
$$X = \int L(\lambda)R(\lambda)\bar{x}(\lambda)d\lambda \qquad \text{(Eq. 2-1-1)}$$

$$Y = \int L(\lambda)R(\lambda)\bar{y}(\lambda)d\lambda \qquad \text{(Eq. 2-1-2)}$$

$$Z = \int L(\lambda)R(\lambda)\bar{z}(\lambda)d\lambda \qquad \text{(Eq. 2-1-3)}$$



(a)



(b)

Fig. 2-6 (a) Original color matching functions, (b) Modified color matching functions

Furthermore, the curvature of $\bar{y}(\lambda)$ is very similar with human luminosity function. Therefore, CIE matches $\bar{y}(\lambda)$ to human luminosity function with multiplying a coefficient, and *Y* parameter describes brightness or luminance of color. The chromaticity of color can be described as x and y, the normalized values from *CIE XYZ* color space in Eq. 2.2-1. The derived color space specified by *x*, *y* and *Y* and is known as *CIE xyY* which is shown as Fig. 2-7(a).

$$x = \frac{X}{X+Y+Z} \qquad \text{(Eq. 2.2-1)}$$

$$y = \frac{Y}{X+Y+Z} \qquad \text{(Eq. 2.2-2)}$$

$$z = \frac{Z}{X+Y+Z} = 1 - x - y \qquad \text{(Eq. 2.2-3)}$$

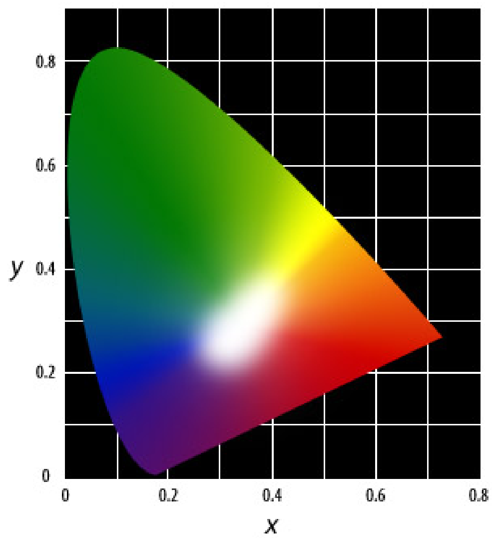
However, *CIE XYZ* or *CIE xyY* color spaces are not uniform to describe color difference correctly. For examining color quality, different color spaces such as *CIELAB*, *CIELUV* had been proposed to quantify the color difference and is shown in Fig. 2-7(b) [16] and Fig. 2-7(c). The *CIELAB* color space is the uniform color space and most close to human opponent vision system. The transformation from *CIEXYZ* to *CIELAB* is non-linear are described in Eq. 2.2-4. The *LAB* means lightness (*L**), color component of red-green (*a**) and color component of yellow-blue (*b**) respectively.

$$\Delta L^* = 116 * f(\frac{Y}{Y_n}) - 16 \qquad \text{(Eq. 2.2-4)}$$

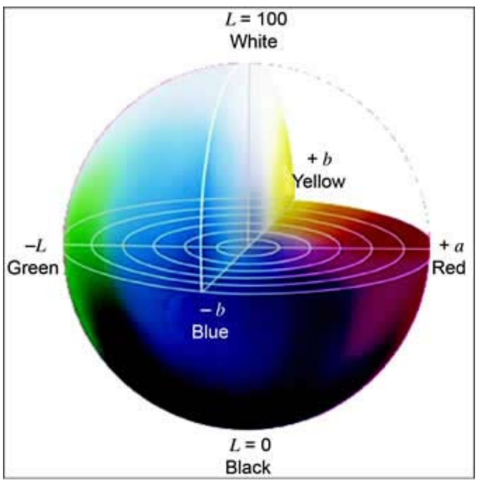
$$a^* = 500 * \left[f(\frac{X}{X_n}) - f(\frac{Y}{Y_n}) \right] \qquad \text{(Eq. 2.2-5)}$$

$$b^* = 200 * \left[f(\frac{Y}{Y_n}) - f(\frac{Z}{Z_n}) \right] \qquad \text{(Eq. 2.2-6)}$$

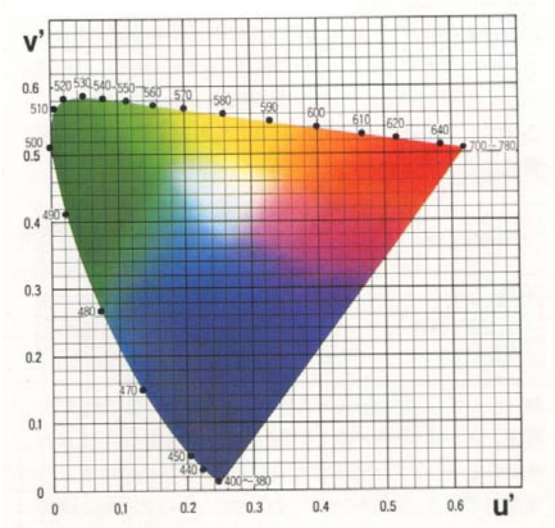
$$f(t) = \begin{cases} t^{1/3} & t > \left(\frac{6}{29}\right)^3 \\ \frac{1}{3} * (\frac{29}{6})^2 t + \frac{4}{29} & \textit{otherwise} \end{cases} \qquad \text{(Eq. 2.2-7)}$$



(a)



(b)



(c)

Fig. 2-7 (a) CIE xyY, (b) CIELAB, (c) CIELUV color spaces

Furthermore, in 2001 the CIEDE2000 color difference formula [17] based on *CIELAB* color space formula is published. The formula compared the standard and the sample using the lightness (L^*), chromaticity (C^*) and hue (H^*) which are derived by Eq. 2.2-8. Then ΔL^*, ΔC^* and ΔH^* calculate the color difference. ΔR term is a error compensation between chromaticity and hue, and the S_L, S_C and S_H are weighting coefficients for lightness, chromaticity and hue respectively. The K_L, K_C and K_H are the factors of different viewing conditional parameters, like textures, backgrounds, etc.

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \qquad \text{(Eq. 2.2-8)}$$

$$H^* = \tan^{-1}\left(\frac{b^*}{a^*}\right) \qquad \text{(Eq. 2.2-9)}$$

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L^*}{K_L S_L}\right)^2 + \left(\frac{\Delta C^*}{K_C S_C}\right)^2 + \left(\frac{\Delta H^*}{K_H S_H}\right)^2 + \Delta R} \qquad \text{(Eq. 2.2-10)}$$

The main purpose of CIEDE2000 formula is to compare color difference between original image and simulated image. CBU phenomenon happens when human eyes observe the rainbow edge. If the color difference area between rainbow edge of simulated CBU image and same position of original image is large, the CBU phenomenon is apparent. Otherwise, if color difference is small the CBU phenomenon is less observed. Therefore, using CIEDE2000 formula to calculate the color difference between rainbow edge of CBU image and the same position of original image and then the CBU phenomenon level is estimated. With CIEDE2000 value, we can compare different simulated CBU images using different methods to estimate how effectively these methods suppress CBU phenomenon.

2.3 Prior Arts to Suppress CBU Phenomenon

The researches on suppressing CBU phenomenon have been improved recently. Different kinds of CBU suppression methods are shown in Fig. 2-8, such as Mono-Color Field, Multi-Color field, and Motion Compensation.

In Mono-Color Field part, the field rate is increased to 360Hz or higher (RGBRGB or RGBKKK) [18][19], inserting complementary color fields to original three primary fields (RGBCY). Above methods are trying to decrease distance of field images on retina while eye movement as simulated in Fig. 2-9.

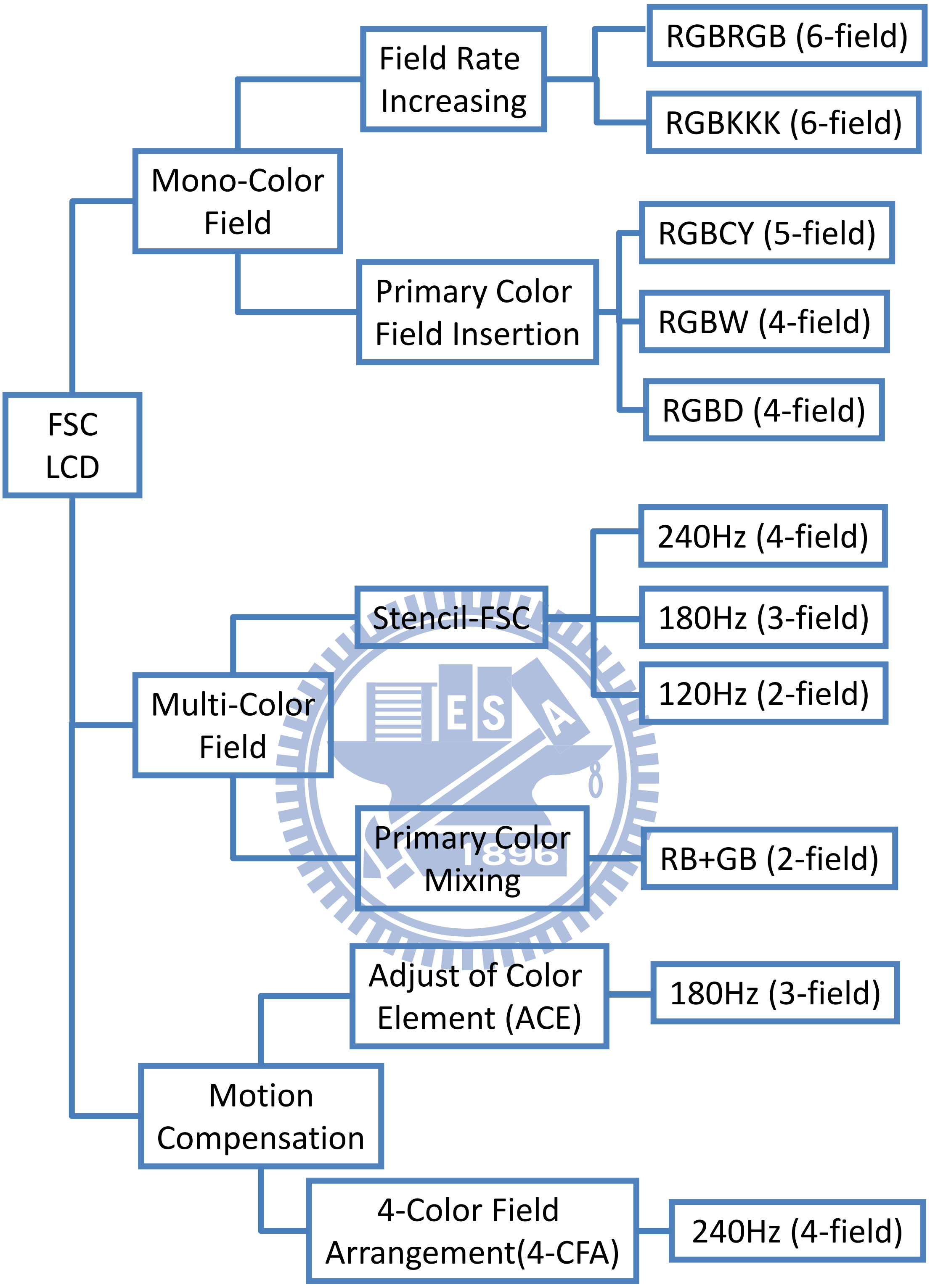


Fig. 2-8 Different kinds of CBU suppression methods in FSC LCD

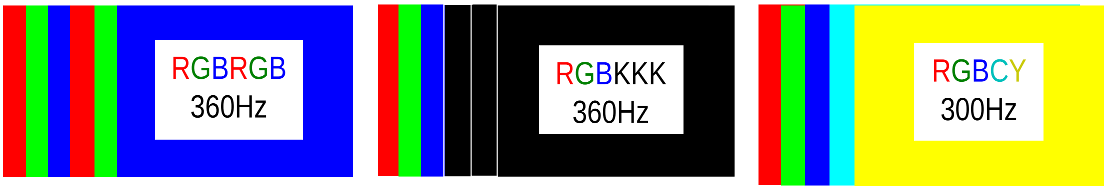
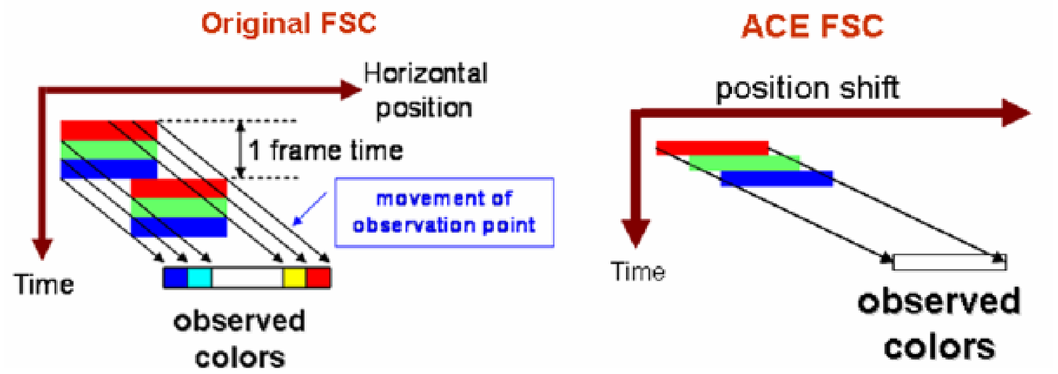


Fig. 2-9 Increasing field rate or adding complementary color to suppress CBU

About Motion Compensation, the dynamic color breakup is suppressed effectively. N. Koma was proposed “Adjust of Color Element on the Eyes” (ACE) [27] and is shown in Fig. 2-10. The ACE method displays red, green and blue fields on different positions of retina when eyes are moving. Therefore, human eyes observe the CBU less image with ACE method. However, if human eyes are moving to positive direction and the ACE method displays negative direction, the CBU phenomenon is observed largely, as shown in Fig. 2-11.



