國立交通大學

顯示科技研究所
碩士論文

應用於 紅, 藍, 綠 發光二極體色彩穩定之控制回饋系統設計

Light Output Feedback Control System Design for RGB LED Color Stabilization

研究生：李仕龍

指導教授：郭浩中 教授
李柏璁 教授

中華民國九十七年六月

應用於 紅, 藍, 綠 發光二極體色彩穩定之控制回饋系統設計

Light Output Feedback Control System Design for RGB LED Color Stabilization

研 究 生: 李仕龍 Student: Shih-Lung Lee
指導教授: 郭浩中 Advisor: Hao-chung Kuo
李柏璁 Po-Tsung Lee

國立交通大學
顯示科技研究所
碩士論文

A Thesis
Submitted to Display Institute
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 2008
HsinChu, Taiwan, Republic of China.

中華民國九十七年六月

應用於 紅,藍,綠 發光二極體色彩穩定之控制回饋系統設計

碩士班研究生:李仕龍　　　指導教授: 郭浩中,李柏璁

國立交通大學 顯示科技研究所

摘要

顯示科技蓬勃發展，液晶顯示器(Liquid Crystal Display)已成為取代陰極射線管顯示器(Cathode Ray Tube Monitor)最強大的主流產品，由於液晶顯示器並非主動發光元件，必須仰賴一個外加的光源系統，此即所謂的背光模組，而背光模組使用冷陰極射線管(Cold Cathode Fluorescent Lamp)充當光源已行之有年；發光二極體(Light Emitting Diode)因較冷陰極射線管具有壽命長,廣色域、省電、環保、反應快速等多項優點，已成為液晶顯示器背光源的新選擇。然而，長時間使用下而產生的熱，往往造成發光二極體的發光顏色偏移，此在顯示器要求高色彩品質的標準下，是最不樂見的。

本論文提出了使用光二極體感測發光二極體的光輸出訊號，經類比數位轉換的裝置，套用反覆逼近的程式，設計建立一組μA等級的電流逼近的發光二極體色彩穩定回饋系統。回饋系統在 13 位元解析下，可將對應於使用 3250, 3969, 及4462小時的紅色，藍色及綠色發光二極體的色偏值(Δu’v’)維持在內 0.005（人眼恰可接受的範圍）內。使用 14 位元解析下，可將紅，藍及綠色發光二極體的色偏值維持在內 0.004 之內。

Light Output Feedback Control System Design for RGB LED Color Stabilization

Student : Shih-Lung Lee **Advisor:** Hao-chung Kuo
Po-Tsung Lee

Display Institute
National Chiao-Tung University

Abstract

LCD (Liquid Crystal Display) is the mainstream product to replace CRT (Cathode Ray Tube). Conventionally, CCFL (Cold Cathode Fluorescent Lamp) is used as a light source of LCD backlight. However, LED (Light Emitting Diode) is regarded as the candidate to replace CCFL (Cold Cathode Fluorescent Lamp) as light source of LCD backlight due to its wide color gamut, low operation voltage, mercuryfree characteristic, and fast switch response. The color shift due to heat effect after long time usage is an issue needed to resolve. In this thesis, a 14 bits recursive feedback control system is proposed and realized to stabilize the light output of RGB (red, green, and blue) LEDs by generating tiny recursive current in μA order. Whereas the just noticeable color difference (Δu'v') of human is 0.005, feedback control system is proved that color difference (Δu'v') of Red, Green, and Blue LEDs are kept within 0.005 under 13 bits resolution, and within 0.004 under 14 bits under aging simulation of 3250, 3969, and 4462 hours usage, respectively.

Acknowledgements

誌謝

本篇論文能夠順利完成與畢業，由衷感謝　前指導教授　謝漢萍的指導提攜　與　指導教授　郭浩中　與李柏璁　老師的協助。除此之外，特別感激口試委員　黃乙白，黃建璋，與盧廷昌　老師　對我論文研究的訂正教導，讓我受益良多。

衷心感激在研究所這段期間中，幫助我，激勵我成長的好朋友們：葉圃成，吳孟修，洪柏瑢，黃俊嘉，何孟寰，邱忠民，傅俊榮，謝杏佳，蔡孟娟，陳怡潔，蔡依陵...等等，多虧你們的扶持陪伴，讓我的研究生活留下深刻感動的回憶。

最後，但也是最重要的，謹將這份畢業的喜悅，獻給我最親愛的父親（李俊銘　先生），母親（郭美雲　女士），與妹妹（李仕佩　小姐）和家人們，謝謝你們一路上給我的愛與支持，我永遠愛你們。

Figure Caption

Table Caption

Table of Contents

Chapter 1

Introduction

1.1 Background

The emergence of TFT LCD (Thin Film Transistor Liquid Crystal Display) technology over the last decade heralds a new era in display technology. The long serving CRT (Cathode Ray Tube) display is in the process of being replaced its perch as the premier display technology. Certainly the CRT will be with us for many years to come, since it is mature and cheap, but clearly the TFT LCD is the current and popular display technology now. [1] Moreover, in recent years, TFT-LCD has become the mainstream product to replace CRT. The cross section configuration of TFT LCD is shown in Fig 1-1.

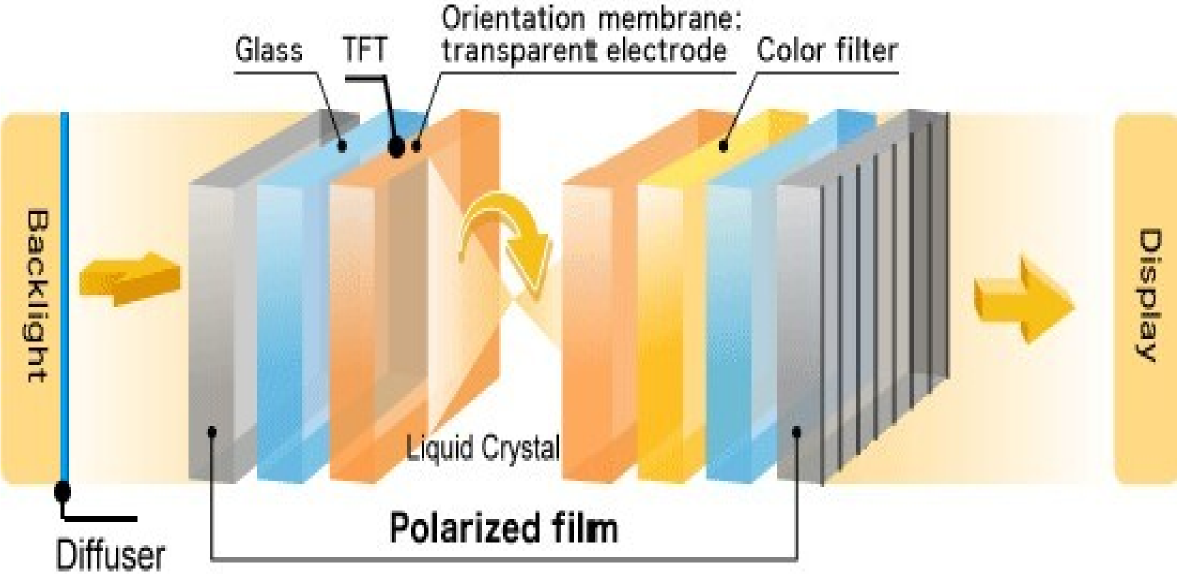


Fig. 1-1 Cross section structure of TFT LCD

The light of LCD comes from backlight. In the following, diffuser film is used to make the light uniform. The purpose of TFT (Thin Film Transistor) is to control the rotation angle of liquid crystal as a function of light valve. After going through the color filter, specific color can be displayed appropriately. Because backlight is an essential part for LCD, LCD is categorized in non-emissive display. Consequently, the stabilization of backlight performance is necessary for LCD.

Conventionally, CCFL (Cold Cathode Fluorescent Lamp) is used as backlight of LCD. However, LED (Light Emitting Diode) backlight is considerably attractive for wider color gamut, long life time, mercuryfree device, low operation voltage, and fast switch response. [2] (Table. 1-1) Undoubtedly, LED backlight is regarded as a candidate to replace CCFL as LCD backlight.

Table. 1-1 LED VS. CCFL in Vehicle [3]

	LED	CCFL
Light Source Efficiency	(Low 30~40lm/W)	High (100lm/W)
Back Light Unit (BLU) Optical Efficiency	Low (140nit/W)	High (250nit/W)
Environmental Protection	Mercury-free	Mercury
Color Gamut	High (Over 90% NTSC)	Low (75% NTSC)
Life time	High (Over 50000 hours)	Low (15000~25000 hours)
Operation voltage	Low (DC 3.6 Volt)	High (AC 110 Volt)
Cost	High	Low

1.2 Motivation

LED backlighting is very attractive for many merits mentioned above. However, LED has thermal and time-based dependencies [4]. Color and luminance levels are not stable over a wide range of temperature due to inherent long term aging characteristics. In order to minimize color difference over time, optical feedback control is a key technology for LED.

1.3 Prior Art

Some researches about stabilization of LED light output have been done.[5][6] Their experimental results indicated that at least 12 bits of PWM generation must be used in order to avoid noticeable color difference [5]. Block diagram of control system loop of prior art is shown in Fig. 1-2.

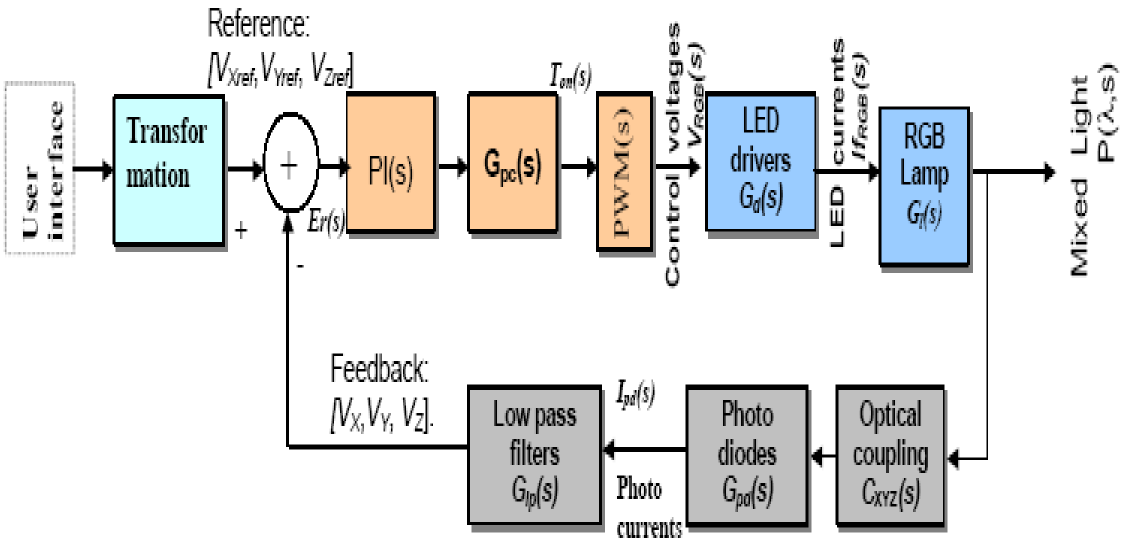


Fig. 1-2 Block diagram of LED light control system [5]

Each block or function stands for an optical or electrical transformation. P(λ,s) denotes the color and the intensity of the light seen by a typical human eye [4][6], is the target control parameters. The values of the reference parameters VXYZref = [VXref,, VYref, VZref] are calculated based on the user input [7][8]. Ton(s) represents the PWM pulse widths supplied by the controller (PI controller with a precompensator, Gpc(s)). $V_{RGB}(s)$ is the control voltage inputs to the RGB LED drivers, $If_{RGB}(s)$ is the RGB forward currents as shown in Fig. 1-2. Ipd(s) are the photo currents from the photo diodes and VXYZ = [VX, VY, VZ] are the (feedback) voltage output of the low-pass filters. The transfer function modeling involves the multi-input multi-output (MIMO) transfer function models of PWM generation PWM(s), RGB LED drivers Gd(s), RGB-LED lamp Gl(s), optical coupling CXYZ(s), photo sensors Gpd(s) and the low pass filters Glp(s). The control outputs are the RGB-LED forward currents. For this control design, the open-loop transfer function (between the error inputs Ton(s) and the feedback VXYZ(s)) is expressed as:

$$G_f(s) = \frac{T_{on}(s)}{V_{XYZ}(s)} = G_{lp}(s)\cdot G_{pd}\cdot(s)\cdot G_l(s)\cdot G_d(s)\cdot PWM(s) \qquad \text{Eq. (1-1)}$$

The methods to obtain the transfer function model for the PWM generation, the RGB LED drivers Gd(s) and the low pass filters are well known [9].

Such method is complex and difficult to implement because of mixing optical and electrical signals, and using a lot of mathematic transformations.

1.4 Objective

Taking aforementioned prior art into account, we propose that all signals are turned into digital ones to transfer or process instead of using many mathematic transformations. Besides, recursive approach method which will be explained in chapter 2 is employed to execute iterative steps. According to prior arts, 12 bits of PWM generation is necessary for feedback control to keep color difference within just noticeable difference. Therefore, the objective aims to make a 14 bits RGB LED light output feedback control system with recursive approach method to make the color difference $\Delta u'v'$ of LED within 0.005, the minimum color difference $\Delta u'v'$ human can perceive. Moreover, the lifetime standard of 5.7 inch TFT LCD with white light LED backlight was published to be 5000 hours. [10]

1.5 Thesis Organization

Five chapters are included in this thesis. The first chapter introduces problems we are encountering and motivation for thesis research. Fundamental theories, principles, evaluation index, and design method are elaborated in the second chapter. Afterwards, the experimental structure and system elements of 14 bits LED light output feedback control are described in the third chapter. Experimental results and analyses are in following fourth chapter. Finally, the fifth chapter is composed of conclusions and future works.

Chapter 2

Principles

2.1 LED

Optoelectronic Devices either produce light or use light in their operation. The first of these devices, the light-emitting diode (LED), was developed to replace the fragile, short-life incandescent light bulbs used to indicate on/off conditions on panels. A Light-Emitting Diode is a diode which, when forward biased, produces visible light. The light may be red, green, blue, white, depending upon the material used to make the diode. Figure 2-1 shows an LED and its schematic symbol. The LED operating voltage is smaller than that of Cold Cathode Fluorescent Lamp (CCFL), about 1.6 volts to 5 volts forward bias and generally about 10 to 100 milliamperes. The life expectancy of the LED is very long, over 100,000 hours of operation.

Fig. 2-1 LED

LEDs are used widely as "power on" indicators of current and as displays for pocket calculators, digital voltmeters, frequency counters, etc. Due to the progress and development of fabrication techniques, LEDs has been widely used as lighting devices, such as flashlights, streetlamps, and LCD backlights.