(a) (b)

Fig. 2-10 (a) Conventional and (b) motion interpolation method in FSC-LCDs

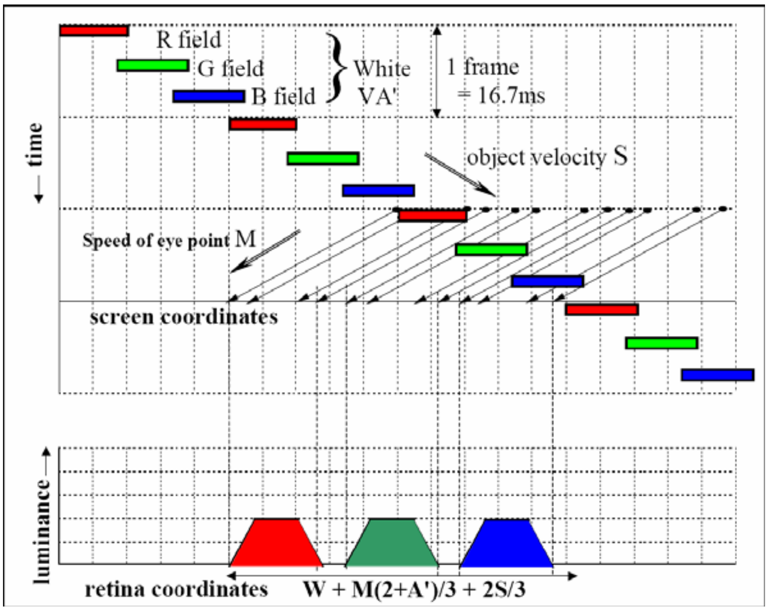
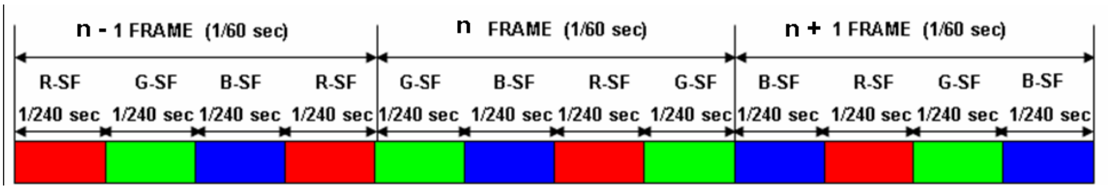
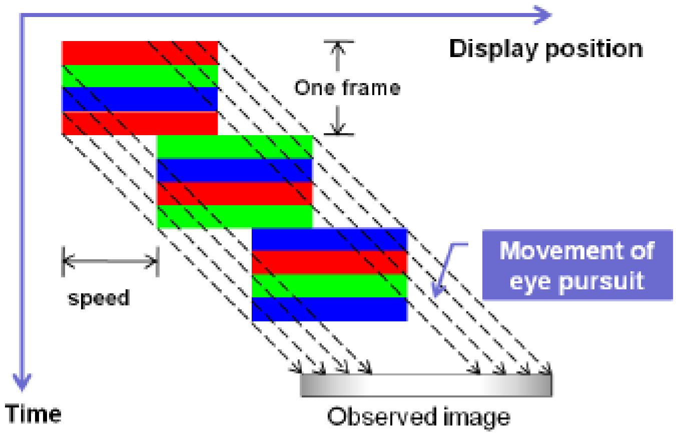


Fig. 2-11 The ACE method displays red, green and blue images from left to right and observer's eyes pursuit the image from right to left.

The Four Color Field Arrangement (4-CFA) of Motion Compensation was proposed by Ya-Ting Hus [28] for suppressing dynamic CBU. The color sequence is displayed as RGBR, GBRG and BRGB in three continuous frames orderly at 240Hz and is shown in Fig. 2-12 (a). This combination of red, green and blue images make the moving edge to be white and the dynamic edge is eliminate, as shown in Fig. 2-12 (b).



(a)



(b)

Fig. 2-12 (a) The color displayed order and (b) the temporal color mixing with 4-CFA method.

Our group further improves the Primary Color Field Insertion of Mono-Color Field. Using 360Hz or higher frame rate is hard to achievable for hardware, because of being constricted to the current technology of liquid crystal response time. The 240Hz frame rate or less is achievable after upgraded the commercial twist nematic (TN) mode LC. Thus, at 240Hz frame rate the W_{min}RGB (minimum white extract from three primary colors) method [20], DRGB (dominant color field of input image plus three primary) method [9] using global backlight.

Our group also proposed the Multi-Color Field, the Stencil Field-Sequential-Color Method [21] using local backlight. These methods greatly suppressed CBU phenomenon. Furthermore, 180Hz stencil method [22] and two-field-sequential method at 120Hz [23] were also proposed for different applications on different panel size.

The main concept of these methods is putting the majority of image contents in the first field, and the intensities of three primary fields are lowered down and are shown in Fig. 2-13. Then four field images combine together to make a full color image. Human will be less sensitive to CBU edge during saccadic eye movement on still image or smooth pursuit movement on moving object and is illustrated in

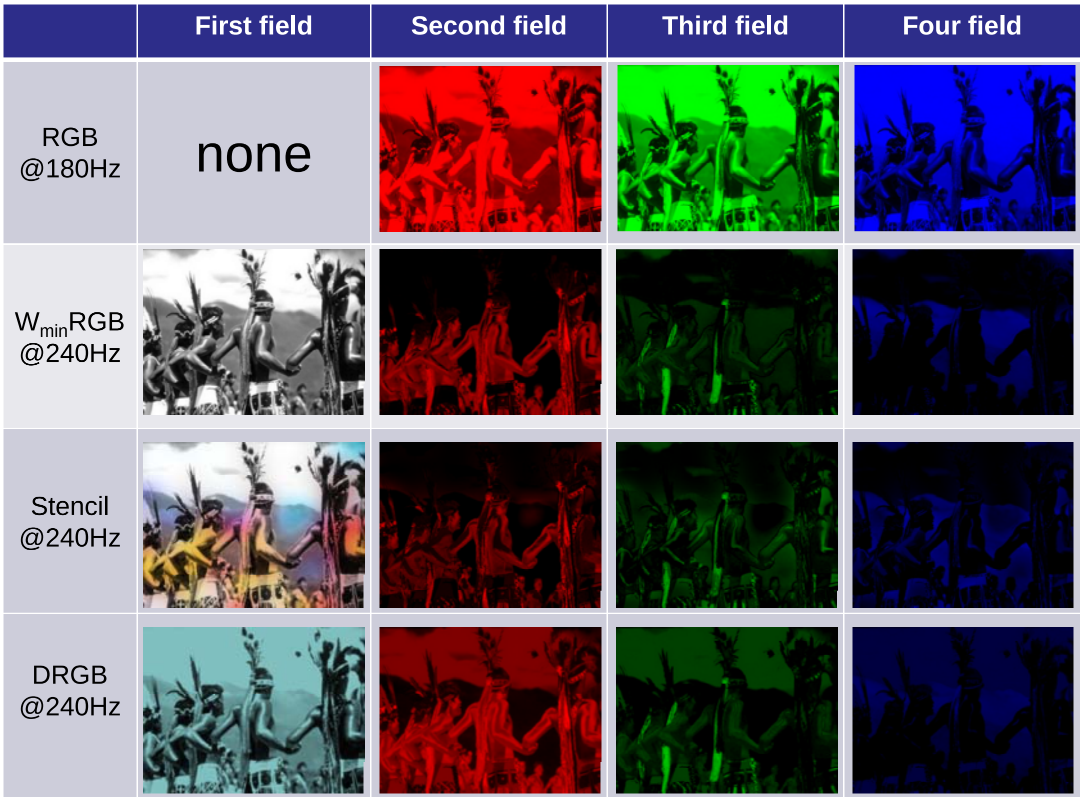


Fig. 2-13 First field contains majority image so than decreasing intensities of rest fields

At 240Hz driving methods are mentioned above, W_{min}RGB and DRGB methods are using global backlight; Stencil method is using local backlight. Because the constriction of hardware specification in 15.4” panel, the support backlight is global, the Stencil method is not included in our choices. Comparing W_{min}RGB and DRGB methods, W_{min}RGB method always displays white backlight in the first field and DRGB method can display majority color in the first field depending on input image. Therefore, WminRGB method averagely consumes more power when comparing with DRGB method does.

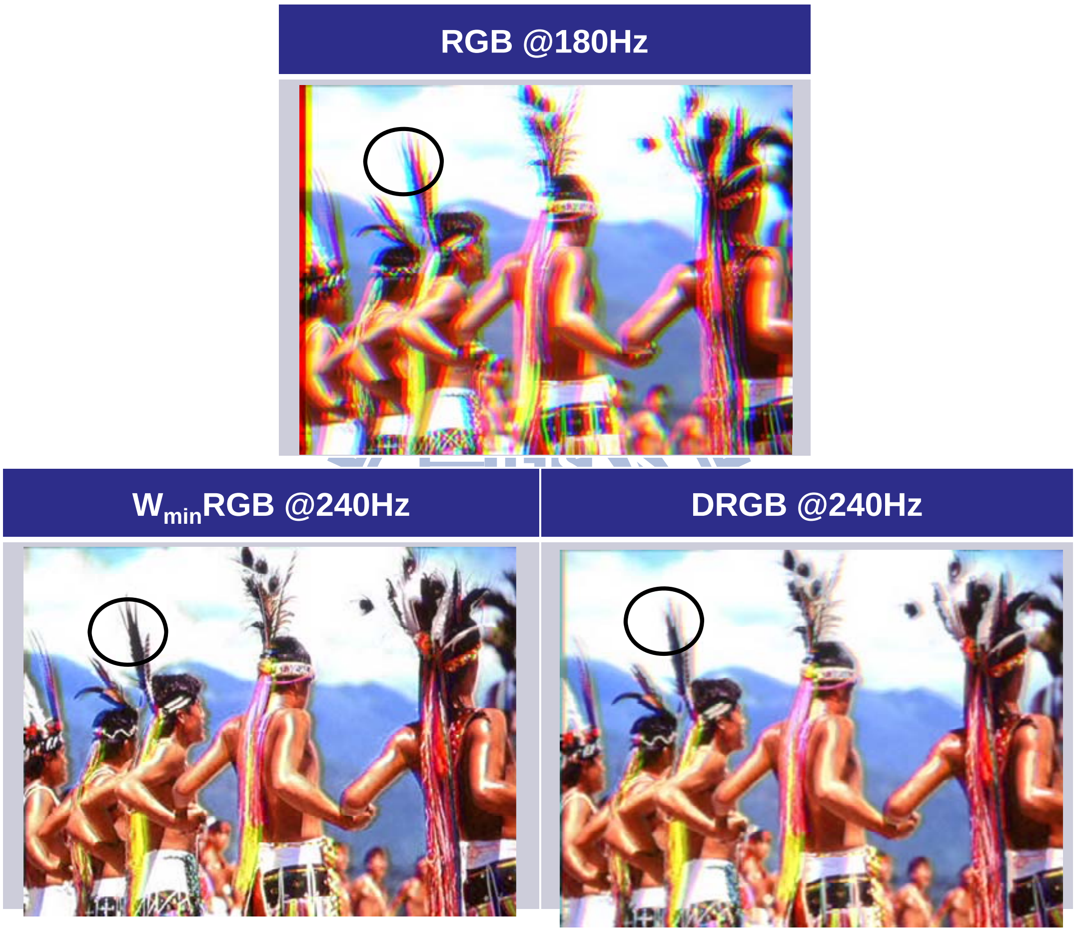


Fig. 2-14 Simulated CBU images from 3 different methods

2.3.1 Concept of the DRGB Method

Ideally, total optical throughput can be simplified into a relation of backlight and digital gray scale value, which is described in Eq. 2-3-1,

$$BL * T(i) = total\ optical\ throughput \qquad \text{(Eq. 2.3-1)}$$

Where *T(i)* is the transfer function from digital gray scale values *i* to transmittance of liquid crystal and T^{-1} is the inverse function. The gamma curve is shown in Fig. 2-155. Between digital values and transmittance should be considered to maintain the white balance.

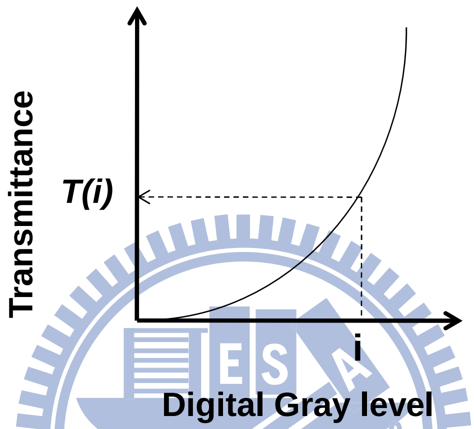


Fig. 2-15 Gamma curve function is related between digital value and transmittance

The DRGB method finds the majority of image information in dominant field according to input image. So, the dominant field image is different image by image. The algorithm of DRGB method is using adaptive backlight to determine the dominant field backlight color (D-field backlight color). According to total optical throughput of the image in conventional LCDs, we can deduce the digital gray scale values and backlight gray scale values in FSC-LCDs by the equation. In the D-field, the gray scale values of backlights are set as BL_r, BL_g and BL_b and backlight on rest of three primary fields are full on. After the D-field backlight (BL_r, BL_g, BL_b) is determined by the DRGB algorithm, Eq. 2-3-2 shows the additional digital gray scale values *d is* calculated and then *r',g',b'* are derived in the following.

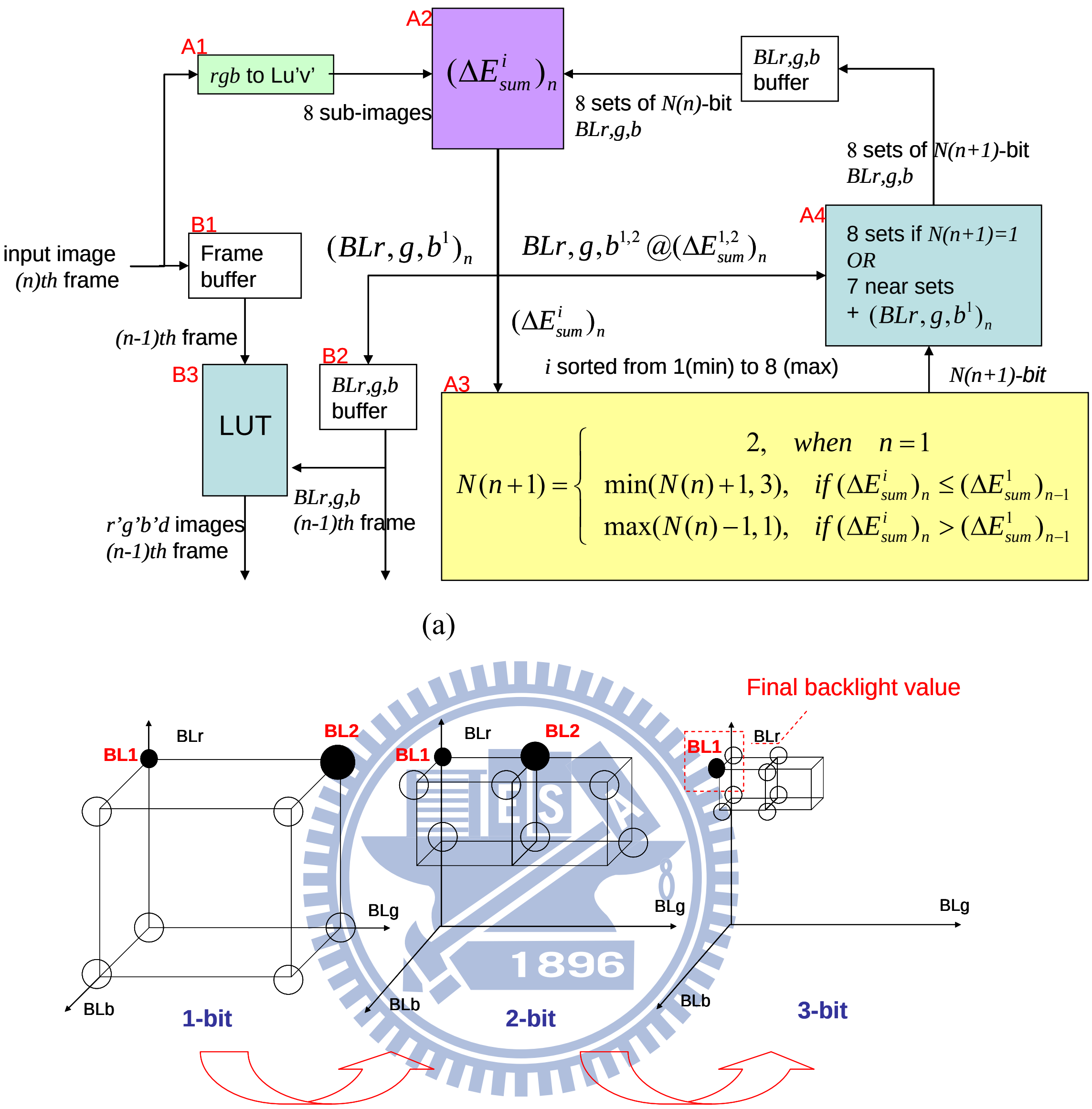
$$d = T^{-1}(\min(\frac{T(r)}{BL_r}, \frac{T(g)}{BL_g}, \frac{T(b)}{BL_b}, 1)) \quad \text{(Eq. 2.3-2)}$$

$$r' = T^{-1}(T(r) - T(d) \times BL_r) \quad \text{(Eq. 2.3-3)}$$

$$b' = T^{-1}(T(b) - T(d) \times BL_b) \quad \text{(Eq. 2.3-4)}$$

$$g' = T^{-1}(T(g) - T(d) \times BL_g) \quad \text{(Eq. 2.3-5)}$$

The feedback control is used on determining the D-field backlight color from backlight choices. When image is loaded into the algorithm, the image is transformed to *CIELUV* color space and down sampled in 2-by-4 sampling rate for decreasing calculation. Then criterion ΔE_{00} is calculated between original input image and simulated CBU image and because there are eight sets of (BL_r, BL_g, BL_b) in first feedback control, there are eight ΔE_{00} values coming in first calculation. Finding the smallest one from eight ΔE_{00} values and then keeping shrink the range of backlight choices. After 3 bit accuracy feedback control approach, the final backlight sets are applicable D-field backlight color for the input image to suppress CBU artifact. The flowchart of DRGB is shown in Fig. 2-16.



(a)

(b)

Fig. 2-16 (a) Flowchart of DRGB algorithm, (b) 3-bit accuracy approach

Because DRGB method needed the whole image contents three times for 3 bit accuracy feedback control approach. The frame buffers are need to storage the whole image contents for calculation. If we want to implement on 15.4" panel without frame buffers, the method can be utilized. Besides, the transformed color space CIELUV is complicated. So the proposed method Fast-DRGB method will simplify the calculation of the DRGB method for hardware implementation and with almost identical CBU suppression effect.

The panel supported by CPT uses commercial upgraded TN mode LC, so the response time of LC is not fast for ideal FSC-LCDs, and then color distortion might happen. In the following section, the factors causing color distortion are discussed.

2.4 Mechanism of Color Distortion

FSC-LCDs are well known to have a wider color gamut by using multi-colored LEDs as a backlight source instead of using color filters to mix color. Therefore, the saturations of three primary LEDs are very high so that increase the 3 apexes of triangle in the color gamut and is shown Fig. 2-17. [24]

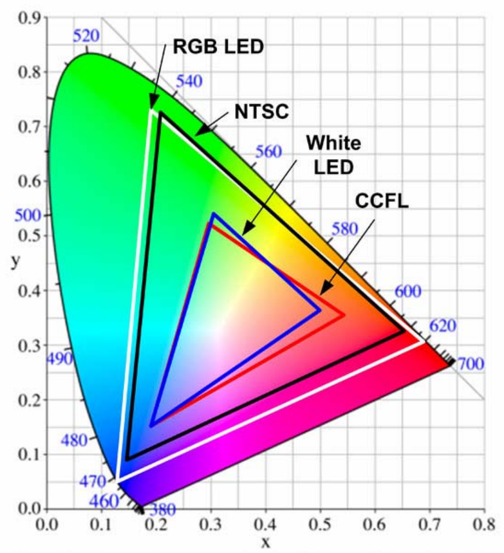


Fig. 2-17 Color gamuts with different backlight sources in CIE xyY color space

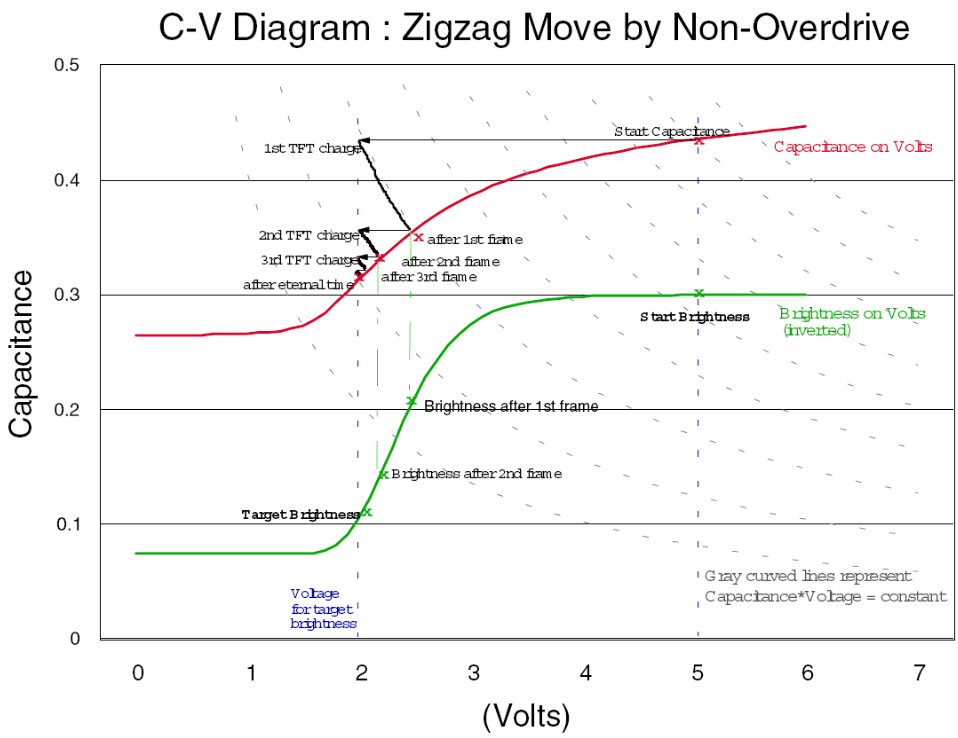
However, as mentioned before FSC-LCDs need at least 180Hz frame rate to make a color image. Thus, the LC response time is needed higher than 180Hz so that LC can be rotated to the specific position in each field. When LEDs emit through LC, the color of image is correct. Optically Compensated Bend (OCB) mode LC is most used in FSC-LCDs for its fast response time. However even the OCB has fast response time LC, they still have color distortion issue because of the structure of thin film transistor (TFT) arrays.

Furthermore, OCB mode LC is not popular in commercial product. Twist nematic (TN) mode LC is still mainly applied on LCDs by companies. After upgrading TN mode, different kinds of functional TN mode LCs are created such as speed-up TN mode LC. Although the response time of speed-up TN is not fast than one of OCB mode, the TN mode LC has enough time to rotate to certain position with modified driving methods on circuit board.

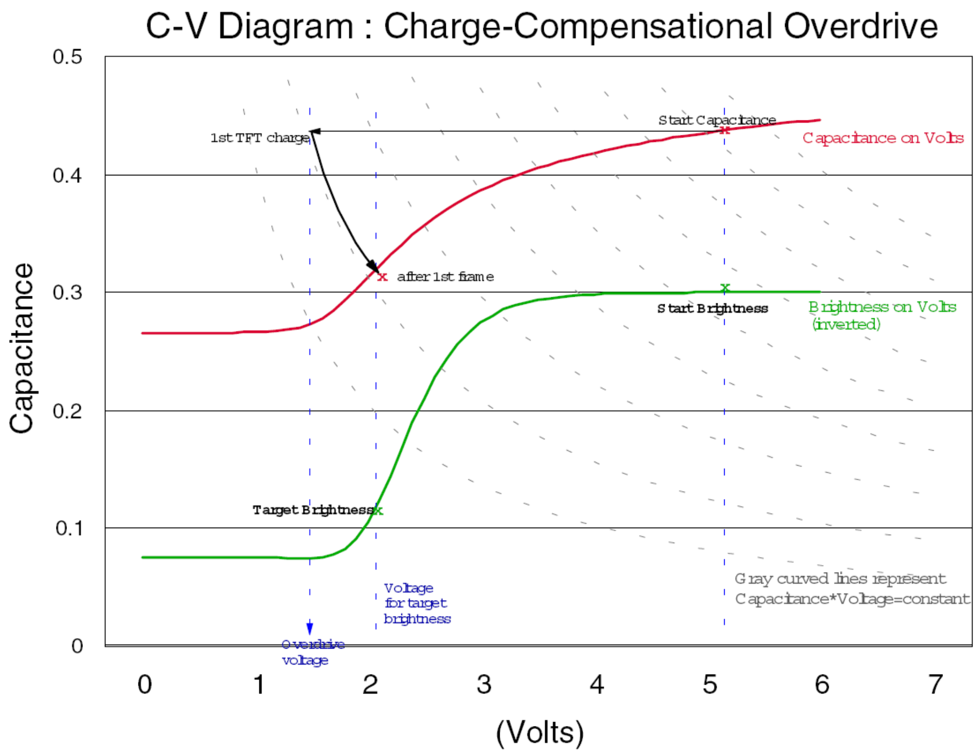
However, TN mode LC is not fast enough for the proposed Fast-DRGB method to implement on hardware. So when rotating the liquid crystal in dominant field, the target position is hardly achieved. The chance of achieving target position depends on how much time gray to gray requires. And the situation is the same in the rest three primary fields, the finally presented image is not correct.

2.5 Prior Arts to Characterize Color Distortion

The color distortion on OCB mode seems irrational, the reason is the capacitance multiple voltage is constant. Figure 2.18 (a) shows that setting the voltage from start to target value, and later the voltage will follow the CV=constant curve to make the target value wrong. Therefore, a method called overdrive was proposed to solve the issue as shown in Fig. 2-18 (b) [25]. Setting the target value higher than estimated value, the correct voltage will be achieved after stabilization in LC.



(a)



(b)

Fig. 2-18 (a) Target voltage is unachievable in one frame time, (b) Target voltage is achievable using overdrive method

Overdrive method needs to give higher voltage in the beginning. If the voltage is too large and LED backlights cannot afford it, the LED backlights are easily burned-out.