2.2 Photodiode

Another special optoelectronic device in common use today is the photodiode. Unlike the LED, which produces light, the photodiode uses light to accomplish special circuit functions. Basically, the photodiode is a light-controlled variable resistor. In total darkness, it has a relatively high resistance and therefore conducts little current. However, when the PN junction is exposed to an external light source, internal resistance decreases and current flow increases. The photodiode is operated with reverse-bias and conducts current in direct proportion to the intensity of the light source. Figure 2-2 shows a photodiode with its schematic symbol. The arrows pointing toward the symbol indicate that light is required for operation of the device. A light source is aimed at the photodiode through a transparent "window" placed over the semiconductor chip. To switch the light source on or off changes the conduction level of the photodiode. Varying the light intensity controls the amount of conduction. Because photodiodes respond quickly to changes in light intensity, they are extremely useful in digital applications such as computer card readers, paper tape readers, and photographic light meters. They are also used in some types of optical scanning equipment.

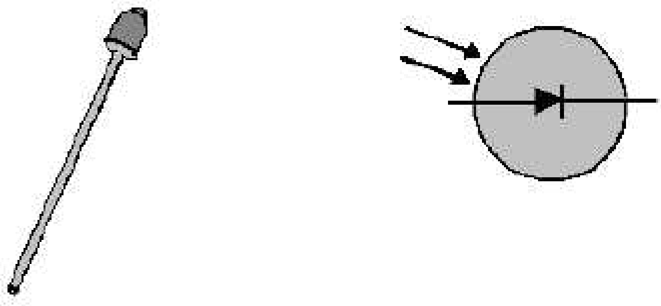


Fig. 2-2 Photodiode

2.3 The CIE System of Colorimetry

By far the most important of all color specification system is that developed by the Commission Internationale de l'Eclairage (CIE). Not only because it is based on careful psychophysical experiment, but because it is thoroughly documented as well, the CIE system has the force of an international standard and has become the basis of all industrial colorimetry.

In 1931, the CIE recommended the concept of a standard observer, whose color vision is representative of that of all humans who have normal color vision, and defined a linear transformation so-called tristimulus functions as follows: [11]

$$\begin{aligned}\bar{x}(\lambda) &= 0.49\bar{\mathrm{r}}(\lambda) + 0.31\bar{\mathrm{g}}(\lambda) + 0.20\bar{\mathrm{b}}(\lambda)\\ \bar{\mathrm{y}}(\lambda) &= 0.1769\bar{\mathrm{r}}(\lambda) + 0.82140\bar{\mathrm{g}}(\lambda) + 0.0131063\bar{\mathrm{b}}(\lambda)\\ \bar{\mathrm{z}}(\lambda) &= 0.00\bar{\mathrm{r}}(\lambda) + 0.01\bar{\mathrm{g}}(\lambda) + 0.99\bar{\mathrm{b}}(\lambda)\end{aligned} \qquad \text{Eq. (2-1)}$$

The transformation was defined in this way for two reasons: first that the $\bar{\mathrm{y}}(\lambda)$ curve thereby becomes identical to the photopic spectral luminous efficiency function $\mathrm{V}(\lambda)$, which is a basic photometric function defining the perceived relative luminance of a monochromatic light source at each wavelength across the spectrum; and second that negative values of $\bar{x}$, $\bar{\mathrm{y}}$, $\bar{\mathrm{z}}$ are eliminated, thus simplifying computation.

2.3.1 Standard Observer

CIE has two specifications for establishing a standard observer: the original 1931 specification and a revised 1964 specification. In both cases the standard observer is a composite made from small groups of individuals (about 15-20) and is representative of normal human color vision. Both specifications used a similar technique to match colors to an equivalent RGB tristimulus value. The observer viewed a split screen with 100% reflectance (that is, pure white). On one half, a test lamp cast a pure spectral color on the screen. On the other half, three lamps emitting varying amounts of red, green, and blue light attempted to match the spectral light of the test lamp. The observer viewed the screen through an aperture and determined when the two halves of the split screen were identical. The RGB tristimulus values for each distinct color could be obtained as Fig. 2-3 sketched.

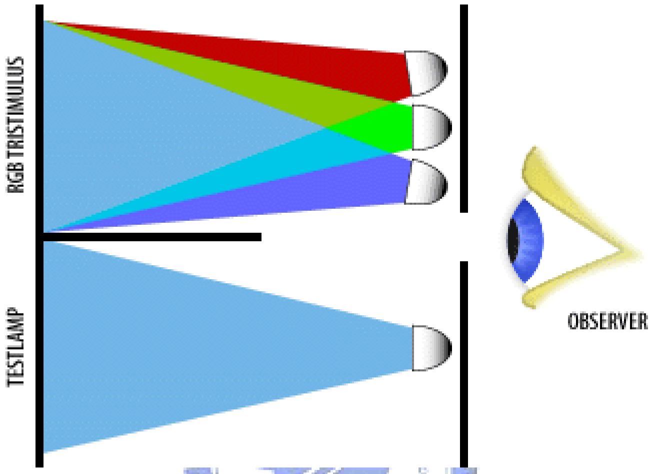


Fig. 2-3 two specifications for a standard observer [12]

The significant difference between the 1931 and 1964 standard observers was the field of vision used to view the screens. The 1931 observer had a 2° field of vision (i.e., the amount taken in by the fovea alone). This was later considered inadequate in many cases since it did not take in enough data of the observer's peripheral vision. The 1964 specification widened the observer's field of vision to 10° in order to get tristimulus values that reflect a wider retinal sensitivity.

2.3.2 CIE Models

Due to gamut restraints, the RGB color model could not reproduce all spectral light without introducing the effect of negative RGB values (this was done by mixing red, green or blue light with the test lamp as needed). CIE thought a system that used negative values would not be acceptable as an international standard. Accordingly, CIE translated the RGB tristimulus values into a different set of all positive tristimulus values, called XYZ, which formed the first CIE color model. From this first model, other models were derived in response to various concerns.

According to CIE definition of the 1931 Standard Observer, Fig. 2-4 shows the spectral sensitivity curves corresponding to the human eye. These lines are referred to as the color matching function $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$, which have high sensitivity in red, green, and blue wavelength region, respectively [12]. The colors that we see are the result of different $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ proportions with reflected light.

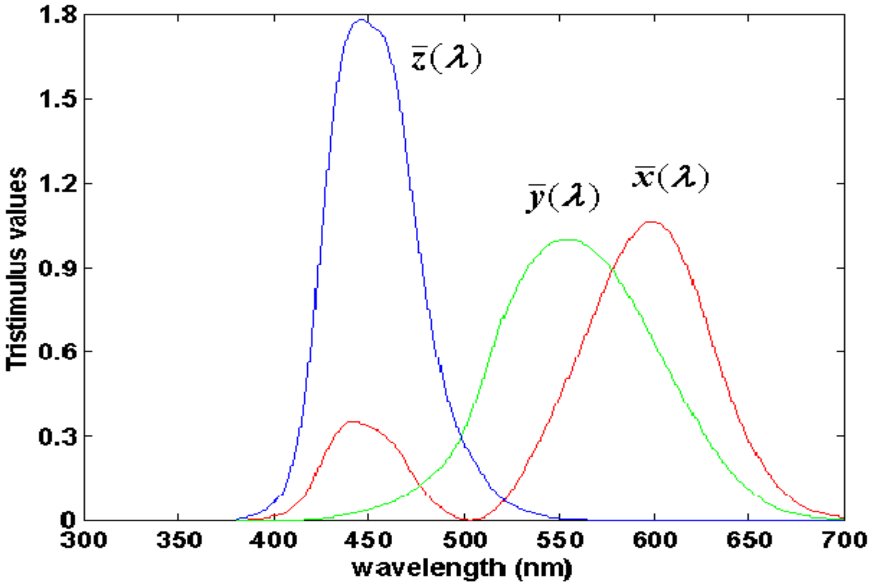


Fig. 2-4 Spectral sensitivity corresponding to the human eye (color-matching function of the CIE 1931 Standard Observer) [12]

The CIE developed the XYZ color system, also called the "norm color system". The system is often represented as a two-dimensional graphic which more or less corresponds to the shape of a horseshoe as shown in Fig. 2-5.

According to the aforementioned content, CIE considered the tristimulus values for red, green, and blue to be undesirable for creating a standardized color model. Instead, they used a mathematical formula to convert the RGB data to a system that uses only positive integers as values. The reformulated tristimulus values were indicated as *XYZ*. These values do not directly correspond to red, green, and blue, but are approximately so. The curve for the *Y* tristimulus value is equal to the curve that indicates the human eye's response to the total power of a light source. For this reason the value Y is called the luminance factor and the *XYZ* values have been normalized so that *Y* always has a value of 100.

Obtaining the *XYZ* tristimulus values is only part of defining the color. The color itself is more readily understood in terms of hue and chroma. To make this possible, CIE used the *XYZ* tristimulus values to formulate a new set of chromaticity coordinates that are denoted *xyz*. **Note:** The tristumulus values *XYZ* are always denoted in upper case while the chromaticity coordinates, *xyz*, are always in lower case.

The chromaticity coordinates are used in conjunction with a chromaticity diagram, the most familiar one being CIE's 1931 *xyY* Chromaticity Diagram:

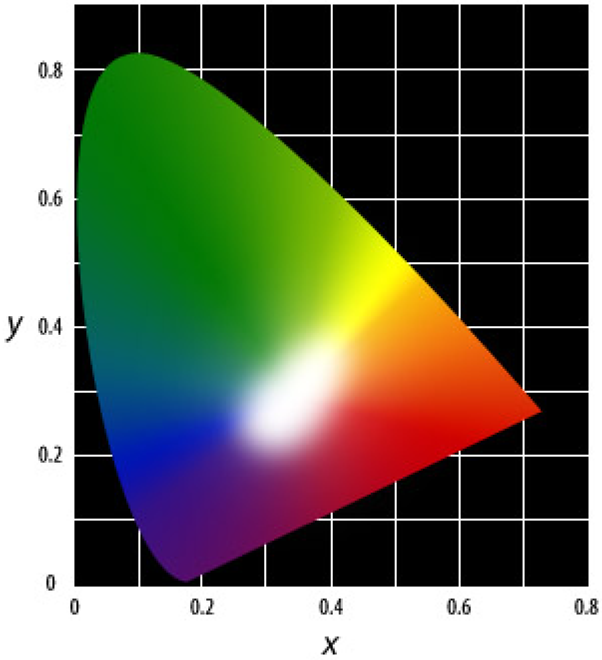


Fig. 2-5 CIE1931 *xyY* Chromaticity Diagram

The horseshoe-shaped color space is set in a grid using the chromaticity coordinates x and y as a locator for any value of hue and chroma. These correspond to the color itself (e.g., reddish-orange) and the fullness of the color or saturation. The coordinate z is not used, but can be inferred from the other two since the sum of the coordinates $x + y + z$ is always 1.

The white spot in Fig. 2-6 represents the location of the illuminant. The third dimension is indicated by the tristimulus value *Y*. As previously mentioned, this value indicates the lightness or luminance of the color. The scale for Y extends from the white spot in a line perpendicular to the plane formed by x and y using a scale that runs from 0 to 100. The fullest range of color exists at 0 where the white point is equal to CIE Illuminant C. As the *Y* value increases and the color becomes lighter, the range of color, or gamut, decreases so that the color space at 100 is just a small section of the original area.

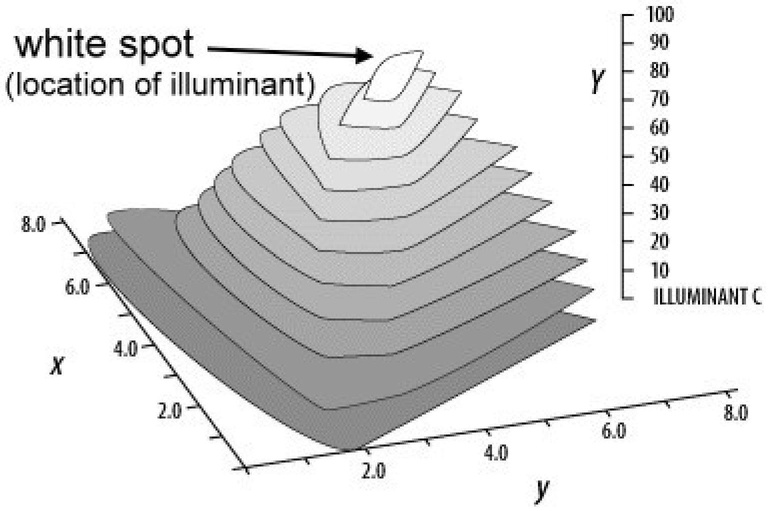


Fig. 2-6 Color space VS. luminance *Y* [13]

Using the *xyY* values, any two colors can be compared to determine whether they match–which is the whole purpose of CIE's standards. It needs to be noted that CIE did not create their system as a means for describing colors or producing a line of samples for use in color production.

It is not possible to use the *xyY* chromaticity diagram as a map for showing the relationships between colors. The diagram is a flat representation of what is really a curved surface. So, parts of it are visibly distorted in relationship to others. Colors of equal amounts of difference appear farther apart in the green part of the diagram than they do in the red or violet part. To resolve the problem of non-uniform color scaling, CIE adopted two different uniform diagrams that became the 1976 specifications for CIELUV and CIELAB.

2.4 CIE 1931 LUV Chromatic System

As indicated in the previous section, the 1931 CIE *x,y* Chromaticity Diagram (or *xyY* diagram) was inadequate because the two-dimensional diagram failed to give a uniformly-spaced visual representation of what is actually a three-dimensional color space. We can see this problem clearly in the following illustration of the *xyY* chromaticity diagram:

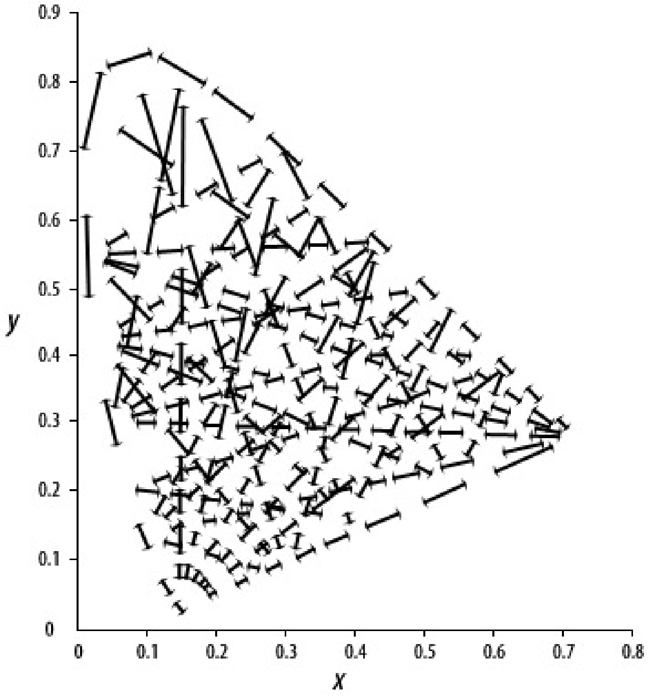


Fig. 2-7 Nonuniformly-spaced visual representation of CIE *x,y* Chromaticity Diagram [13]

Each line in the diagram represents a color difference of equal proportion. The distances between the end points of each line segment are perceptually the same according to the 1931 CIE 2° standard observer. As shown in Fig. 2-7, the lines vary in length, sometimes greatly, depending on what part of the diagram they are in. This disparity in line length indicates the amount of distortion between parts of the diagram.

To correct this, a number of uniform chromaticity scale (UCS) diagrams were proposed. These UCS diagrams used a mathematical formula to transform the *XYZ* values or *x,y* coordinates to a new set of values (*u,v*) that presented a visually more accurate two-dimensional model. In 1960, CIE adopted one of these as the 1960 CIE *u,v* Chromaticity Diagram as shown in Fig. 2-8.

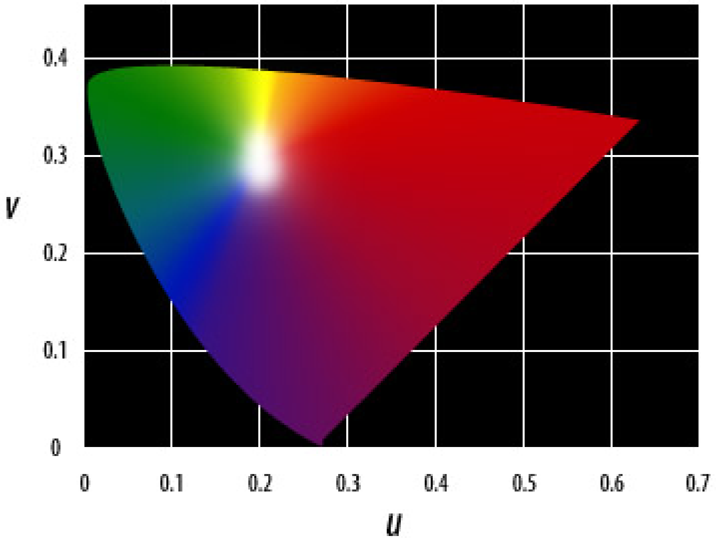


Fig. 2-8 1960 CIE *u,v* chromaticity diagram

Compared with the 1931 diagram in the aforementioned section, the effect was to elongate the blue-red portions of the diagram and relocate the illuminant (or white point) to decrease the visual disparity with the green portion.

However, this was still found unsatisfactory and in 1975, CIE proposed modifying the *u,v* diagram and supplying new (*u',v'*) values. This was done by multiplying the *v* values by 1.5. Thus in the new diagram *u'* = *u* and *v'* = 1.5*v*. The resulting diagram was adopted as the 1976 CIE *u',v'* Chromaticity Diagram as shown in Fig. 2-9.

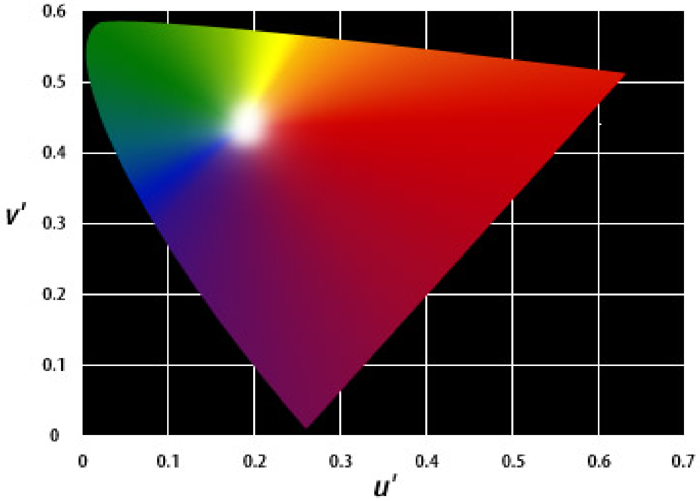


Fig. 2-9 1976 CIE *u'*,*v'* chromaticity diagram

While the representation is not perfect (nor can it ever be), the *u'*,*v'* diagram offers a much better visual uniformity. This can be seen in Fig. 2-10 by comparing the following illustration of the *u'*,*v'* diagram with the *x*,*y* diagram at the top of this section:

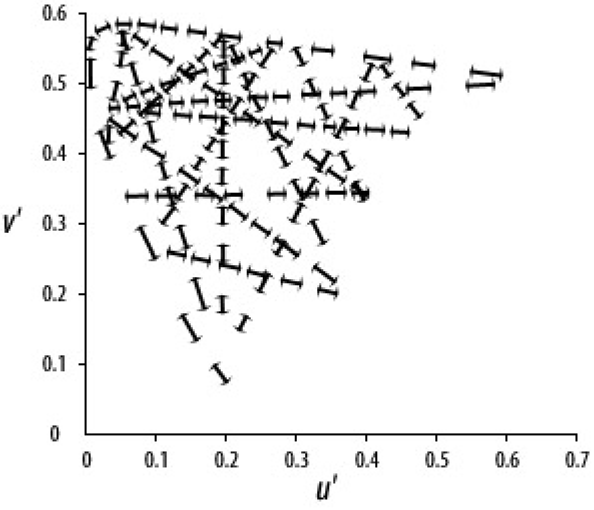


Fig. 2-10 Nonuniformly-spaced visual representation of CIE *u'*,*v'* chromaticity diagram [13]

The lines in the *u'*,*v'* diagram represent the same as in the *x*,*y* illustration, only here we can see the lines are more uniform throughout the diagram. One other point to make about the CIELUV model is the replacement of the *Y* lightness scale with a new scale called *L**. The *Y* scale is a uniform scale of lightness with equal steps between each value. However, this kind of scale is not adequate to represent differences in lightness that are visually equivalent. For example, a difference between values of 10 and 15 on the Y lightness scale differ by the same magnitude as values of 70 and 75. We do not see the values as being the same, however. We have much less ability to differentiate between degrees of lower values than we do of middle and higher values.

Using a mathematical formula, the Y values were translated to other values that are approximately uniformly spaced, but more indicative of the actual visual differences. The resulting scale, L^*, models the Munsell system's scale of value. The major difference is that L^* uses a scale of 0-100, while Munsell's Value uses a scale of 0-10. The L^* lightness scale is used for CIELAB as well as CIELUV. The value of CIELUV lies in the fact that, like CIEXYZ and *xyY*, it is device-independent and therefore not restrained by gamut. It is an improvement over CIEXYZ and *xyY* in that it better represents uniform color spaces.

2.5 Color Difference

The CIE 1976 *Luv* color space is designed to be perceptually uniform, meaning that a given change in value corresponds roughly to the same perceptual difference over any part of the space. Using such a space for quantizing color values decreases the chance that any given step in color value will be noticeable on a display or hardcopy.

The *Luv* space was designed specifically for emissive colors, which correspond to images captured by a camera or computer graphics rendering program. However, we must modify the assumptions used by the CIE slightly, since we want to record high dynamic-range images independent of viewer adaptation. We therefore ignore the part about luminance scale, using instead a log scale to cover a much larger range of values. We also ignore the part about dominant color and encode based on the absolute (u’,v’) coordinates.

1. CIE 1976 Luv color space [13]:

$$\boldsymbol{u}' = \frac{4\boldsymbol{X}}{\boldsymbol{X} + 15\boldsymbol{Y} + 3\boldsymbol{Z}} \quad \boldsymbol{v}' = \frac{9\boldsymbol{Y}}{\boldsymbol{X} + 15\boldsymbol{Y} + 3\boldsymbol{Z}}$$

$$u_n = \frac{4X_n}{X_n + 15Y_n + 3Z_n} \quad v_n = \frac{9Y_n}{X_n + 15Y_n + 3Z_n} \qquad \text{Eq. (2-2)}$$

Derived from Eq. (2-2), (u’ ,v’) is the color coordinate of a sample, (u_n’, v_n’) is the color coordinate of the reference white, X,Y,Z are the tristimulus of a sample, and Xn,Yn,Zn are the tritimulus of the reference white, Yn =100.

2.Color-difference formula of CIE 1976 [13]：

$$L^* = \begin{cases} 116(Y/Yn)1/3-16 & , Y/Yn>0.008856 \\ 903.3(Y/Yn) & , Y/Yn<0.008856 \end{cases}$$

$$u^*=13(u'-u_n')$$

$$v^*=13(v'-v_n')$$

$$\Delta E = [(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2]^{1/2} \qquad \text{Eq. (2-3)}$$

2.6 Just Noticeable Difference

Just Noticeable Difference is a number that stands for the minimum tolerance human can percept between one and its neighbor color. Over the years, various metrics have been proposed to characterize the perceived color of polychromatic light [14]. One such metric for determining color is chromaticity. Chromaticity is used to define the perceived color impression of light, irrespective of its luminance (or “photometric brightness”), in accordance with the standards of the CIE. The CIE 1931 chromaticity standard defines the hue and saturation of light based on a pair of xy coordinates that specify position in a chromaticity diagram. Color gamut of RGB LED and curve of Blackbody Locus are depicted Fig. 2-11. In Fig. 2-11, for each color (i.e., chromaticity), there is a “MacAdam ellipse” that defines a “just noticeable difference” (JND) between it and neighbouring colors.

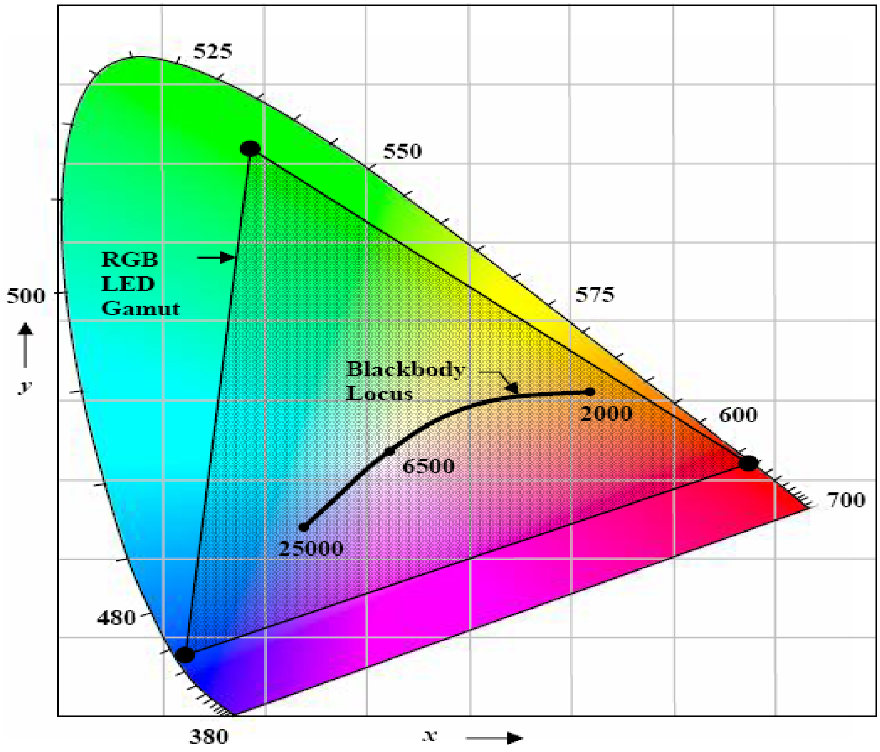


Fig. 2-11 CIE 1931 xy chromaticity diagram

The size and orientation of these ellipses vary with color, and that why a linear transformation of the CIE chromaticity diagram, called the CIE 1976 Uniform Color Space (UCS), was developed to minimize these differences [15].

The transformation is given by:

$$u'=\frac{4x}{-2x+12y+3} \quad v'=\frac{9y}{-2x+12y+3} \qquad \text{Eq. (2-4)}$$

The USC is useful in that:

$$\Delta u'v'=\sqrt{(u'-u_0')^2+(v'-v_0')^2} \qquad \text{Eq. (2-5)}$$

is relatively constant for small differences in u' and v' anywhere along the blackbody locus from 2000 to 6500 Kelvin (Fig. 2-11). Further, $\Delta u'v'=$ 0.0015 offers a reasonable approximation of one JND within this range. The American National Standards Institute (ANSI) and International Electrotechnical Commission (IEC) standards specify four MacAdam ellipses for fluorescent and HID lamps ($\Delta u'v' = 0.006$), but most major lamp manufacturers maintain chromaticity variations to within two or three MacAdam ellipses (at full rated light output and 25 ℃ ambient temperature) for quality control purposes. It is therefore reasonable to adopt two MacAdam ellipses, or $\Delta u'v' = 0.005$, as a target tolerance for Just Noticeable Difference of LEDs [16].

Similarly, Δuv is the deviation in color point (u, v) from the reference (u_r, v_r) in CIE 1960 UCS plane and is defined as:

$$\Delta uv = \sqrt{(u - u_0)^2 + (v - v_0)^2} \qquad \text{Eq. (2-6)}$$

This equation form is the same as Eq. (2-4). And Typical human eye can notice a color difference $\Delta uv > 0.0035$ in uv plane [12][17]. Hence the Just Noticeable Difference is regarded as 0.0035 in CIE 1960 UCS plane.

2.7 Recursive Approach

Recursive Approach is the repetition of a process within a computer program. It can be used both as a general term, synonymous with repetition, and to describe a specific form of repetition with a mutable state. Therefore, recursive approach is an example of iteration, but typically set a declarative condition as desired condition. Only when the desired condition reached will the recursive approach stop. In computer programming, recursive approach is coded in using ‘while loop’ or ‘if sentence’ frequently. Therefore, recursive approach method detailed in the third chapter is applied on feedback control system for LED light output stabilization. An example of flow chart of recursive approach to reach 100 is shown as Fig. 2-12.

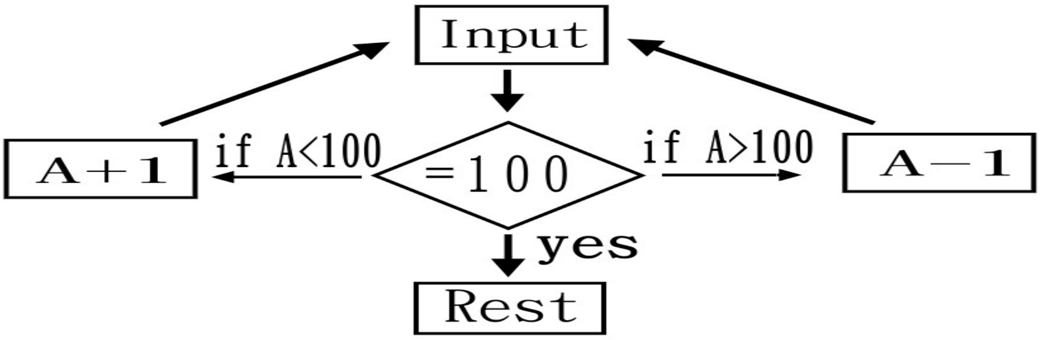


Fig. 2-12 Flow chart of recursive approach to reach 100

2.8 PWM and Duty Ratio

2.8.1 PWM

Pulse-width modulation (PWM) uses a square wave whose duty ratio is modulated resulting in the variation of the average value of the waveform.