The other method is building a color model to characterize color distortion issue. The model consists of two stages. First is a linear transform from radiometric scalars to tristimulus values. Equation 2.5-1 shows the basic form of linear transformation. Equation 2.5-2 shows more precious and complicated transformation. The symbol N means the accuracy bit number of display system and d_R is the digital signal value of red field. The second stage is non-leaner transform between digital signal values in each color field and each radiometric scalar. These models are GOG, S-curve, and polynomial and are shown in Eq. 2.5-3, Eq. 2.5-4 and Eq. 2.5-5 [26]. Symbol i means the each radiometric scalar (R, G, and B). These models derive the new digital signal values. Then, inputting the new digital signal values into panel can measure expected tristimulus values.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = A * \begin{bmatrix} R(\frac{d_R}{2^N - 1}) \\ G(\frac{d_B}{2^N - 1}) \\ B(\frac{d_G}{2^N - 1}) \end{bmatrix}, \text{ where } A = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix} \qquad \text{(Eq. 2.5-1)}$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = A * \begin{bmatrix} 1 & R & G & B & RG & GB & BR & RGB & R^2 & G^2 & B^2 \end{bmatrix}^T \qquad \text{(Eq. 2.5-2)}$$

GOG model: $i = \begin{cases} \left\{ k_{g,i} * \left(\frac{d_i}{2^N - 1} \right) + k_{o,i} \right\}^{r_i} & , \left\{ k_{g,i} * \left(\frac{d_i}{2^N - 1} \right) + k_{o,i} \right\} \geq 0 \\ 0 & , \left\{ k_{g,i} * \left(\frac{d_i}{2^N - 1} \right) + k_{o,i} \right\} \leq 0 \end{cases}$ (Eq. 2.5-3)

S-curve model: $i = a_i * \left(\frac{d_i}{2^N - 1} \right)^2 + b_i * \left(\frac{d_i}{2^N - 1} \right) + c_i$ (Eq. 2.5-4)

Polynomial model: $i = A_{RR} * f\left(\frac{d_i}{2^N - 1} \right) + A_{RG} * f'\left(\frac{d_i}{2^N - 1} \right) + A_{RB} * f'\left(\frac{d_i}{2^N - 1} \right)$

, where $f\left(\frac{d_i}{2^N - 1} \right) = \frac{\left(\frac{d_i}{2^N - 1} \right)^{\alpha}}{\left(\frac{d_i}{2^N - 1} \right)^{\beta} + c}$ and f' is the first derivative of f (Eq. 2.5-5)

Device independent and each field channel independent are prior calibrations to build the color model. Because the new digital signal values are derived from linear and non-linear transformation, some new digital signal values are the same even in different luminance. Therefore, this characterization might lower down some color saturations. However, the color distortion can be calibrated to make acceptable image quality. Trade off happens between color saturation and image quality.

2.6 Summary

In previous discussion, CBU phenomenon accompanies with FSC-LCDs during eye movement. DRGB method uses a adaptive backlight color as a dominant field image to decrease the intensities of rest field images. Therefore, less CBU edges are perceived. However, hardware implementation with DRGB method is still not achievable. The main reason is the complicated calculation in DRGB method. Therefore, simplifying DRGB method is a must. In next chapter, the three separated image is used to decrease calculation time, and different criterion on determining adaptive backlight with less complicity are utilized in the Fast-DRGB method.

Chapter 3

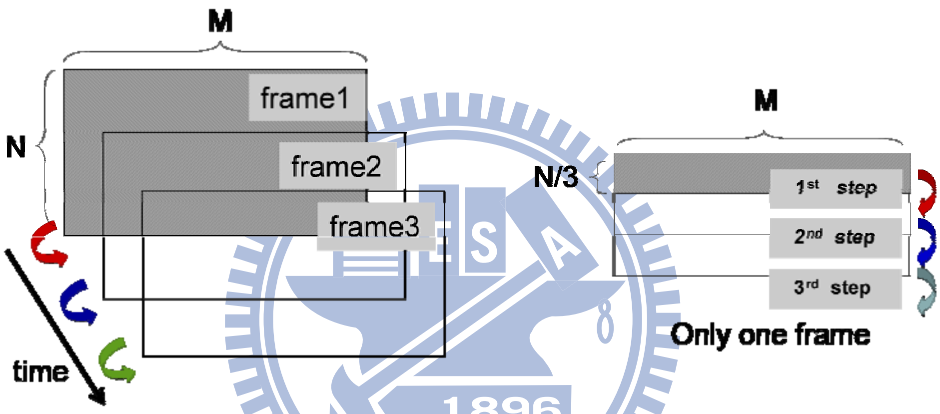
Real-Time Adaptive Backlight Algorithm Using the Fast-DRGB Method

In order to realize the Fast-DRGB concept in FSC-LCDs, the real-time adaptive backlight algorithm of the Fast-DRGB method was proposed. The proposed algorithm can determine one set of backlight colors (combination of red, green, and blue colors) in less than one frame time. When input signals are inserted into the FPGA which is configured the Fast-DRGB algorithm, the 15.4" panel displays a dominant field image, red, green and blue images at 240Hz sequentially in a real-time process.

3.1 Concept of Real-Time Adaptive Backlight in Fast-DRGB

The FSC-LCDs used temporal integration of red, green, and blue images at 180Hz field rate to make a colorful image. However, CBU accompanied FSC technology when a relative velocity existed between human eyes and image. The reason for CBU is human eyes perceive high intensity in each field at different locations of the retina. Therefore, adding a majority image color into the dominant field (D-field) causes red, green, and blue fields to decrease their intensity. Then four field images combine into a full color image with less rainbow effect during eye movement.

The concept of DRGB method is fully discussed in section 2.3.1. However, the calculation of the DRGB method is too complicated for hardware implementation. Therefore, we modified the DRGB method for simplicity. First, we abandoned transforming color space to CIELUV, and used the original digital signal values in RGB color space. Then, the criterion for judging the applicable color in three step convergence was replaced by summing the difference of digital signal values between the original image and the simulated CBU image. Second, the DRGB method used the entire image contents three times during three step convergence. Fig. 3-1 shows Fast-DRGB simply separates the image into three parts and uses three parts of image to derive the applicable backlight color during three step convergence approach. Each part has the relationship with other two parts so image can be separated into three parts. Therefore, determining the applicable backlight color required less one frame time for hardware implementation.



(a) (b)

Fig. 3-1 (a) Three frame times required using DRGB, (b) Less than one frame time required using Fast-DRGB

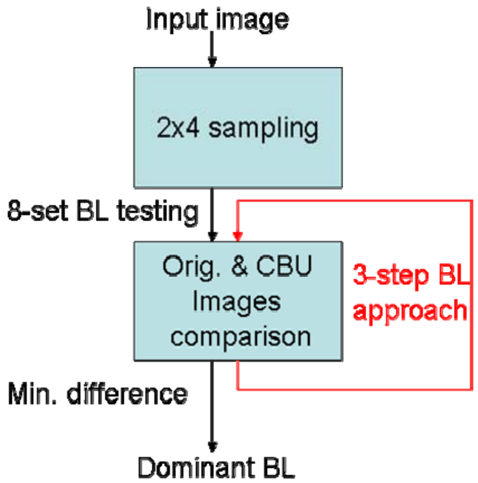


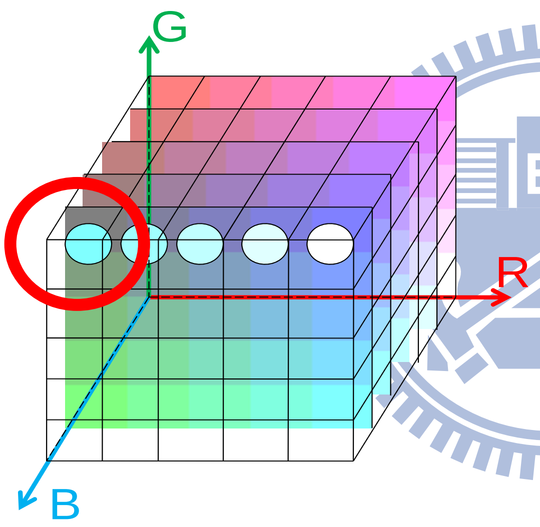
Fig. 3-2 Flowchart of Fast-DRGB algorithm

3.2 Algorithm of Real-Time Adaptive Backlight in Fast-DRGB

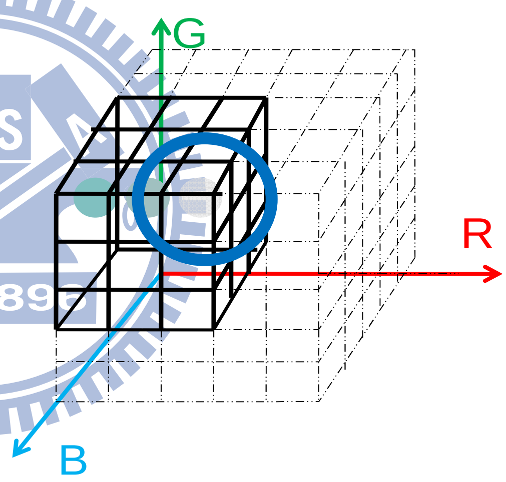
The algorithm flowchart for determining adaptive backlight is shown in Fig. 3-2. The input image was sampled in 1/8 sample period rate and tested by eight backlight colors from the D-field backlight choices. Then, we subtracted digital image value of original image from digital image value of simulated CBU image in eight tested backlight colors. The criterion judges what color is applicable from eight tested colors. The smallest criterion was chosen from eight criterion values. After using three step convergence approach, the applicable D-field backlight color was determined.

The algorithm needed backlight choices symbolized as a large cube. The little cube represented a color set (BL_r, BL_g, BL_b). For instance, there are 125 total color sets in a large cube used for algorithm and are shown in Fig. 3-3.

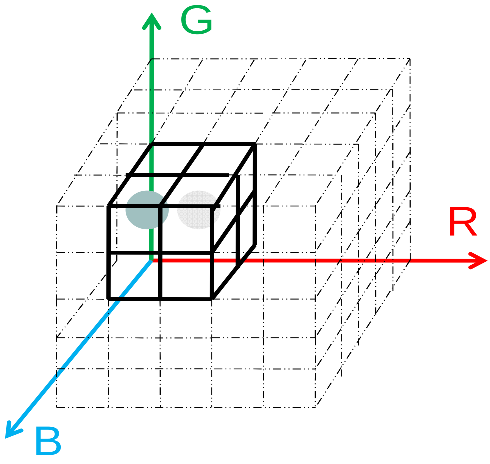
In the first step of convergence process, the eight chosen colors in the corner of cube were selected as the first tested backlight colors and are shown in Fig. 3-3(a). Using eight tested colors to calculate summing of differences (criteria) between the original image and the simulated CBU image, the smallest difference were found (inside of the red circle as shown in Fig. 3-3(b)). The found smallest difference corresponds to the applicable backlight color in the first convergence. The color circled in red is the majority color of first step backlight determining process. Before the second convergence began, backlight choices as in Fig. 3-3(a) converged as in Fig. 3-3(b). Following the same testing convergence as first calculation, we find the second smallest difference (e.g. inside of the blue circle as shown in Fig. 3-3(b)). The color circled in blue also is the majority color of first and second areas of image. In the third step convergence process, backlight color choices are converged in only eight testing colors as shown in Fig. 3-3(c). Then the D-field backlight color was finally determined from eight testing colors left.



(a)



(b)



(c)

Fig. 3-3 Backlight choices in (a) 1st approach, (b) 2nd approach, (c) 3rd approach

The Fast-DRGB method used three separated images to calculate majority backlight color using three step convergence approach. The DRGB method used entire image details to determine backlight color, so the Fast-DRGB method decreased calculation time. The DRGB method transformed the color space to CIE LUV and the Fast-DRGB method simply used digital signal values in the RGB color space. The DRGB method calculated CIEDE2000 (E_{00}) values between the original image and the simulated CBU image to determine a set of adaptive backlight color in dominant field. The Fast-DRGB method used summing of difference in digital signal values between the original image and the simulated CBU image to determine a set of adaptive backlight color in dominant field. Therefore, the Fast-DRGB method simplified procedures during determining a set of adaptive backlight color.

3.3 Summary

The DRGB method indeed suppresses CBU phenomenon effectively. However, the DRGB method considered so many details, thus increasing its complication. Therefore, the Fast-DRGB method improved the procedure for implementing on 15.4” panel. The panel was developed and was cooperation with Chunghwa Picture

Tube, LTD.

The simulated comparison of Fast-DRGB method and DRGB was used to prove that the CBU phenomenon was suppressed similarly and will be discussed in next chapter. Then the hardware implementation of Fast-DRGB will be discussed.

Chapter 4

Simulation in the Fast-DRGB Method

Concept of the Fast-DRGB method was introduced in the previous chapter. The Fast-DRGB method simplified the calculation of DRGB method so that the Fast-DRGB method could be implemented on hardware. Simulation of Fast-DRGB in suppressing CBU phenomenon was compared with those of DRGB, KRGB and W_{min}RGB methods at 240Hz field rate. Testing images were presented to show how effectively the CBU phenomenon was suppressed.

4.1 Color Breakup (CBU) Phenomenon Simulation using software

As previous chapters discussed, the CBU phenomenon happens when human eyes perceive a relative velocity with displayed image. Different field images are located at different positions of the retina, so after temporal color mixing the brain perceives CBU. However, color temporal mixing cannot be simulated in software. Therefore, we assume different field images are moving and human eyes are unmoving, creating a relative velocity between images and human eyes. In this study, CBU images were simulated using conventional LCDs and are shown in Fig. 4-1. Using this simulation, different CBU suppression methods were verified directly.

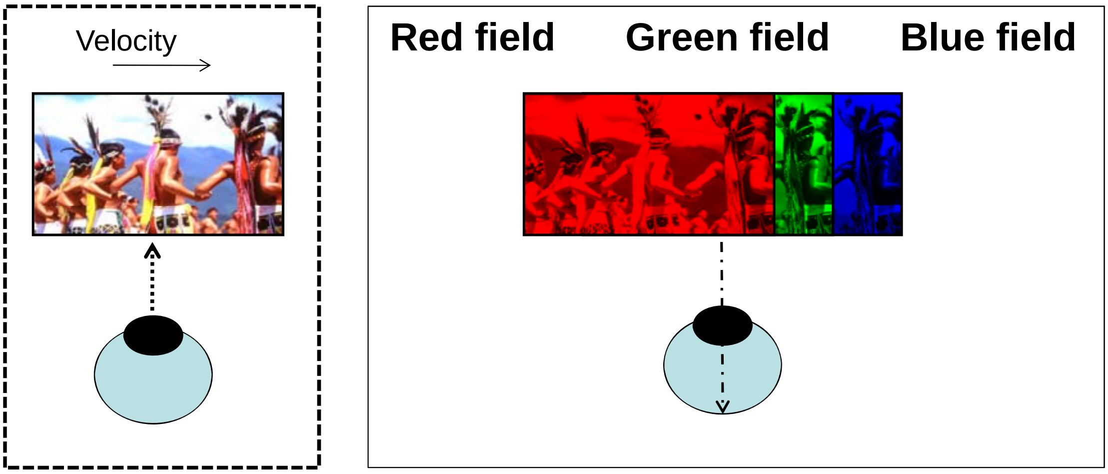


Fig. 4-1 Concept of simulated CBU image

Besides the directly simulated CBU images, CIEDE2000 formula was used to estimate the CBU suppression level. A simulated CBU image using the proposed method derived a CIEDE2000 value (ΔE_{00}) and then compared with ΔE_{00} in conventional FSC-LCD at 180Hz. So, a relative CBU value was calculated from ΔE_{00} between the proposed method and conventional method. The smaller the relative CBU value, the more effective the proposed method is in suppresses CBU.