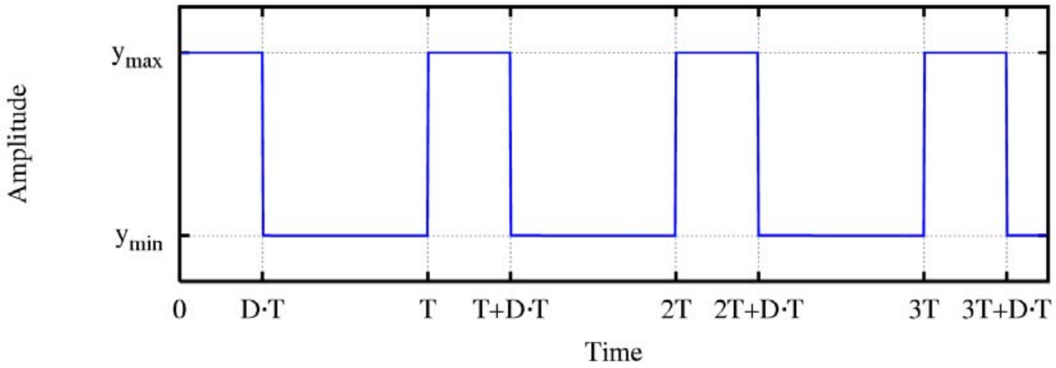


Fig. 2-13 Square wave, showing the definitions of y_{min}, y_{max} and D.

If we consider a square waveform f(t) with a low value y_{min}, a high value y_{max} and a duty cycle D (Fig. 2-11), the average value of the waveform is given by:

$$\overline{y} = \frac{1}{T}\int_{0}^{T} f(t)dt$$

Eq. (2-7)

As f(t) is a square wave, its value is y_{max} for $0 < t < D \cdot T$ and y_{min} for $D \cdot T < t < T$. The above expression then becomes:

$$\bar{y} = \frac{1}{T}\left(\int_0^{DT} y_{max}\, dt + \int_{DT}^{T} y_{min}\, dt \right)$$

$$= \frac{D \times T \times y_{max} + T \times (1 - D) \times y_{min}}{T}$$

$$= D \times y_{max} + (1 - D) \times y_{min} \qquad \text{Eq. (2-8)}$$

This latter expression can be fairly simplified in many cases where $y_{min} = 0$ as $\bar{y} = D \cdot y_{max}$. It is obvious that the average value of the signal $(\bar{y})$ is directly dependent on the duty cycle D.

2.8.2 Duty Ratio

In a square wave of PWM signal (Fig. 2-12), the most important factor is duty ratio. The duty ratio D is defined as the ratio between the pulse duration (τ) and the period (T).

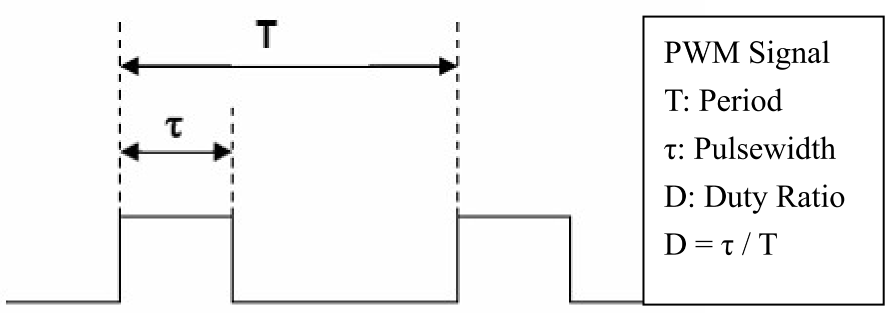


Fig.2-14 Definition of Duty Ratio in a PWM signal of rectangular waveform

2.9 Design Rules

The system structure is shown in Fig. 2-15. As soon as we adjust the variable transistor and set up desired LED light output, the processor will keep the electrical digital signal of desired color as setup value. Whenever the sensor senses the variation of LED light output by transferring electric digital signal into processor via (through) analog to digital converter, the feedback recursive function will be initiated and begin to run. Finally, by increasing or decreasing duty ratio of PWM signals of LCD driving current, the desired color is approached.

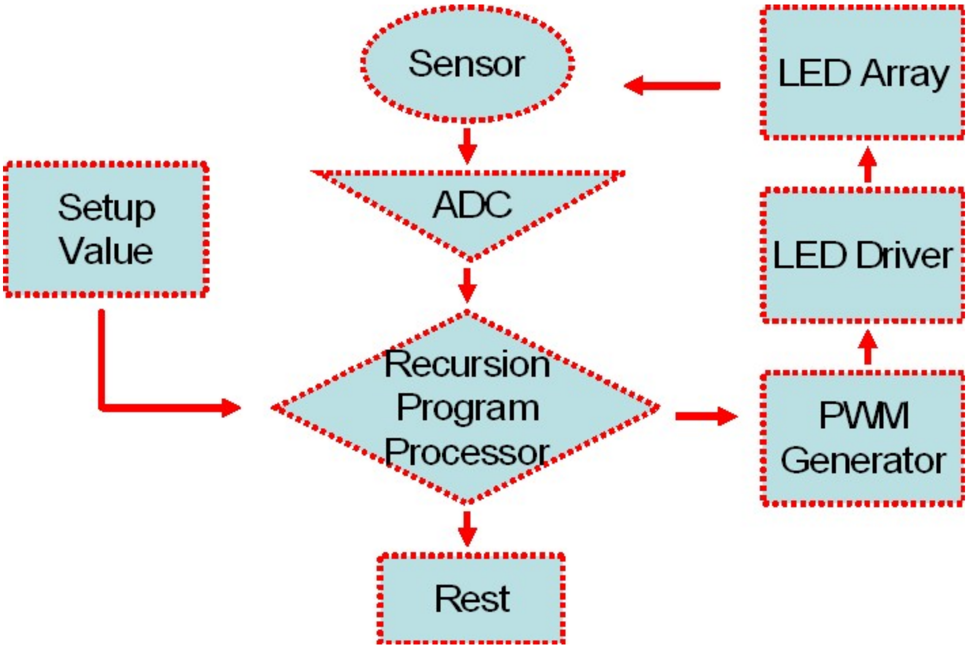


Fig.2-15 Feedback control system structure flow

2.10 Summary

In this chapter, we have described not only the history of LED, Photodiode, CIE and fundamental PWM theories, but also selected $\Delta u'v' = 0.005$ (Just Noticeable Difference) as our evaluation index. In addition, basic concepts of recursive approach have been explained as well. In the following chapter 3, the realization of feedback control system with recursive approach is going to be presented.

Chapter 3

System Implementation and Measurement

3.1 System Implementation

LED light output feedback control system is going to be established by combining several devices. According to the device functionalities and requirements, the whole system is divided into 7 sections shown in the system block diagram (Fig. 3-1). The setup value block represents that the desired color of LEDs is set up by adjusting the external variable resistor. Meanwhile, the system is initiated and begins to function. As soon as sensor senses the color variation in spite of manmade or naturally decayed and transfers electric digital signal into central processor through analog to digital converter, the feedback recursive function will be initiated and begin to run. Comparator program processor runs the recursive program and triggers the PWM signal generator and constant current driver to obtain the desired LED color.

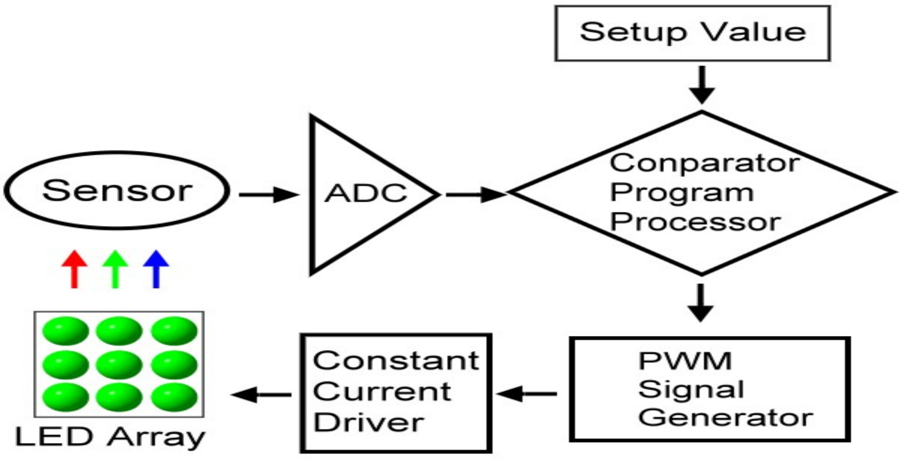
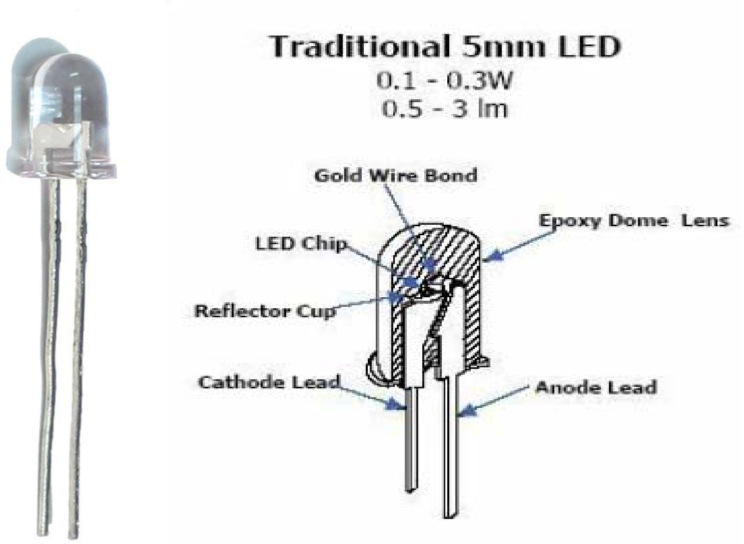


Fig.3-1 System block diagram of LED light output feedback control system

3.1.1 Setup Value

The desired colors of RGB LEDs are set up by adjusting the external 10KΩ variable resistors of LED driver to change the driving current of LEDs. Because LED is a current-driven device, the color of LED will vary when the driving current is changed.

3.1.2 LED Array



(a) (b)

Fig. 3-2(a) Photograph and (b) Structure of LED [18]

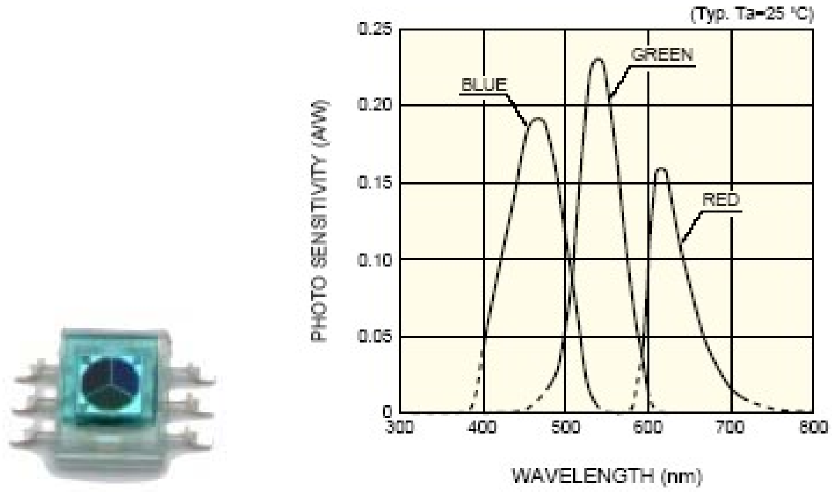
Diameter 5mm RGB LEDs (Fig. 3-2) are used to conduct this experiment because of convenience of availability and ease of sensing the color variation (Bottom Emitting) without light guide structure. Optical characteristics of LEDs are shown in Table. 3-1. However, the choice of sensor is dependent on the optical characteristics of LEDs.

Table. 3-1 Optical Characteristics of LEDs

	Red	**Green**	**Blue**
Wavelength (nm)	625	525	460
(x , y)	(0.68, 0.30)	(0.18, 0.71)	(0.12, 0.06)

3.1.3 Sensor

In order to fit the spectral sensitivity of LEDs and simplify the system complexity, 3-channel (R, G, B) photodiode color sensor is chosen to sense the color variation of LED array. The spectral response of sensor is shown in Fig.3-3. This photodiode color sensor features no sensitivity in the near infrared region. Its spectral response range is close to the human eye sensitivity. Therefore, such sensor is appropriate for the color sensing of LED array.



(a) (b)

Fig. 3-3 (a) Photograph and (b) Spectral Response of Photodiode Color Sensor [18]

Table. 3-2 Optical Characteristics of Photodiode Color Sensor [18]

Spectral Response Range（λ）	Blue	400 to 500 nm
	Green	480 to 600 nm
	Red	590 to 720 nm
Peak Sensitivity Wavelength（λp）	Blue	460 nm
	Green	540 nm
	Red	620 nm

Undoubtedly, Photo Sensor and RGB LEDs are indispensable in this experiment, 3-in-1 high sensitivity photo diode and 5mm Lamp LEDs are chosen because their wavelengths correspond to each other (Tables. 3-1 and 3-2).

3.1.4 ADC (Analog to Digital Converter)

The purpose of the A/D converter (ADC0804) is to take analog input of senor signal in the range of 0 to 5V and digitize it into 8-bits to transfer into the Lattice microprocessor. Though the A/D converter is designed with clock inputs for a synchronous connection to a microprocessor, A/D converter can be used freely in color feedback control system. Fig. 3-4 shows the configuration of the ADC0804 in free-running mode.

To configure the ADC0804 to function in free-running mode, CS* and RD* are grounded and WR* and INTR* are tied together. The N.O. on the WR* and INTR* pins stands for normally open. When the A/D is first turned on, the WR* and INTR* must be momentarily grounded. CLK R is tied back to CLK IN. V^+ (V_{REF}) is set as 5V and determines the input voltage range. AGND and DGND are tied together on the same ground plane. In this mode, the A/D will convert its input at pin 6 to the outputs DB0-DB7 within 135 ns.

In free running mode, only 8 output pins are connected to the Lattice microprocessor, freeing up pins that would have been used for clocking, chip select, etc, for use in other modules. In addition, free-running mode eliminates complicated synchronization and timing issues with the Lattice microprocessor has existed to run the chip at another sampling rate.