4.2 Evaluation of Color Breakup - ΔE00 Comparison

4.2.1 DRGB, W_{min}RGB, and KRGB methods

The testing images from the USC-SIPI image database simulated how CBU phenomenon is suppressed and are shown in Fig. 4-2. The chosen pictures were tested in the DRGB, W_{min}RGB and KRGB methods to calculate relative CBU values. The DRGB method had lower relative CBU values than other two methods did. This meant the DRGB method suppressed CBU effectively than W_{min}RGB and KRGB methods and is shown in Fig. 4-3. Simulated CBU images in these methods are illustrated in Fig. 4-4.

In Lena pictures, the brim of hat and wood behind her shows that less CBU phenomenon was observed in the DRGB method. In the KRGB method, obvious CBU phenomenon was perceived in the brim of hat and other places. In W_{min}RGB method, the CBU suppression level was effective than it in KRGB. However the CBU suppression level was not effective in W_{min}RGB method than in the DRGB method.

In Bean2 pictures, simulated CBU image in the DRGB method seemed worse than in the KRGB method. Because the backlight color was global full on and beans had many edges between each other, the determined backlight color in dominant field was not applicable for every bean. Therefore, simulated image seemed not suppress CBU effectively. However, if the local backlight was used the multi-edge issue could be improved.

Fig. 4-2 Images from USC-SIPI image data base

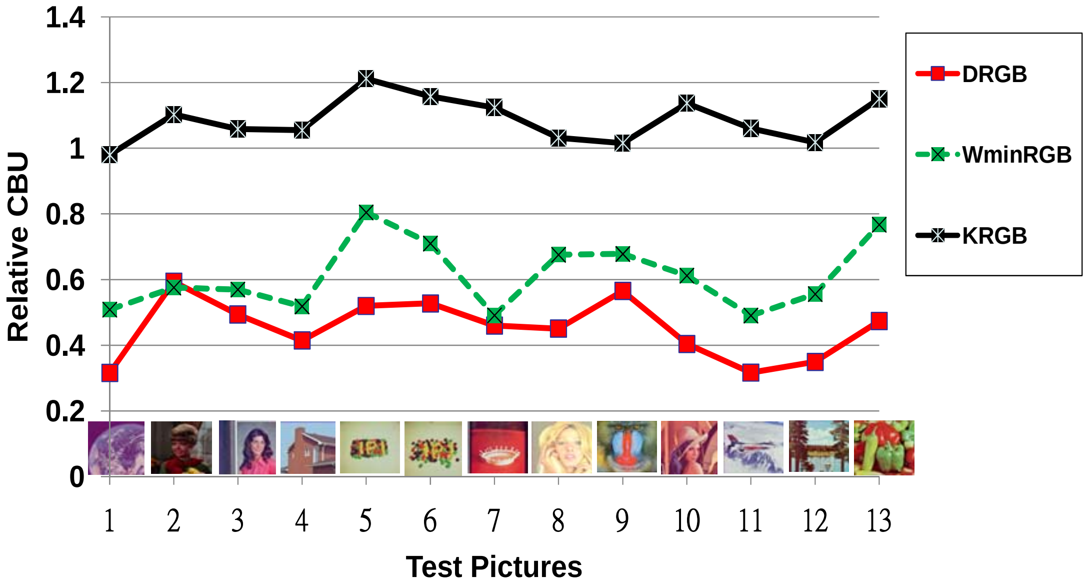
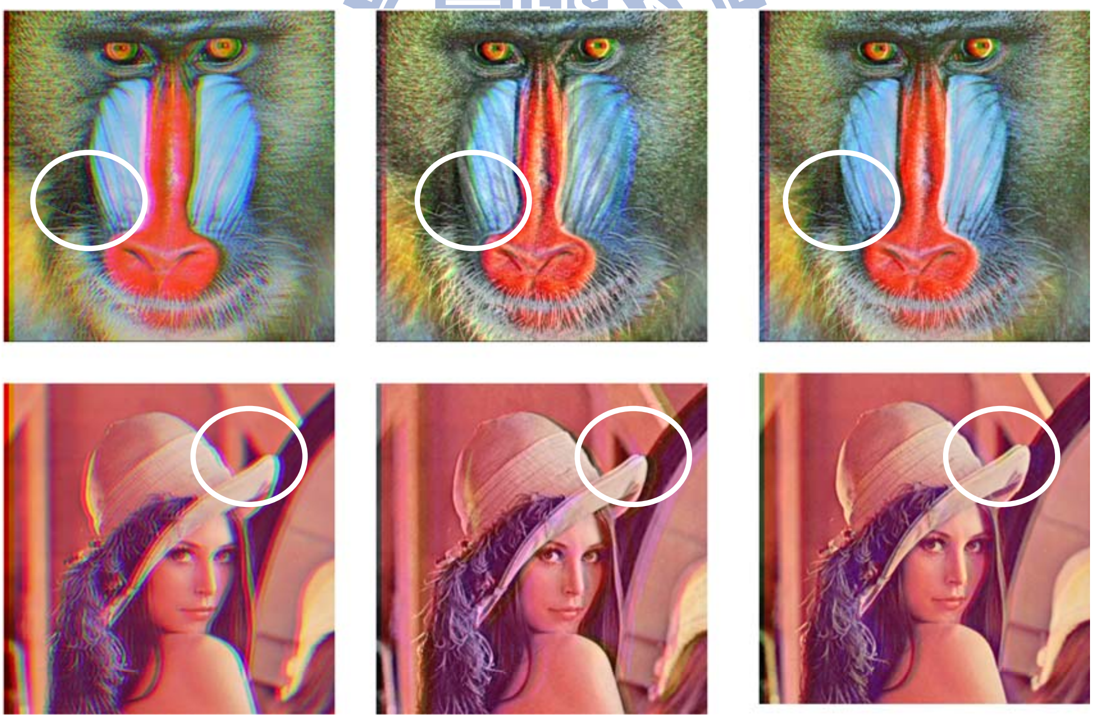


Fig. 4-3 Relative CBU values in DRGB, W_{min}RGB and KRGB methods.



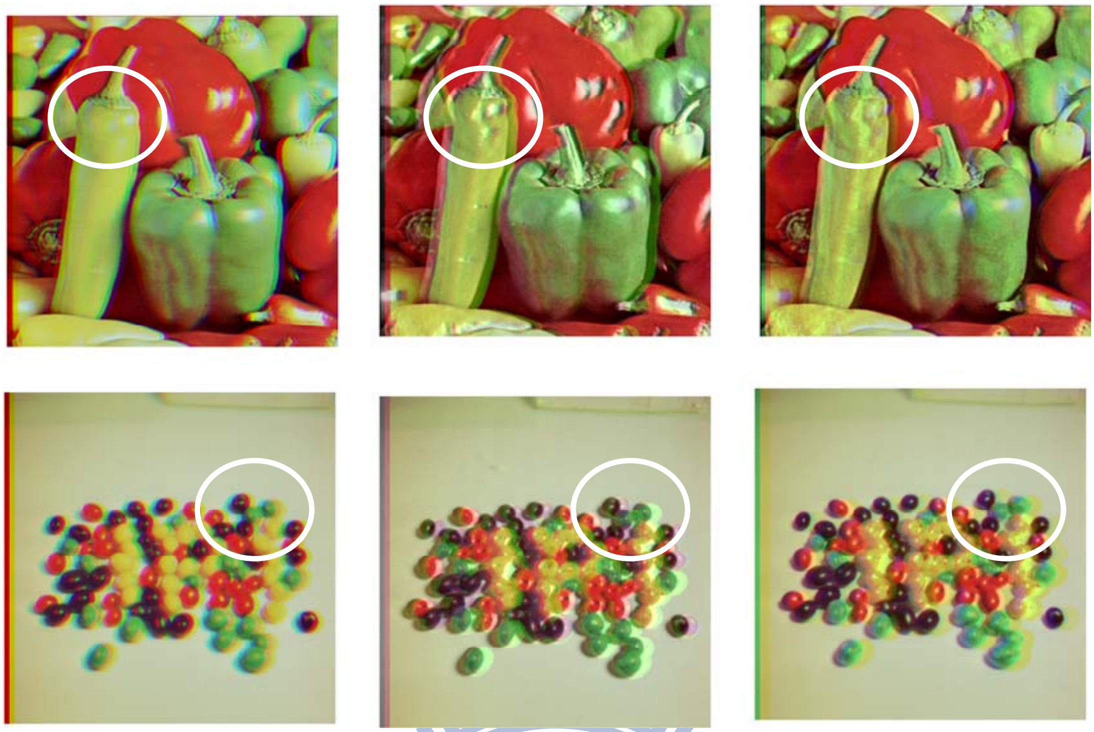

(a) (b) (c)

Fig. 4-4 Simulated CBU images in (a) KRGB, (b) $W_{min}RGB$, and (c) DRGB methods.

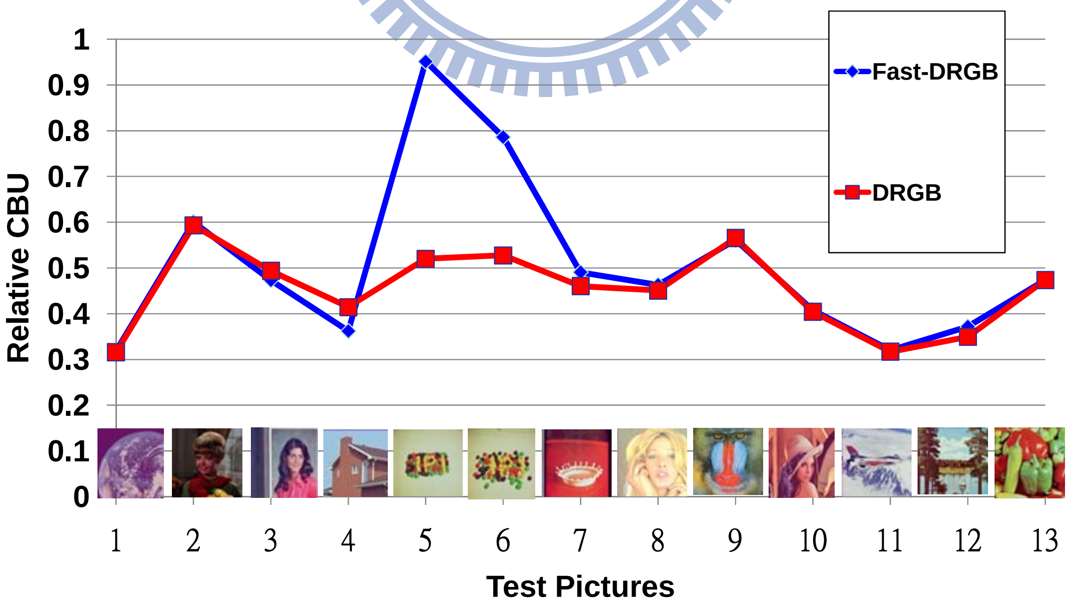


Fig. 4-5 Relative CBU values in DRGB and Fast-DRGB methods.

4.2.2 Fast-DRGB and DRGB methods

Using the same pictures to derive relative CBU values in the Fast-DRGB method and comparing with values in the DRGB method. The comparison is shown in Fig. 4-5. In most part of images, the relative CBU values were similar. However, some images such as Bean1 and Bean2 had higher relative CBU values. Because the Fast-DRGB method used three separated parts of original image to derive three-step convergence approach as shown in Fig. 4-6, the first chosen backlight color was not suitable when doing the first step convergence. In second step convergence the backlight color was not converged applicably to match the second area of image. Therefore, the backlight color was not applicable for CBU suppression. Although some testing pictures had higher relative CBU values in the Fast-DRGB method than those in the DRGB method, the average relative CBU value remained similar. This described the Fast-DRGB method had similar CBU suppression effect. However, the Fast-DRGB method needed less calculation time than DRGB methods.

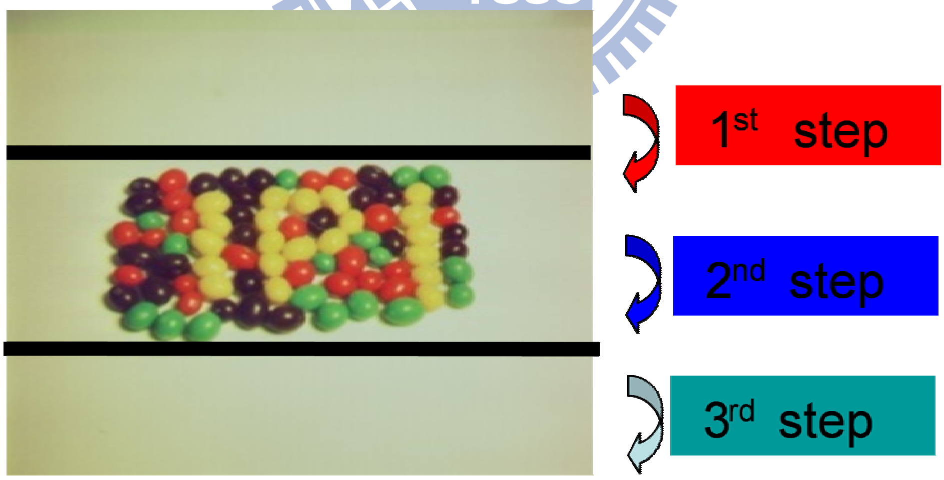


Fig. 4-6 Three-step convergence approach illustration

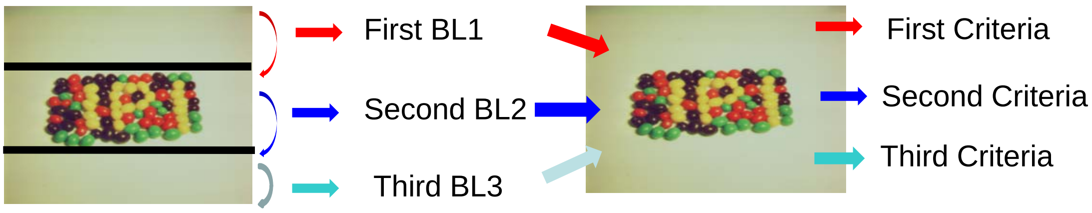


Fig. 4-7 Solution of inapplicable backlight determination

The solution of inapplicable backlight color is shown in Fig. 4-7. In three step convergence approach, each step determines a backlight color. Then using each backlight determines each criterion in whole image. The backlight corresponds smallest criterion is the adaptive backlight color of this image.

4.3 Summary

Using software to simulate CBU phenomenon images was a direct way to know how effective CBU was suppressed. Another method to quantify CBU suppression used CIEDE2000 value (ΔE_{00}). Relative CBU value was derived from dividing ΔE_{00} of a proposed method by ΔE_{00} of the conventional FSC method. The DRGB method had lower relative CBU values compared with W_{min}RGB and KRGB did. Simulated CBU phenomenon images showed the DRGB methods suppressed CBU effectively than other two methods. Besides, the Fast-DRGB method had similar relative CBU values compared with the DRGB method. This meant the Fast-DRGB method also suppressed CBU effectively. Although in some images had higher relative CBU values in Fast-DRGB method than those in the DRGB method, the Fast-DRGB method still suppresses CBU effectively. And Fast-DRGB had the advantage of simplicity in calculating applicable in dominant field for hardware implementation. After simulation of the proposed Fast-DRGB method, we already knew how effectively the Fast-DRGB method did. The next section will discuss hardware implementation using the concept of the Fast-DRGB method.

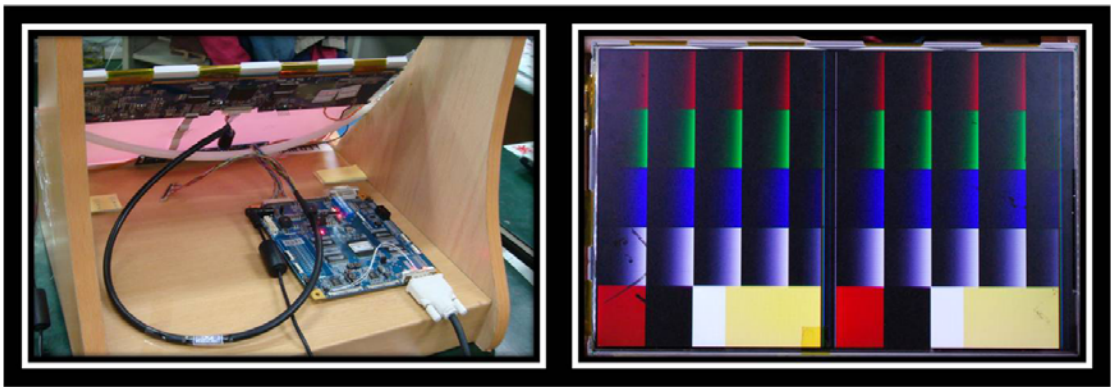
Chapter 5

Hardware Implementation in the Fast-DRGB Method

Previous simulation described that the Fast-DRGB method has similar CBU suppression level compared with the DRGB method. However, the Fast-DRGB method simplifies the calculation of the DRGB method. Therefore, in this chapter implementing the Fast-DRGB method on hardware was discussed. Using the 15.4" panel to display the image and taking CBU pictures. The pictures with the Fast-DRGB algorithm showed that the calculation time is workable for hardware. The CBU pictures directly verified how effectively the Fast-DRGB method suppressed CBU. The results were correspondent to simulation of the Fast-DRGB method.

5.1 Hardware Platform

The project was cooperation with Chunghwa Picture Tube, LTD. CPT supported a 15.4" panel and a field programmable gate arrays (FPGA) and are shown in Fig. 5-1. The panel used two-gate-line driving at the same time to gain more charging time for LC and the panel field frequency rate was 240Hz as shown in Fig. 5-2. The 15.4" panel consisted of a timing control module (region 3), two SDRAM modules (region 4), a source control module (region 1), a gate control module (region 2), a 3-in-1 LED driver module (region 5), and a power supply (region 6) and are shown in Fig. 5-3.



(a) (b)

Fig. 5-1 (a) panel circuit and FPGA (b) 15.4” panel

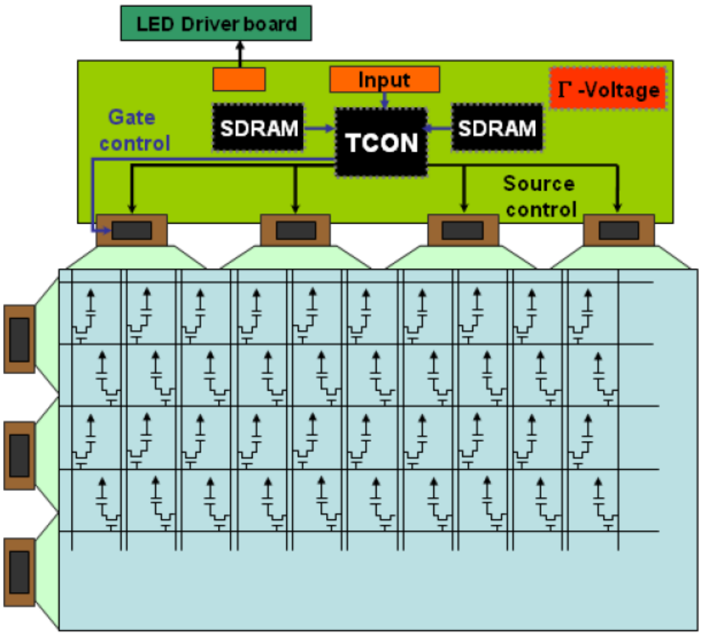


Fig. 5-2 15.4” FSC panel cell array and driving circuit

A field programmable gate arrays (FPGA) was configured the Fast-DRGB algorithm using HDL hardware language. The FPGA had three channels. Input signal channel was DVI, digital visual Interface, which transmitted high quality image data stream from input source (region 7). A power channel was 12 volt (region 8). Output signal channel used LVDS, Low Voltage Differential Signaling, transmitted real-time process image data stream into 15.4” panel modules. The above descriptions are shown in Fig. 5-4.

Therefore, when the notebook connected to input channel of FPGA, the data stream transmitted into FPGA and started to calculate new image data stream using Fast-DRGB algorithm in a real-time process. Then, the output channel transmitted new image data stream into 15.4" panel modules, and displayed a real-time FSC-LCD image.

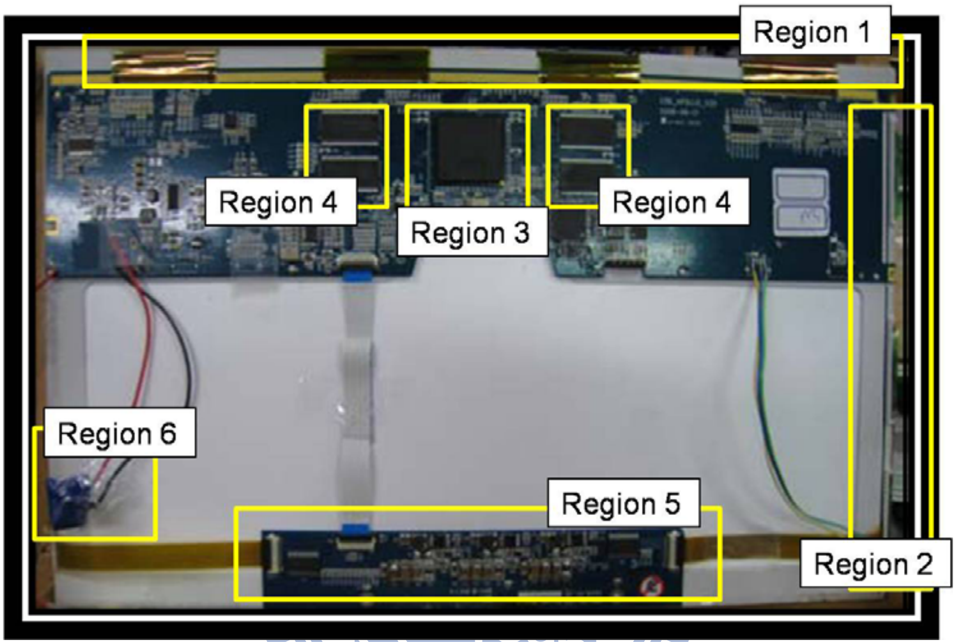


Fig. 5-3 15.4" display circuit contains different modules

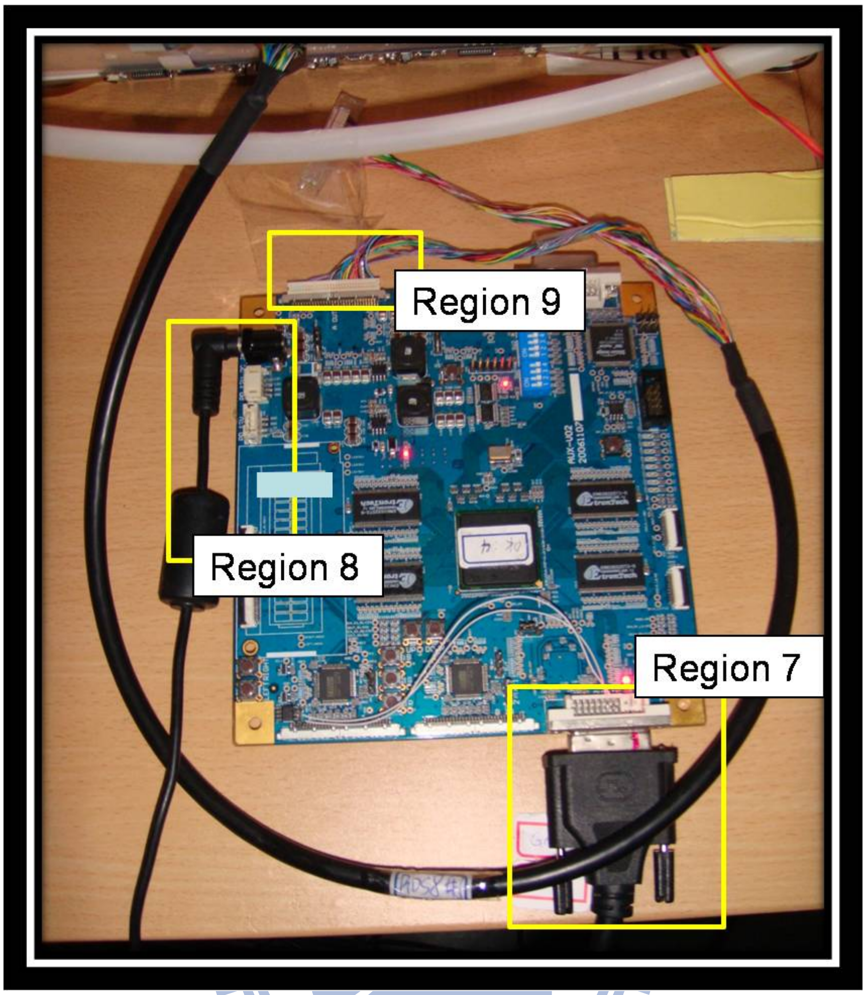


Fig. 5-4 FPGA with Fast-DRGB algorithm contains three modules

5.2 CBU Images Comparison in a Real-Time Process

After settling up the hardware, we had to verify how effectively the Fast-DRGB method suppressed CBU effect. The direct way was taking the CBU pictures. As Fig. 5-5 shows that the laptop transmitted data stream into the Fast-DRGB modules and then derived a new data stream into 15.4” panel modules. And the laptop also sent a control signal into X-Y moving table to move back and forth and a camera settled above the X-Y moving table took CBU pictures at a certain time.