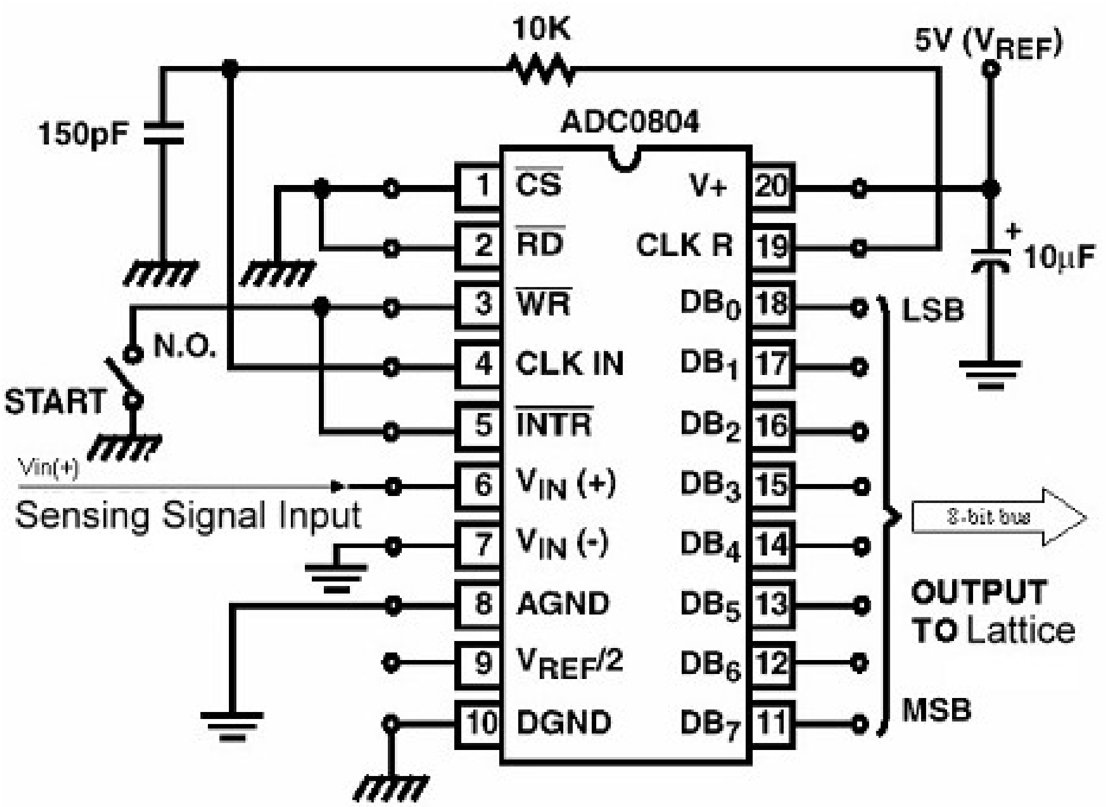


Fig. 3-4 Schematic for A/D Converter in Free-Running Mode

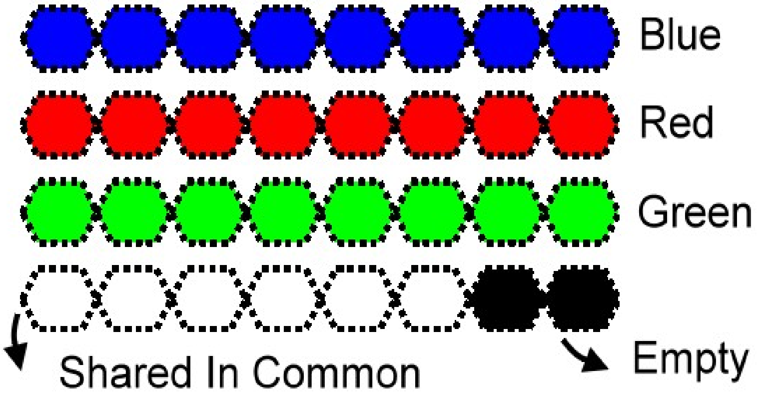


Fig. 3-5 Analog to Digital Bits Arrangement

Four 8-bits A/D converters are used to quantize the analog signals of photo sensor. Totally there are 32 bits to process, and the arrangement of 32 bits for color resolution is shown in Fig. 3-5. Two black solid circles represent unused empty bits, whereas the other six white circles denote the bits shared in common by RGB color. Consequently, 14 bits resolution for single color can be achieved.

3.1.5 Central Processor

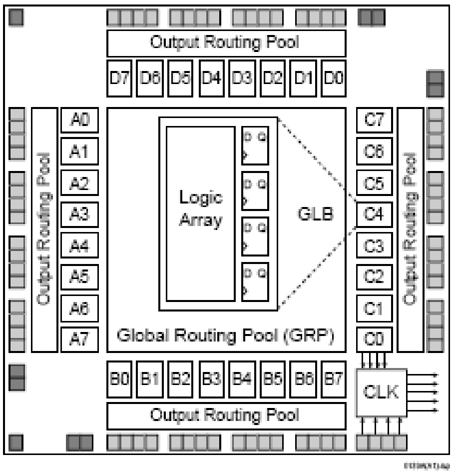


Fig. 3-6 Functional Block diagram of Central Processor

Control processor (Fig. 3-6) is the kernel of the whole feedback control system, and it collects all electric digital signals to process.

```
While ( sensor_signal != setup_value)
{
If (sensor_signal < setup_value)
PWM_intensity = PWM_intensity + 1;
Else
PWM_intensity = PWM_intensity – 1;
}
```

The code shown above denotes the function of recursive program. Actually, central processor not only links the sensor signals to PWM generator, it also compares sensor signal to setup value and decides the feedback signal. *While* loop begins to run when *sensor_signal* doesn't equal *setup_value*. After that, when the *sensor_signal* is lower than the *setup_value*, the LED light output is getting weaker. At this moment, the *PWM_intensity* signal of LED driving current is assigned to be another increased one to enhance LED light output as feedback, and vice versa. As *sensor_signal* is higher than *setup_value*, the LED light output is getting brighter. At this moment, the *PWM_intensity* signal is assigned to be lower to decrease LED light output as feedback.

3.1.6 LED Driver

DD313 is a constant current driver designed for LED lighting application. This current driver incorporates three-channel constant current circuitry with current value set by three external resistors. The three enable pins are specifically designed for independent control over each of the three output terminals, which are R, G, B LED channels in the experiment. The fast response of the output current can adapt to high dimming resolution and high refresh rate applications up to 1MHz. The pin connection and description data of LED driver, DD313, are shown in Appendix (a).

The schematic diagram of LED driver, DD313, is shown in Fig. 3-7. 18V is applied to V_{LED}. Five, Seven, and Nine LEDs are driven in series connection for Blue, Red, and Green color separately. The Constant-Current Outputs of DD313 for RGB LEDs are adjustable. Constant-current value of each output channel is set by an external resistor connected between the REXT(R, G, B) pin and GND individually. Besides, varying the resistor value can adjust the current up to 500mA. The equation of REXT(R, G, B) and Output current is shown as follows:

$$\mathrm{Iout(R,G,B)\ (A)} = 0.5\ \mathrm{(V)} / \mathrm{REXT(R,G,B)}\ (\Omega) \qquad \text{Eq. (3-1)}$$

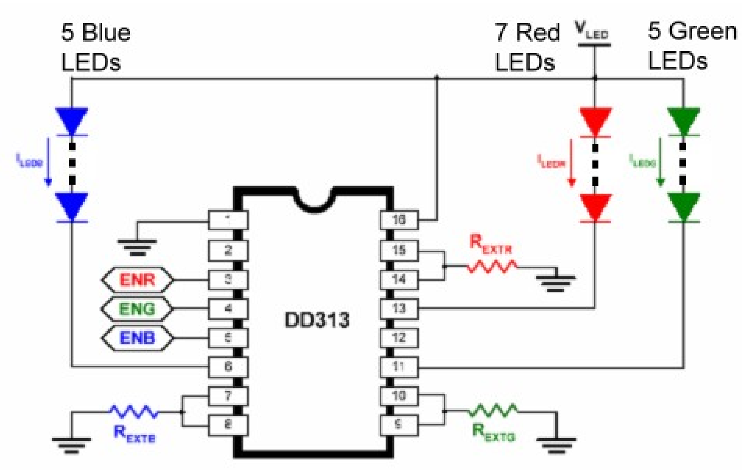


Fig. 3-7 Schematic Diagram of LED driver, DD313 [19]

3.1.7 PWM Generator

PWM generator is used to switch Enable-Pins(ENR, ENG, and ENB) of LED driver to accomplish dimming function. DM413 is a PWM enabled LED driver specifically designed for LED lighting or display applications. DM413 incorporates shift registers, data latches, 3-channel constant current circuitry with current value set by 3 external resistors, and built-in oscillator for PWM functioning. Data and clock buffer outputs are designed for cascading another chip. Additionally the Output Polarity Reverse function is designed to adapt to high power LED applications. The pin connection and description data of PWM Generator, DM413, are shown in Appendix (b).

Configuration of PWM generator and LED driver is shown in Fig. 3-8. 5V is applied to VCC. The Duty Ratio of PWM signal can be adjusted by changing Pull-High Resistance. Due to 400 Hz of PWM wave, flicker can be avoided. Because 14 bits PWM generator is utilized, the driving current of LED is divided by 14 bits. If the driving current were 20 mA, then the PWM recursive current scale would be 1.2 µA.

$$20\ (\text{mA}) \div 2^{14} = 1.2\ (\mu\text{A}) \qquad \text{Eq. (3-2)}$$

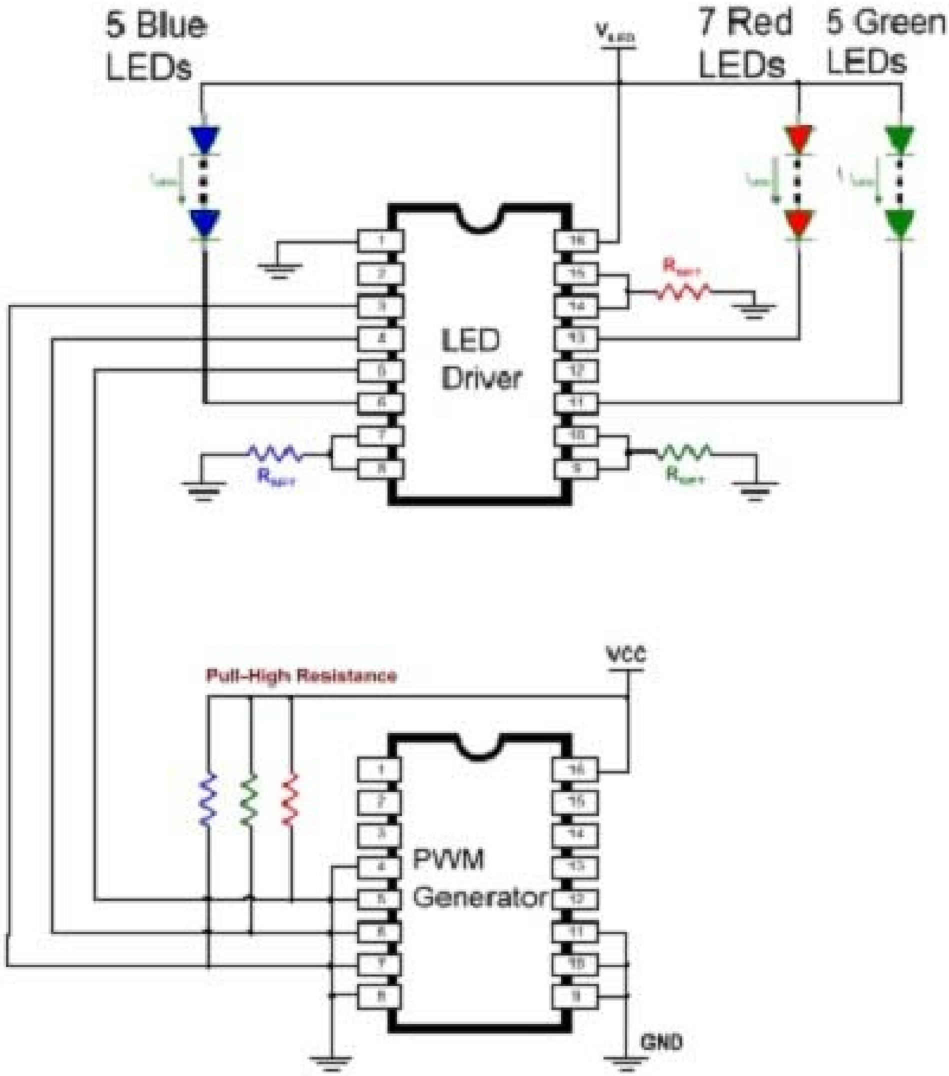


Fig. 3-8 Configuration of PWM generator and LED driver [20]

3.2 Measurement

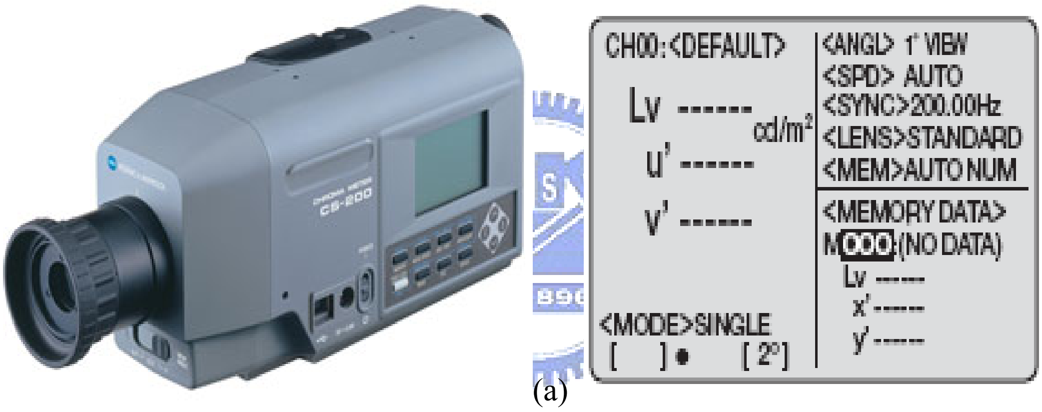
3.2.1 Evaluation Index

Color difference $\Delta u'v'$ in CIE 1976 color space is taken as evaluation index because this color space is more uniform than CIE 1960 color space. As described in Chapter 2, Eq. (2-5) is used to calculate the color difference. u_0' and v_0' are initial color coordinate of RGB LEDs at specific driving currents.