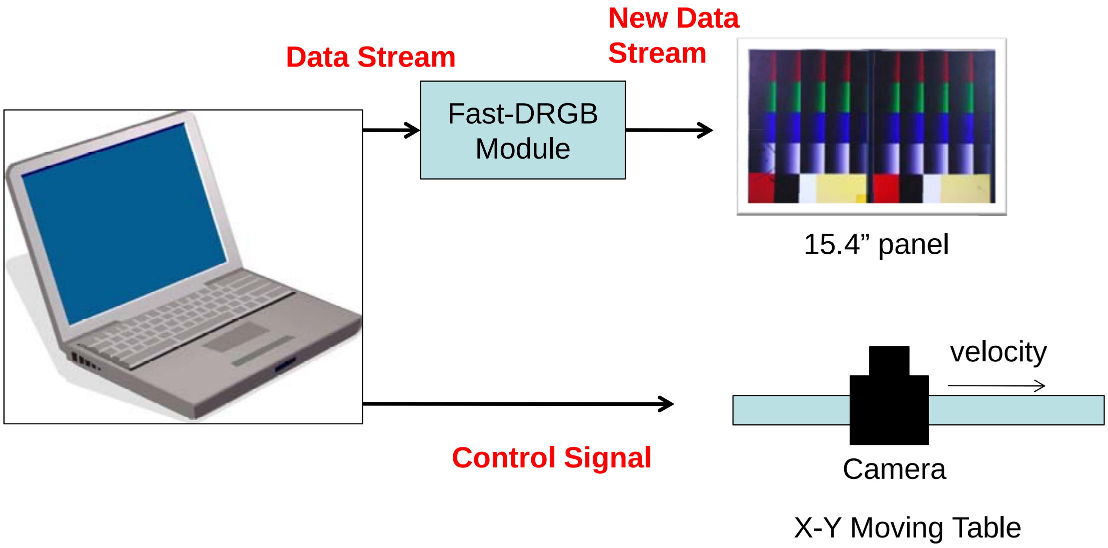
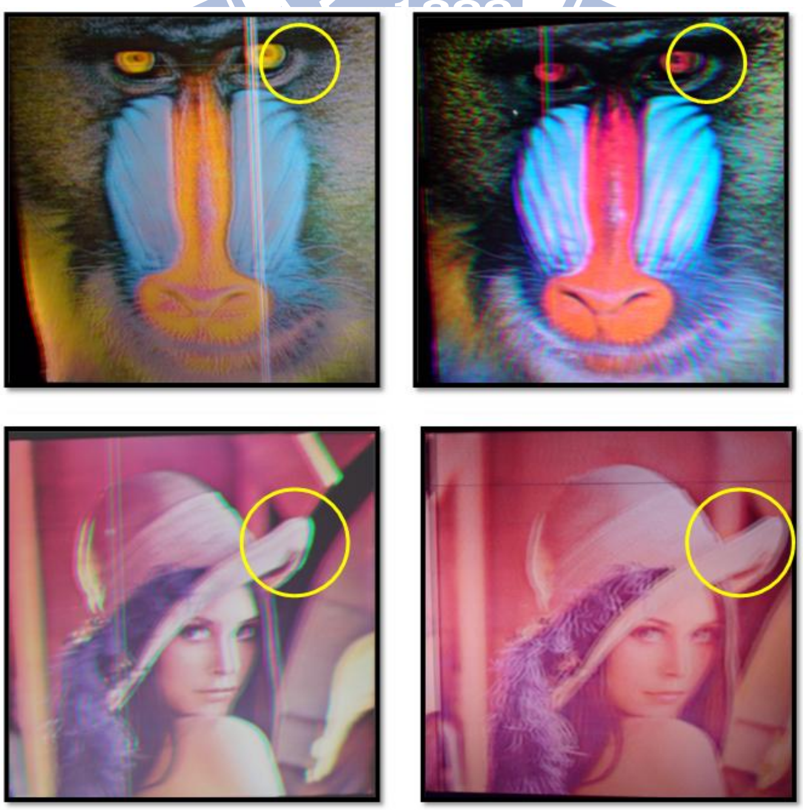


Fig. 5-5 Using camera tracking to take CBU pictures

We used camera on the X-Y moving table to take CBU pictures of two driving methods. One is conventional driving method at 180Hz field frequency. The other is the Fast-DRGB method at 240Hz field frequency. Therefore, comparing these two kinds of CBU pictures could verify how effectively the Fast-DRGB method suppressed CBU artifact.



(a) (b)

Fig. 5-6 CBU images (a)with conventional driving RGB method (b)with the Fast-RGB method

In these CBU pictures, we observed the clear CBU artifact on the edge in conventional method which is circled in yellow as shown in Fig. 5-6(a). The eyes of baboon, the brim in Lena's hat, the surface of pepper, and the edge of beans showed that the Fast-DRGB method suppressed CBU artifact than conventional method did and are shown in Fig. 5-6(b). The videos showed that the comparison between conventional RGB driving method and Fast-DRGB method. When moving camera back and forth horizontally, we could compare the CBU suppression level between two methods.

Conventional RGB driving method: http://www.youtube.com/watch?v=3srhHeHpkJM

Fast-DRGB method: http://www.youtube.com/watch?v=yZZSEvHdl7w

5.3 Discussions

In this chapter we used the FPGA to verify the concept of the Fast-DRGB method to suppress CBU artifact existed in FSC LCDs, and implemented the Fast-DRGB algorithm on hardware. Using the notebook to input the data stream into FPGA and output modified data stream transmitted into the 15.4” panel supported by CPT, then the panel displayed the FSC image in a real-time process.

We compared the conventional FSC panel using red, green, and blue driving method at field frequency 180Hz and the Fast-DRGB algorithm implemented on hardware at field frequency 240Hz. Using the X-Y moving table took the CBU pictures of two methods. Through the CBU pictures, the CBU suppression level was evaluated by human eyes directly. The Fast-DRGB method suppressed CBU effectively compared with the conventional RGB driving method.

However, when human eye observed two kinds of CBU pictures, both pictures did not have the same colors. Comparing two driving methods, the conventional FSC LCD used 180Hz field frequency and the Fast-DRGB method used 240Hz field frequency. Thus, in conventional FSC LCD each field had 1/180 second to let LC rotate and backlight flash, but in the Fast-DRGB method only had 1/240 second. Because the 15.4” panel used the commercial TN mode LC, the LC response time was not fast enough to rotate to the specific position in 1/240 second. Therefore, human eyes might observe the incorrect colors in CBU pictures using the 240Hz field frequency.

The conventional FSC LCD flashed one pure color from three primary LEDs in 1/180 second and combined three colors into a full color image using additive color mixing. The FSC LCD using the Fast-DRGB method calculated a set of adaptive backlight color in dominant field and this color changed image by image. The dominant field color was a mixing color using multi-color LEDs. The mixing color would affect three primary colors because LEDs on 15.4" panel did not obey color independent. This was another reason why color distortion happened.

We will build a color correction model to adjust the color distortion. The color correction model is the transformation from original digital signal values to modified digital signal values. After inserting the color correction model into modules in FPGA, the color will be adjusted correctly. These will discuss in my future work.

Chapter 6

Conclusions and Future Works

6.1 Conclusions

The FSC-LCDs are without color filters requirement and use temporal integration of red, green, blue images at 180Hz field rate to make a colorful image. However, CBU artifact accompanies with FSC technology when a relative velocity between human eyes and displayed images. Therefore, out lab proposed the DRGB method to suppress CBU artifact at field frequency 240Hz. The DRGB method chose a set of adaptive backlight (red, green, and blue) during three step convergence approach. The adaptive backlight was the first field backlight and rest three primary fields decreased their intensities and then human eyes observed less CBU artifact. However, the DRGB method needed complicated calculation to derive the adaptive backlight. We could not implement on hardware using the DRGB method without any frame buffers.

Thus, we proposed a modified method called the Fast-DRGB method. The Fast-DRGB method simplified the calculation of the DRGB method. Simulation results said the Fast-DRGB method had similar CBU suppression level using CIEDE2000 formula compared with the DRGB method. And the Fast-DRGB needed less calculation process for hardware implementation. CPT supported the 15.4” panel and the FPGA. We programmed the Fast-DRGB method into FPGA with a hardware language. Outer source connected to the FPGA and the FPGA transmitted the new data stream to 15.4” panel and then displayed the FSC images and videos in a real-time process. Compared with the traditional red, green, and blue driving

FSC-LCDs, the 15.4” panel displayed the images with less CBU artifact.

6.2 Future Works

The Fast-DRGB method was implemented on hardware and displayed the FSC images and videos in a real-time process. The displayed FSC images and videos had less CBU artifact during human eyes movement. However, because the LC used in 15.4” panel is TN mode. The response time of LC might be not fast enough for 240Hz field frequency. After temporal color mixing in 1/60 second, human eyes perceived incorrect color of the displayed images compared with the original images. The other reason was color dependence occurs between different fields, this caused the color additive color mixing failed.

So we will build a color correction model to adjust the modified data stream from the Fast-DRGB algorithm and are shown in Fig. 6-1. The algorithm will output LC signal and transmit into color correction model to derive the modified LC signal. The 15.4” panel will receive the modified LC signal and original backlight signal, and then display the correct FSC images.

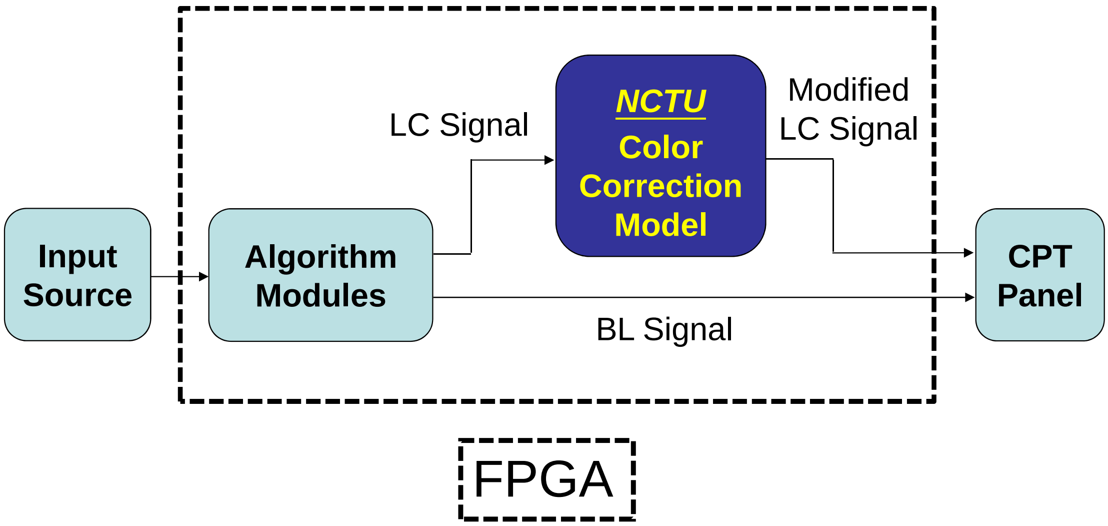


Fig. 6-1 Concept of color correction model adds into the FPGA

The color correction model will be built using colorimeter, KONICA MINOLTA CA-210 to measure the CIEXYZ coordinates on the panel. The sRGB color checker will input into the algorithm and output signal transmit into 15.4” panel and measure the CIE XYZ color coordinates of each color and obtain Data Original. And then measuring color checker on the input source (notebook) panel to obtain Data Target, as shown in Fig. 6-2.

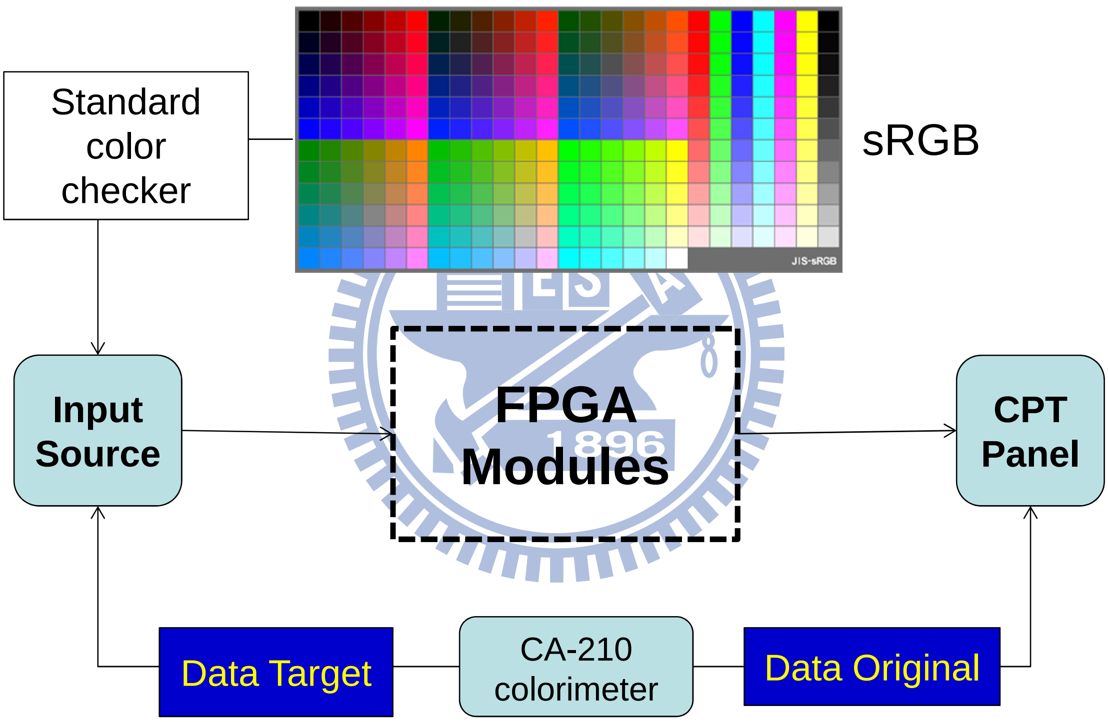
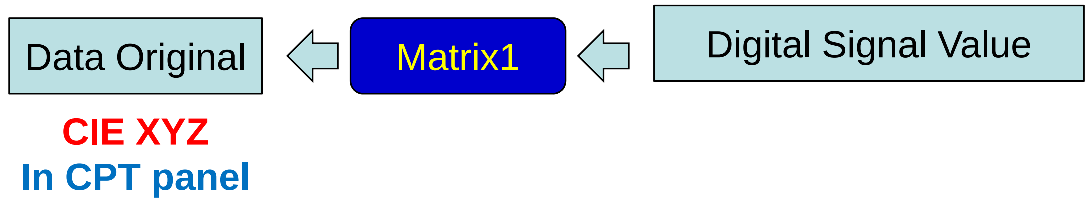
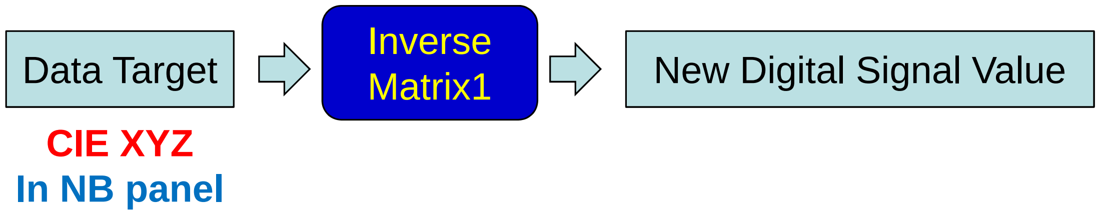


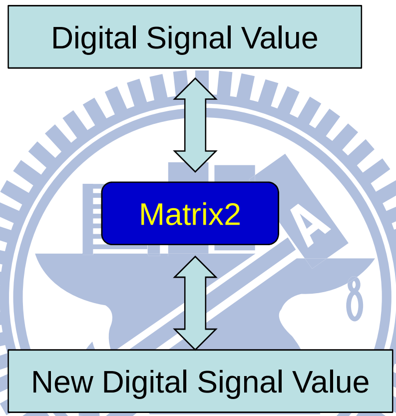
Fig. 6-2 Measurement of standard color checker using CA-210 colorimeter



(a) Step one



(b) Step two



(c) Step three

Fig. 6-3 Transformation between each data values in color correction model

(a) Relationship between Data Original and digital signal value in CPT panel.