3.2.2 Measuring Instrument

CS-200 chroma meter is employed to measure color coordinate of RGB LEDs. It displays and outputs in luminance Lv (cd/m^2) and $u'v'$ chromaticity diagram (CIE 1976 UCS chromaticity diagram). The photograph and setting coordinate of CS-200 are shown in Fig. 3-9. According to the specification of chroma meter CS-200, measured $u'v'$ data are 4 bits below point. Reliable accuracy is three bits below and the last bit is regarded as reference value. Therefore, worst error of color difference is 0.0012. The calculation is shown below.

$$\Delta u'v' = \sqrt{(0.0009)^2 + (0.0009)^2} = 0.0013$$



CH00:<DEFAULT>
Lv ------ cd/m^2
u' ------
v' ------
<MODE>SINGLE
[ ]● [2°]
<ANGL> 1° VIEW
<SPD> AUTO
<SYNC>200.00Hz
<LENS>STANDARD
<MEM>AUTO NUM
<MEMORY DATA>
M000:(NO DATA)
Lv ------
x' -----
y' -----

(a) (b)

Fig. 3-9 (a) Photograph and (b) color coordinate setting of CS-200 chroma meter

3.2.3 Measuring Criterion

$u_0'v_0'$ data of LEDs are the initial values of each LED. When taking measurement, the $u'v'$ data are accepted when brightness Lv are within 10% variation. Such standard is according to the prior art. [5] After taking the forward voltages of RGB LEDs into account, Seven, Nine, and Five points $u'v'$ color data are measured for Red, Green, and Blue LED Arrays separately. In the following, Color difference $\Delta u'v'$ is calculated. Besides, average value of $\Delta u'v'$ is adopted to avoid measurement fluctuation. The measurement and experiment setting are depicted in

Figs. 3-10 and 3-11. LEDs are arranged on the left PCB board. Holes are distributed in order in the right PCB boards. In order to ensure measuring the identical points of LEDs, CS-200 chroma meter is used to take the measurement of LEDs through the measuring points.

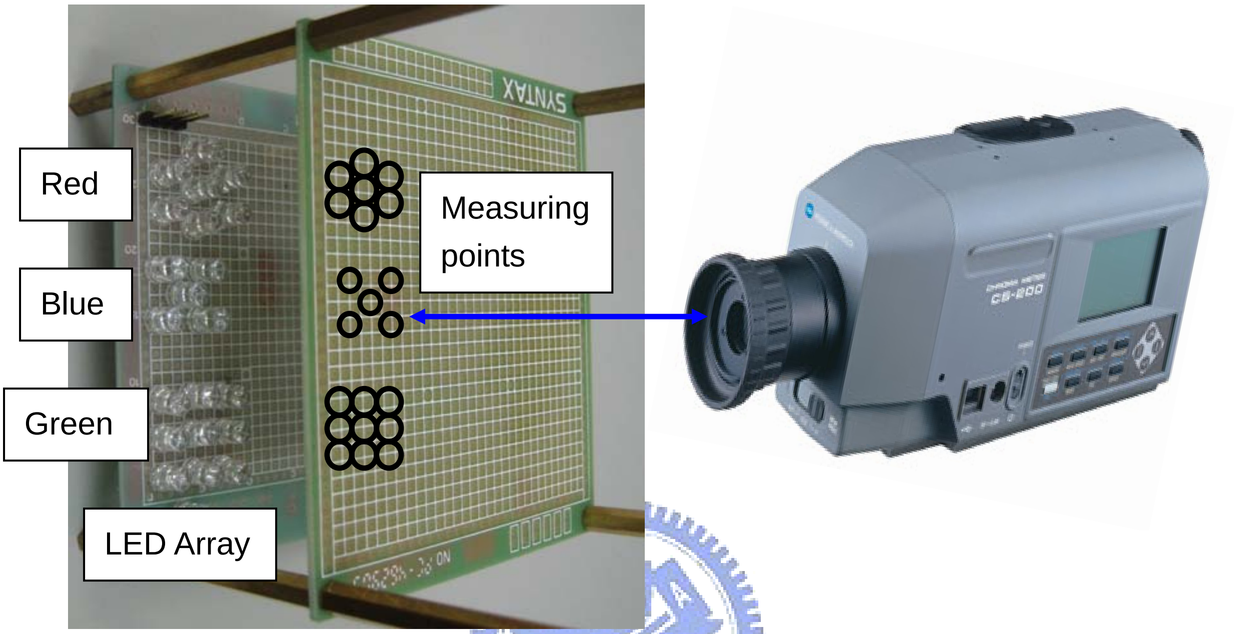


Fig. 3-10 Measurement setting of CS-200 chroma meter and LED arrays

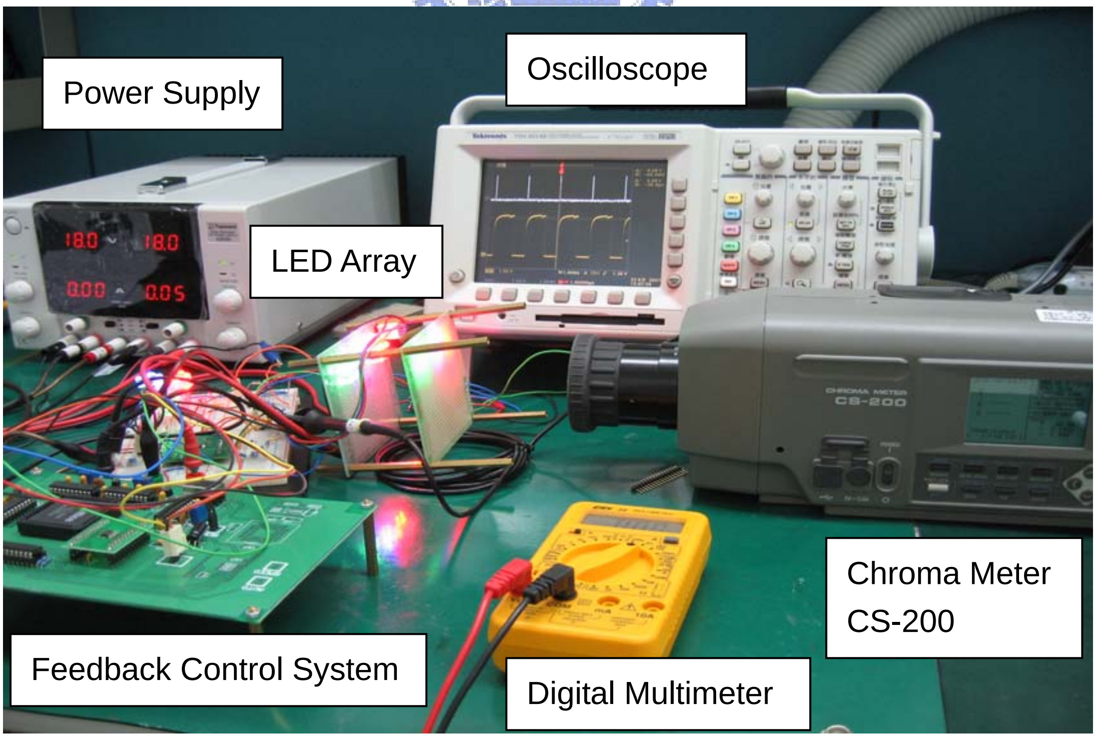


Fig. 3-11 Experiment setting of recursive feedback control system

3.3 Summary

The system structure and functionality of each device have been elaborated, as well as the setting of measurement. Central processor, which is the kernel of the feedback control system, collects all electric digital signals to process, compares sensor signal to setup value of desired LED color and decides the feedback signal. After deciding increasing or decreasing duty ratio of PWM signals to generate, the original desired color of LED is approached step by step. As a result, recursive approach feedback control system is realized. The experimental results will be presented in chapter 4.

Chapter 4

Experimental Results

4.1 Introduction

Experimental setup and performance of reducing color difference are presented and discussed. Ambient temperature dependency and aging condition were studied and simulated to ensure reliability of feedback control system. In addition, variations of LED's qualities and measurement fluctuations have been taken into consideration. Finally, different resolution bits of feedback control system were used to evaluate the effects of reducing LED color difference. The structure of data analyses is shown in Fig. 4-1. Schematically, the data analyses are divided into two flows. One is about experimental setup of feedback control system, and the other is for evaluation of system performance.

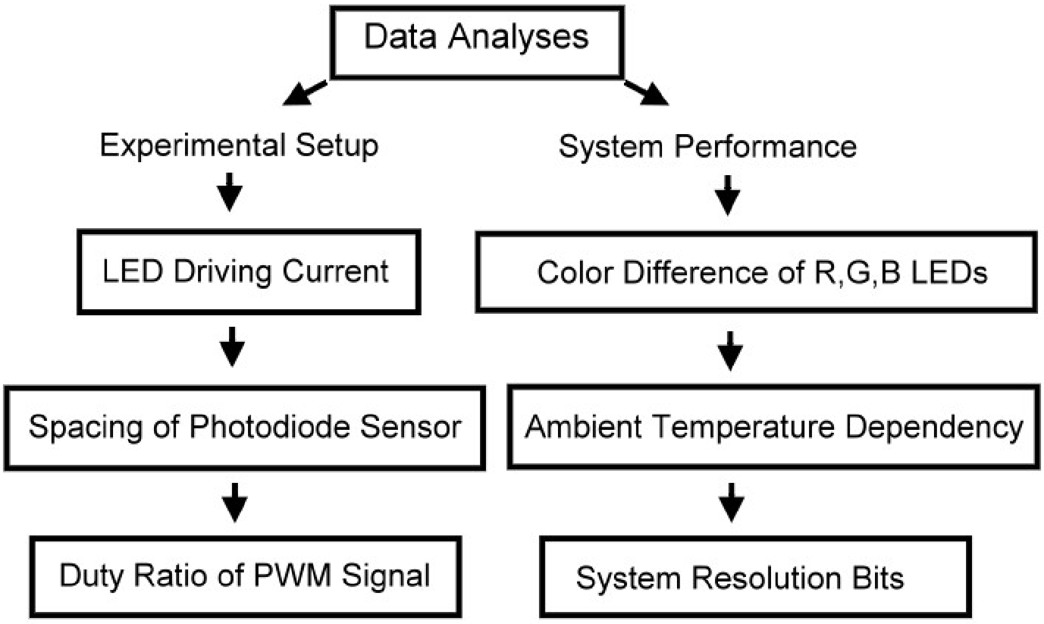


Fig. 4-1 Flow Structure of Data Analyses

4.2 LEDs' Efficacy

LED is known as a current-driven device. However, in terms of LED's efficacy, the most apparent and distinct one is the Brightness to Current curve of LED. After driving RGB LEDs in different currents and measured by chroma meter CS-200, the electro-optical characteristic curves of RGB LEDs are shown in Fig. 4-1.

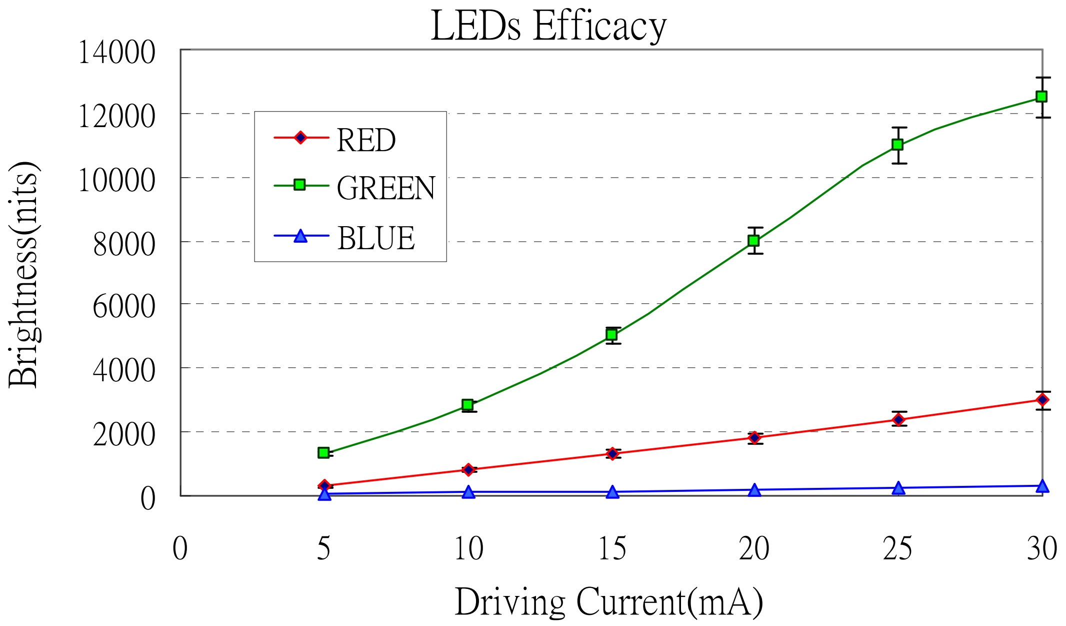


Fig. 4-2 Luminous Intensity VS. Forward Current Curves of RGB LEDs

In order to obtain standard brightness of LED backlight of 10000 nits [21], glassine is applied to shade and diffuse LEDs' light output. Without glassine, the brightness of LEDs can not be measured because the brightness measurement limitation of chroma meter CS-200 is 90000 nits. According to the specifications of LEDs, the forward current of LEDs is 20 mA. [18] The brightness of Red, Green, and Blue LEDs are 1800, 8000, and 200 nits, respectively. [22] Therefore, 10000 nits can be obtained as a summation of brightness of Red, Green, and Blue LEDs. The error bar in Fig. 4-1 denotes the deviation value of measured brightness.

4.3 Sensor's Placement

Before conducting experiments, the placement of sensor ought to be taken into consideration in advance. The measured results of sensing voltage of RGB LEDs and height of sensor above LEDs arrays are shown in Fig. 4-2. The sensitivity at 5 cm height is high because the absolute value of slope is large. In regard to intensity and sensitivity of sensing voltage, 5 cm height above the center of LED array is found preferable than others. As a result, 5 cm is chosen to be the spacing of sensor placement perpendicular to surface of LEDs arrays.

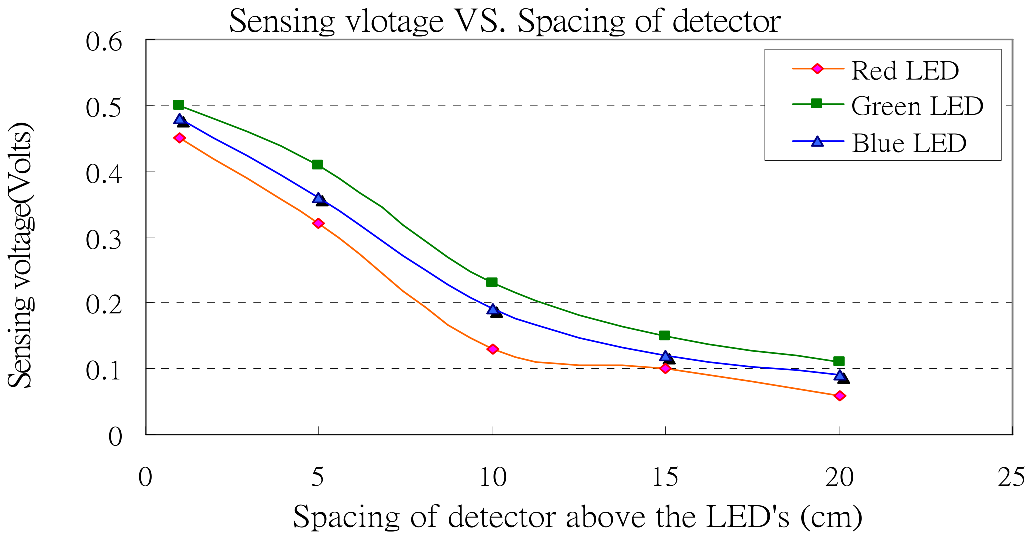


Fig. 4-3 Sensing voltage of sensor VS. Height of detector above the LED's

4.4 Duty Ratio

Because of using PWM signals to drive LED, the duty ratio becomes another factor to investigate. 20 mA, the default driving current of LED, has been chosen according to data sheets of LEDs. Therefore, various duty ratios are applied to evaluate the differences of LED's performance. The effective driving current is the same as 20 mA. If 200 mA is applied to drive LED at 10% duty ratio, the effective driving current is equivalent to apply 40 mA at 50% duty ratio.

The calculation is listed below:

200 mA @ 10% duty = 40 mA @ 50% duty

$$200 \times 10\% = 40 \times 50\% = 20 \tag{4-1}$$

In terms of duty ratio, color coordinate u’, v’ are measured and color difference Δu’v’ are calculated under 120 hours usage. (Figs. 4-3 and 4-4)

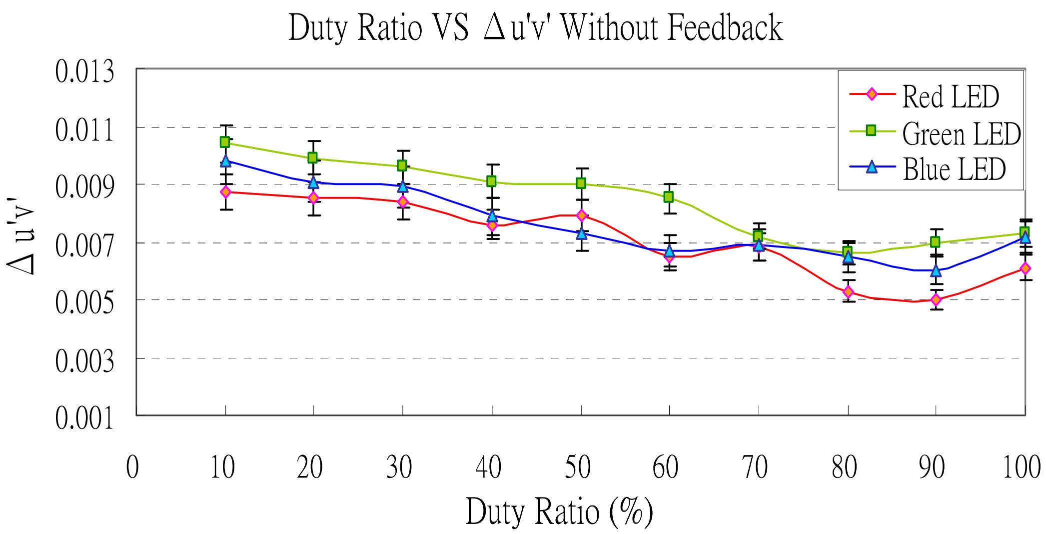


Fig. 4-4 Color difference Δu’v’ at various Duty Ratios without feedback control system

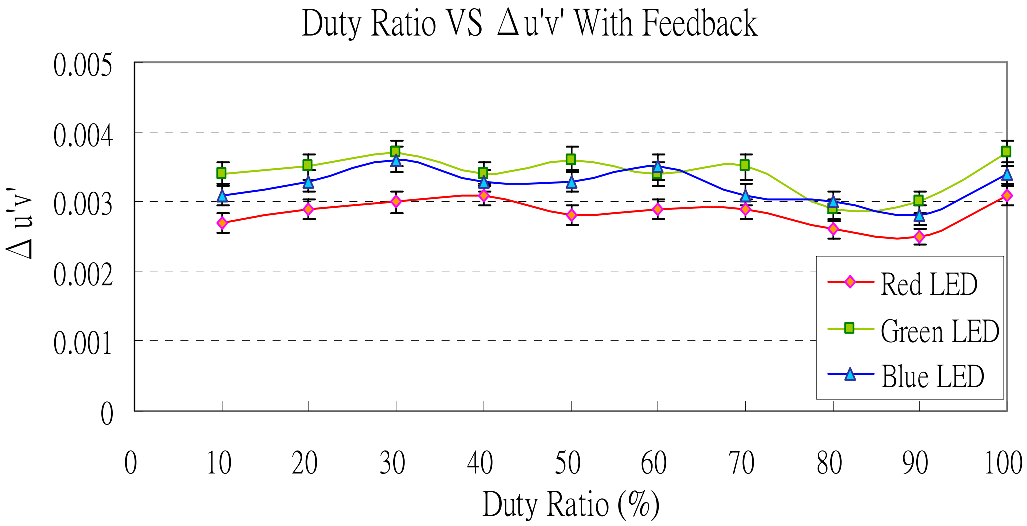


Fig. 4-5 Color difference Δu’v’ at various Duty Ratios with feedback control system

The performance of reducing color difference is obviously improved when feedback control system is applied. Moreover, RGB LED arrays show similar trends at specific duty ratios whether feedback control system is applied or not. This experimental result is in consistent with Gu’s research.[23] By comparing Fig. 4-3 with Fig. 4-4, it is found that Red and Blue LEDs have better performance in color difference Δu’v’ at 90% duty ratio, and the Green is at 80% duty ratio.

4.5 Aging condition

LED aging condition and aging environment were simulated under high current driving to investigate if feedback control system contributed to reduce color difference Δu’v’ over time. According to LED’s specification, RGB LEDs are supposed to be driven by 20 mA. LEDs with 100 mA operating current at room temperature 25 ℃ were experimented to simulate HALT (High Accelerated Life Test). [24][25] Light outputs of Red, Green, and Blue LEDs with 100 mA driving current fall down to 85%, 82, and 80% respectively when feedback control system was not applied. According to the calculation formulas of research about HALT (Eq. (4-2),(4-3)), the usage period of LEDs can be projected. [26] where α denotes decay constant, t denotes projection usage period in Hour scale, I denotes driving current in Ampere scale, and y denotes relative light output. Therefore, RGB LEDs with 120 hours usage under 100 mA can be projected to 3250, 3969, and 4462 hours usage, respectively.

$$y = e^{-\alpha t} \qquad \text{Eq. (4-2)}$$

$$\alpha = 0.00005 \times \exp[(0.0375) \times \mathrm{I}] \qquad \text{Eq. (4-3)}$$

In Figs. 4-5 to 4-10 straight linear curves denote the linear regression lines of measured data. Their functions are shown next to linear curves. These linear regression lines represent the relationships between color difference Δu’v’ and operation time. The slopes which represent the increasing rate of color differences with time are all positive. It is obvious that the slopes of 100 mA driving current are larger than those of 20 mA driving current. And the slopes of color difference of LEDs without feedback control system are always larger than those with feedback control system as well. Compare the linear regression line functions with each other pair by pair, and the coefficient of slope with feedback control system is smaller than that without feedback control system by at least one order. Which means feedback control system contributes to reduce the increasing rate of color difference of LEDs.

4.5.1 Δu'v' of Red LED

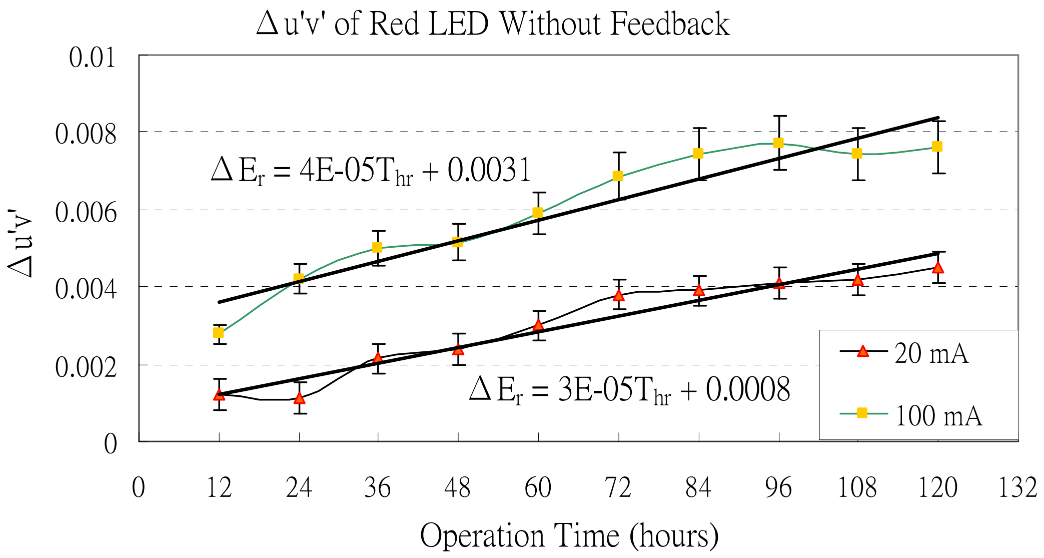


Fig. 4-6 Color difference Δu'v' of Red LED Without Feedback control

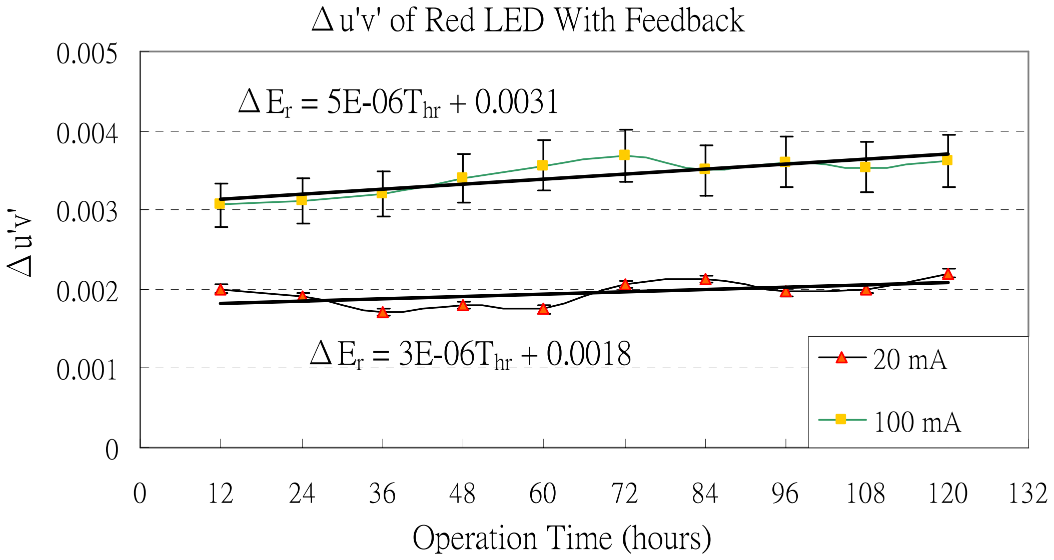


Fig. 4-7 Color difference Δu'v' of Red LED With Feedback control

According to Fig. 4-6, when feedback control system is applied, the color difference Δu'v' of red LED is kept within 0.004.

4.5.2 Δu'v' of Green LED

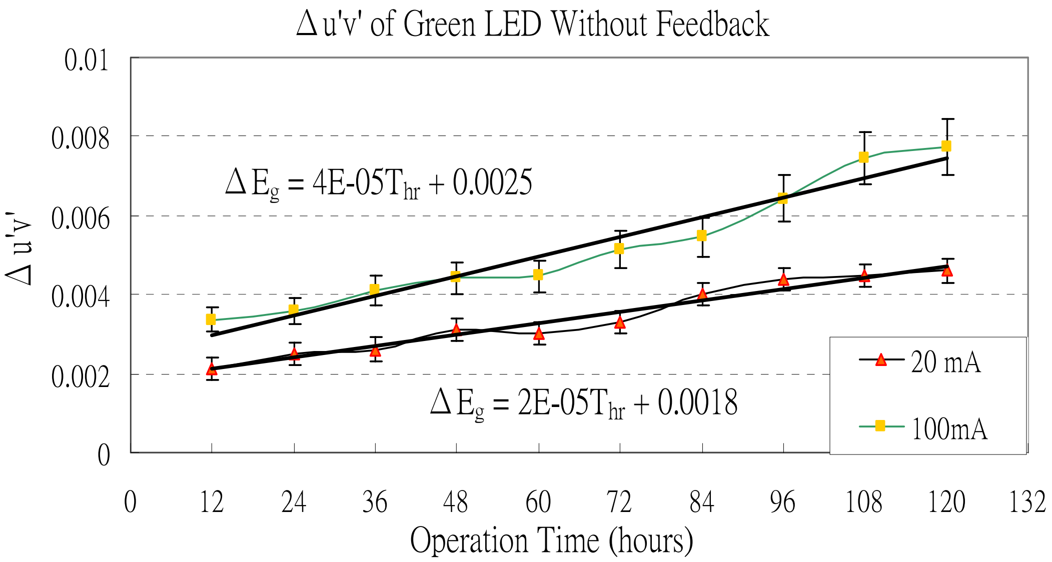


Fig. 4-8 Color difference Δu'v' of Green LED Without Feedback control

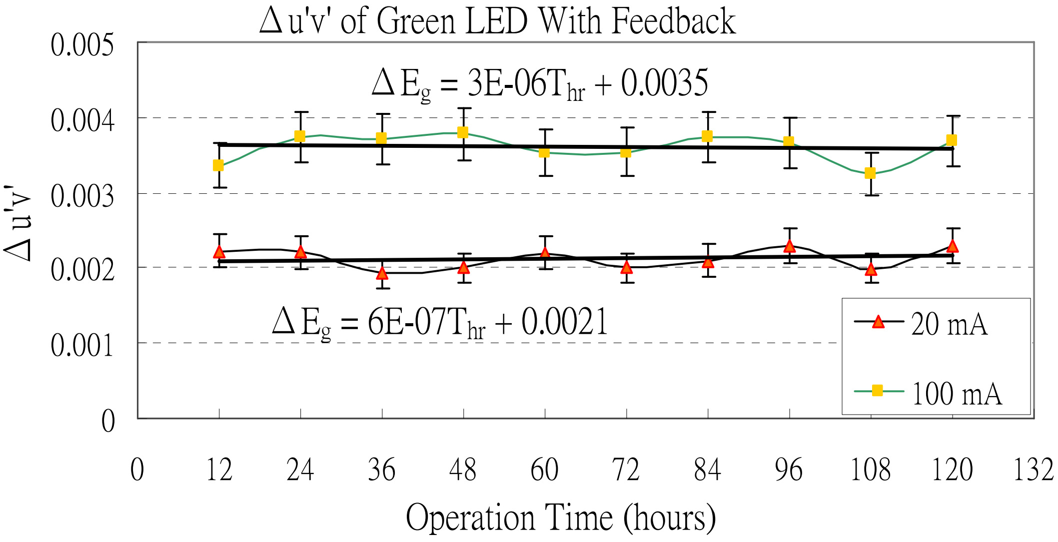


Fig. 4-9 Color difference Δu'v' of Green LED With Feedback control

After comparing Fig. 4-7 with Fig. 4-8, When feedback control system is applied, the color difference Δu'v' of Green LED is reduced and kept within 0.004.