(b) Inverse the relationship in (a) to derive new digital signal value.

(c) Relationship between digital signal value and new digital signal value.

After deriving the CIE XYZ data from two panels, we build the color correction model in the procedure as shown in Fig. 6-3. In step one, finding the relationship between digital signal value and Data Original from CPT panel. Then, inverse the relationship and find new digital signal value from Data Target from source panel.

Finally, find the relationship between digital signal value and new digital signal value. Therefore, in the color correction model the modified LC signal transmits into the 15.4” panel. The coordinates of colors shows in panel would match the target color coordinates.

After inserting the color correction model into Fast-DRGB module, the 15.4” panel will display the image with correct color. And the color correction model is not only used in FSC LCDs, but also used in different kinds of displays. If color distortion happens, building the color correction model in the procedure and will adjust the correct color.

Program of Fast-DRGB

Simplified Matlab Code

```
%---------------------------------------------------------------------------------------------%
% 3 approaches, a1(I,:) a2(I,:) a3(I,:),
% for red, green, blue B/L values, and sum of pixel difference (simplified delta E)
% B/L values 1->128, 2->160, 3->192, 4->224, 5->256,
% Shih-Hsun Chien
%---------------------------------------------------------------------------------------------%
input_image=im2double(imresize(read_image,[1280,800],'bicubic'));
[X,Y,Z]=size(input_image);
region_part = 300;
%------------------ 1st approach: from 1 to 300 -----------------%
i = 1;
a1 = zeros(8,4);
for a, b, c = 0:1
   a1(i,1)=a*4+1;    a1(i,2)=b*4+1;      a1(i,3)=c*4+1;
   blr=(a1(i,1)-1)*32+128;     blg=(a1(i,2)-1)*32+128;       blb=(a1(i,3)-1)*32+128;
   rp(1:region_part,:,1)=input_image(1:region_part,:,1);
   gp(1:region_part,:,2)=input_image(1:region_part,:,2);
   bp(1:region_part,:,3)=input_image(1:region_part,:,3);

   for x=1:region_part     for y=1:Y
      min_rgb(x,y)=
      min(input_image(x,y,1)/blr,input_image(x,y,2)/blg),input_image(x,y,3)/blb),1);
      rp(x,y,1)=rp(x,y,1)-min_rgb(x,y)*blr;
      gp(x,y,2)=gp(x,y,2)-min_rgb(x,y)*blg;
      bp(x,y,3)=bp(x,y,3)-min_rgb(x,y)*blb;
   end                          end

   rp_shift(:,13:Y,:)=rp(:,9:Y-4,:);
   gp_shift(:,13:Y,:)=gp(:,5:Y-8,:);
   bp_shift(:,13:Y,:)=bp(:,1:Y-12,:);
   rp_origin(:,13:Y,:)=rp(:,13:Y,:);
   gp_origin(:,13:Y,:)=gp(:,13:Y,:);
   bp_origin(:,13:Y,:)=bp(:,13:Y,:);
```

```
    delta_e=abs(rp_shift-rp_origin)+abs(gp_shift-gp_origin)+abs(bp_shift-bp_origin);
    a1(i,4)=sqrt(sum(delta_e));
    i=i+1;
end
    cc=a1(:,4)
    [cc,I]=min(cc);
    a1(I,:)
    a2base=(a1(I,1:3)-1)/4;
%--------------2nd approach - from 301 to 600 ----------------%
i=1;
a2=zeros(8,4);
for a, b, c = 0:1
    a2(i,1)=a1(I,1)-a2base(1)*2+a*2;
    a2(i,2)=a1(I,2)-a2base(2)*2+b*2;
    a2(i,3)=a1(I,3)-a2base(3)*2+c*2;
    blr=(a2(i,1)-1)*32+128;
    blg=(a2(i,2)-1)*32+128;
    blb=(a2(i,3)-1)*32+128;
rp(region_part+1:2*region_part,:,1)=input_image(region_part+1:2*region_part,:,1);
gp(region_part+1:2*region_part,:,2)=input_image(region_part+1:2*region_part,:,2);
bp(region_part+1:2*region_part,:,3)=input_image(region_part+1:2*region_part,:,3);

    for x=region_part+1:2*region_part          for y=1:Y
        min_rgb(x,y)=
        min(input_image(x,y,1)/blr,input_image(x,y,2)/blg),input_image(x,y,3)/blb),1);
        rp(x,y,1)=rp(x,y,1)-min_rgb(x,y)*blr;
        gp(x,y,2)=gp(x,y,2)-min_rgb(x,y)*blg;
        bp(x,y,3)=bp(x,y,3)-min_rgb(x,y)*blb;
    end                                         end

    rp_shift(:,13:Y,:)=rp(:,9:Y-4,:);
    gp_shift(:,13:Y,:)=gp(:,5:Y-8,:);
    bp_shift(:,13:y,:)=bp(:,1:Y-12,:);
    rp_origin(:,13:Y,:)=rp(:,13:Y,:);
    gp_origin(:,13:Y,:)=gp(:,13:Y,:);
    bp_origin(:,13:Y,:)=bp(:,13:Y,:);
    delta_e=abs(rp_shift-rp_origin)+abs(gp_shift-gp_origin)+abs(bp_shift-bp_origin);
    a2(i,4)=sqrt( (sum(delta_e));
```

```
    i=i+1;
end
    cc2=a2(:,4)
    [cc2,I]=min(cc2);
    a2(I,:)
    a3base=(a2(I,1:3)-a2(1,1:3))/2;
%---------------- 3rd approach: from 601~800 -----------------%
i=1;
a3=zeros(8,4);
for a, b, c=0:1
    a3(i,1)=a2(I,1)-a3base(1)+a;
    a3(i,2)=a2(I,2)-a3base(2)+b;
    a3(i,3)=a2(I,3)-a3base(3)+c;
    blr=(a3(i,1)-1)*32+128;
    blg=(a3(i,2)-1)*32+128;
    blb=(a3(i,3)-1)*32+128;
    rp(2*region_part+1:X,:,1)=input_image(2*region_part+1:X,:,1);
    gp(2*region_part+1:X,:,2)=input_image(2*region_part+1:X,:,2);
    bp(2*region_part+1:X,:,3)=input_image(2*region_part+1:X,:,3);

    for x=2*region_part+1:X    for y=1:Y
        min_rgb(x,y)=
        min(input_image(x,y,1)/blr,input_image(x,y,2)/blg),input_image(x,y,3)/blb),1);
        rp(x,y,1)=rp(x,y,1)-min_rgb(x,y)*blr;
        gp(x,y,2)=gp(x,y,2)-min_rgb(x,y)*blg;
        bp(x,y,3)=bp(x,y,3)-min_rgb(x,y)*blb;
    end                                    end

    rp_shift(:,13:Y,:)=rp(:,9:Y-4,:);
    gp_shift(:,13:Y,:)=gp(:,5:Y-8,:);
    bp_shift(:,13:Y,:)=bp(:,1:Y-12,:);
    rp_origin(:,13:Y,:)=rp(:,13:Y,:);
    gp_origin(:,13:Y,:)=gp(:,13:Y,:);
    bp_origin(:,13:Y,:)=bp(:,13:Y,:);
    delta_e=abs(rp_shift-rp_origin)+abs(gp_shift-gp_origin)+abs(bp_shift-bp_origin);
    a3(i,4)=sqrt(sum(delta_e));
    i=i+1;
end
```

```
    cc3=a3(:,4)
    [cc3,I]=min(cc3);
% choose adaptive backlight color
for i=1:length(a3(I,:))
        switch a3(I,i)
                case 1      a(1,i)=128;
                case 2      a(1,i)=160;
                case 3      a(1,i)=192;
                case 4      a(1,i)=224;
                case 5      a(1,i)=256;
                otherwise
        end
end
```

Reference

[1] F. Yamada, H. Nakamura, Y. Sakaguchi, and Y. Taira, "*Sequential-color LCD based on OCB with an LED backlight*," J. Soc. Info. Display **10**, pp. 81-85 (2002).

[2] T. Uchida, K. Saitoh, T. Miyasita, and M. Suzuki, "*Field Sequential Full Color LCD without Color Filter for AM-LCD*", Proc. 17th IDRC, pp. 37-40 (1997).

[3] http://www.electrical-res.com/EX/10-16-18/tft_lcd-1.gif

[4] L. Arend, J. Lubin, J. Gille, and J. Larimer, "*Color Breakup in Sequentially Scanned LCDs," SID Symposium Digest*, pp. 201-204 (1945)

[5] M. Mori, T. Hatada, K. Ishikawa, T. Saishouji, O. Wada, J. Nakamura, and N. Terashima, "*Mechanism of Color Breakup on Field-Sequential Color Projectors*," SID Symposium Digest **30**, pp.350-353 (1999)

[6] A. Yohso and K. Ukai, "*How Color Break-Up Occurs in the Human Visual System: Mechanism of Color Break-Up Phenomenon*," SID Symposium Digest **37**, pp.1225-1228 (2006)

[7] K. Sekiya, K. Wako, S. Nakano, T. Ishinabe, T. Miyashita, and T. Uchida, "*Overdrive for Compensating Color-Shift on Field Sequential Color TFT-LCDs*," SID Symposium Digest **35**, pp.408-411 (2004)

[8] Y.-P. Huang, K.-H. Chen, C.-H. Chen, F.-C. Lin, and H.-P. David Shieh, "*Adaptive LC/BL Feedback Control in Field Sequential Color LCD Technique for Color Breakup Minimization*," IEEE/OSA Journal of Display Technology (JDT) **4**(3), pp.290-295 (2008)

[9] S.-H. Chien, C.-H. Chen, F.-C. Lin, Y.-P. Huang, and H.-P. David Shieh, "*Real-Time Adaptive Backlight Algorithm for Field-Sequential-Color Displays*,"

SID Symposium Digest **12**, pp.350-353 (2010)

[10] Roy S. Berns, Billmeyer and Saltzman's principles of color technology, 3rd Edition, John Wiley & Sons (2000)

[11] http://www.accessexcellence.org/AE/AEC/CC/images/vision_fig2.gif

[12] http://premiumblend.net/2008/12/03/a-natural-history-of-seeing-by-simon-ings/

[13] S. Mateeff, "*Saccadic Eye Movements and Localization of Visual Stimuli*," Percept Psychophys **24**, pp. 215–224 (1978).

[14] W. Hershberger, "*Saccadic Eye Movements and the Perception of Visual Direction*," Percept Psychophys **41**, pp. 35–44 (1987).

[15] H. Honda, "*Perceptual Localization of Visual Stimuli Flashed during Saccades*," Percept Psychophys **45**, No. 2, pp. 162–174 (1989).

[16] http://www.rehab.research.va.gov/jour/05/42/5/bicchierinif04.jpg

[17] M. R. Luo, G. Cui, B. Rigg, "*The Development of CIE 2000 Colour-Difference Formula: CIEDE2000*," Color Research & Application, pp. 340-350 (2000).

[18] H. Yamakita, M. Sakai, Y. Taniguchi, J. Asayama, K. Adachi, "*Field-Sequential Color LCD driven by Optimized Method for Color Breakup Reduction*," IDW'05, pp.83-86 (2005).

[19] K. Sekiya, T. Miyashita, and T. Uchida, "*A Simple and Practical Way to Cope With Color breakup on Field Sequential*," *ColorPapers* **3**, p.1661-1664 (2006).

[20] C.-L. Wu, C.-H. Chen, F.-C. Lin, Y.-P. Huang, and H.-P. David Shieh, "*A 5.6-inch Field Sequential Color LCD with Less Color Break-up*," Optics and Photonics Taiwan, GO-004, (2007)

[21] F.-C. Lin, Y.-P. Huang, C.-M. Wei, and H.-P. David Shieh, "*Color Breakup Suppression and Low Power Consumption by Stencil-FSC Method in Field-Sequential LCDs*," J. Soc. Info. Display **17**, pp. 221-228, (2009)

[22] F.-C. Lin, Y.-P. Huang, and H.-P. David Shieh, "*Color Breakup Reduction by 180Hz Stencil-FSC Method in Large-Sized Color Filter-Less LCD-TVs*," Journal of Display Tech., **6**(3), pp.107-112 (2010)

[23] Y.-K. Cheng, Y.-P. Huang, Y.-R. Cheng, and H.-P. David Shieh, "*Two-Color-Field Sequential Method with Spatial and Temporal Mixing Method*," Journal of Display Tech., **5**(10), pp.385-390 (2009)

[24] http://powerelectronics.com/

[25] K. Sekiya and H. Nakamura, "*Overdrive Method for TN-mode LCDs - Recursive System with Capacitance Prediction* -," SID Symposium Digest **32**, pp.114-117 (2001)

[26] N. Tamura, N. Tsumura, and Y. Miyake, "*Masking model for accurate colorimetric characterization of LCD*," J. Soc. Info. Display **11**, pp. 333-339 (2003)

[27] N. Koma, T. Uchida, "*A new field-sequential-color LCD without moving-object color break-up*" J. Soc. Info. Display 11, pp. 413-417 (2003).

[28] C.-H. Chen, F.-C. Lin, Y.-P. Huang, Y.-T. Hsu, and H.-P. David. Shieh, "*A Field Sequential Color LCD Based on Color Fields Arrangement for Color Breakup and Flicker Reduction*," Journal of Display Tech., **5**(1), pp. 34-39 (2009).