4.5.3 Δu'v' of Blue LED

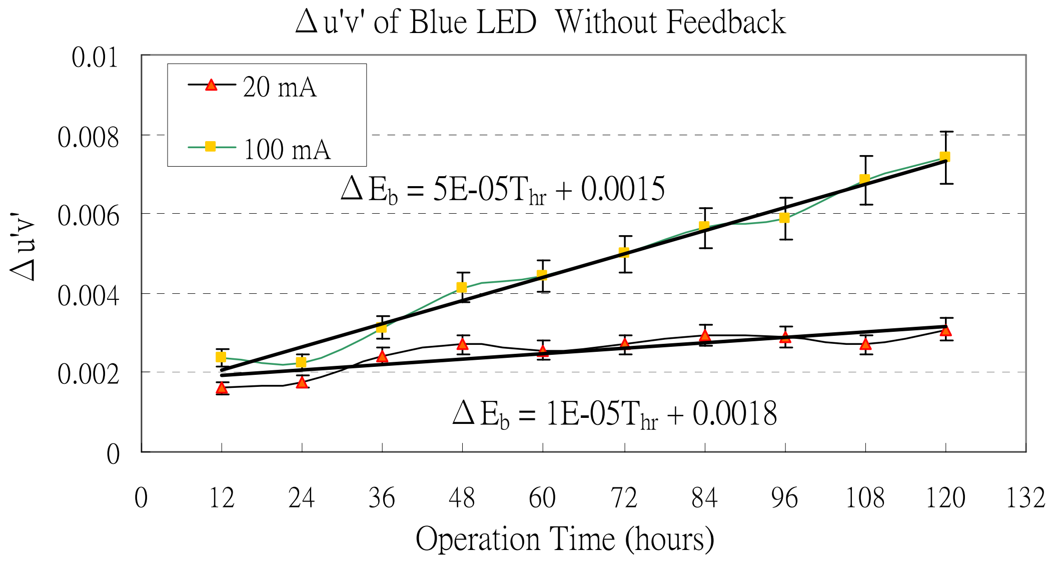


Fig. 4-10 Color difference Δu'v' of Blue LED without Feedback control

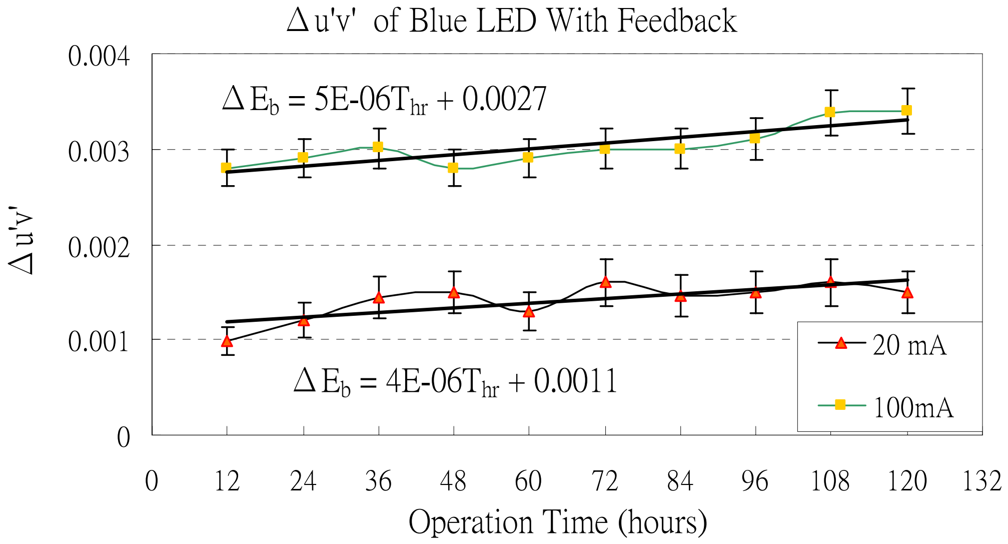


Fig. 4-11 Color difference Δu'v' of Blue LED With Feedback control

Blue LEDs shows consistent result in color difference as well. According Figs. 4-9 and 4-10, when feedback control system is applied, the color difference Δu'v' of Blue LED is reduced and kept within 0.004.

In order to predict the projection usage time of 0.005 color difference, linear regression lines with feedback control system are extended to calculate.

$\Delta Er = 5E\text{-}06\, T_{hr\_Red} + 0.0031$ Linear regression function of Red LED

$\Delta Eg = 3E\text{-}06\, T_{hr\_Green} + 0.0035$ Linear regression function of Green LED

$\Delta Eb = 5E\text{-}06\, T_{hr\_Blue} + 0.0027$ Linear regression function of Blue LED

T_{hr_Red}, T_{hr_Green}, T_{hr_Blue} are 380, 500, and 260 respectively.

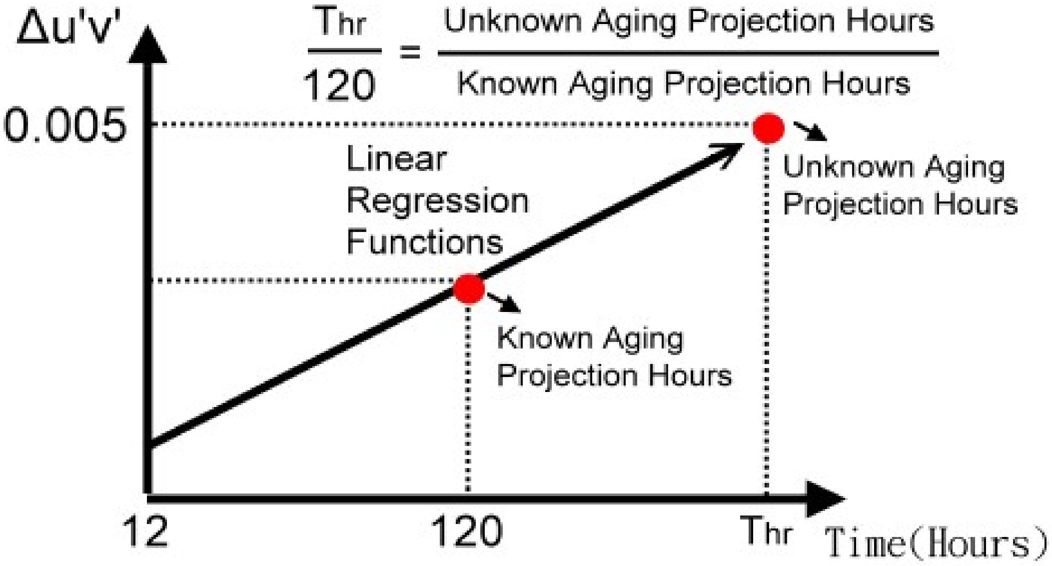


Fig.4-12 Linear calculation method of aging projection time

As mentioned before, feedback control system keeps the light output brightness Lv within 10% variation. Moreover, LEDs are regarded as linear aging before their brightness decreased by 10%. [24][27] Linear calculation method of aging projection time is shown in Fig.4-11. As mention previously, Known Aging Projection Hours are 3250, 3969, and 4462 for red, green, and blue LEDs respectively. Consequently, color differences of red, green, and blue LEDs are calculated to reach 0.005 in 10291, 16537, and 9667 aging projection hours respectively.

4.6 Temperature dependency

To examine the temperature dependency of the LEDs, RGB LEDs are experimented in the range of 0 °C to 50 °C. These limits were chosen to represent the typical ambient temperature range for the operation of TFT LCDs according to LED manufacturer's application note. [28] A temperature and humidity controlled system, GTH-800-40-1P (Fig. 4-12) was utilized to provide environment conditions. Chroma meter was placed to measure color coordinate out of chamber when the door of chamber was open.

Fig. 4-13 A temperature and humidity controlled system, GTH-800-40-1P

The driving currents of RGB LEDs needed to be changed because of color shifts due to temperature changes. Feedback control system reacted by adjusting duty ratio of PWM signal. RGB LEDs were experimented at various ambient temperatures with feedback control system or not. Experimental results are shown in Figs. 4-13~18.

According to Figs 4-13~18, the color differences of RGB LEDs with feedback control are invariant in ambient temperature ranges from 0 °C to 50 °C. Comparing to the experimental results without feedback control, no matter what degree ambient temperature affects the color shift of RGB LEDs, feedback control system keeps color difference of RGB LCDs within 0.004. Moreover, the smaller the LED driving current is, the smaller the color difference of RGB LEDs is. The difference between 20 mA and 100 mA driving current with 14 bits feedback control system lies in recursive current scale. Recursive current scales of 20 mA are 1.2 μA, and 6 μA for 100 mA. The calculation is listed below.

$$20\ (\mathrm{mA}) \div 2^{14} = 1.2\ (\mu\mathrm{A})$$

$$100\ (\mathrm{mA}) \div 2^{14} = 6\ (\mu\mathrm{A}) \qquad \text{Eq. (4-3)}$$

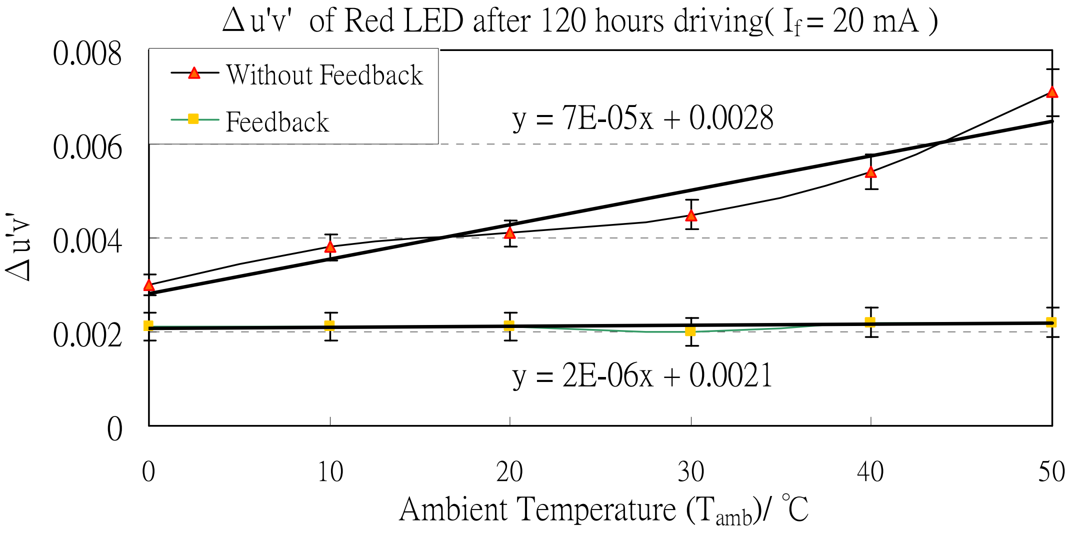


Fig. 4-14 Color difference of Red LED in relation to ambient temperature (I_f=20mA)

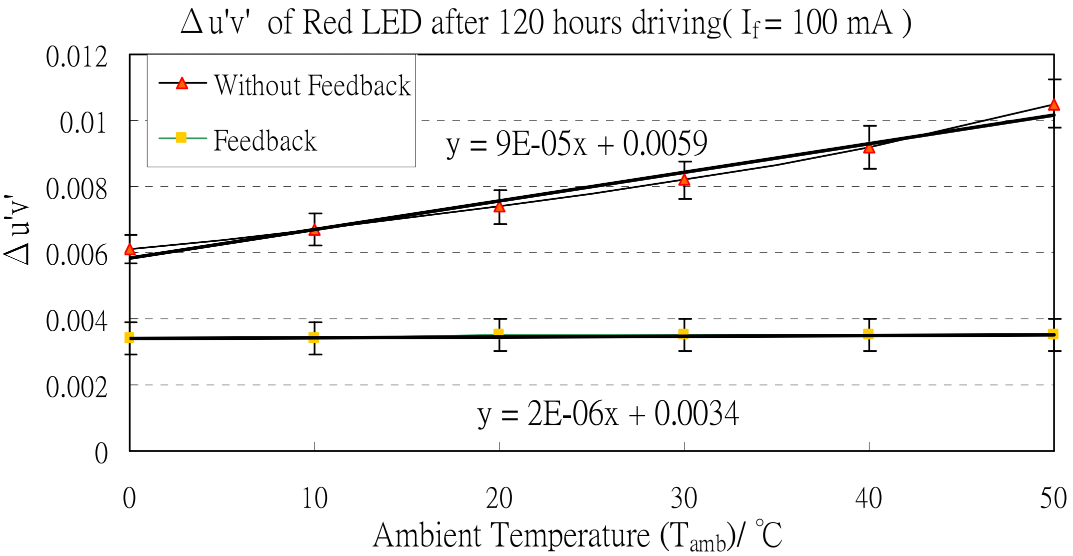


Fig. 4-15 Color difference of Red LED in relation to ambient temperature

(I$_f$=100mA)

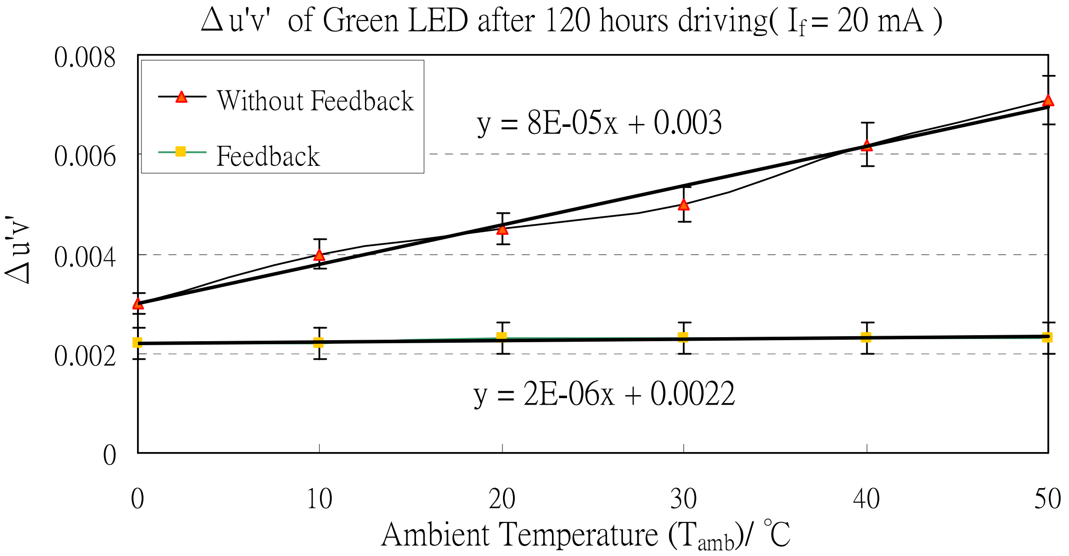


Fig. 4-16 Color difference of Green LED in relation to ambient temperature

(I$_f$=20mA)

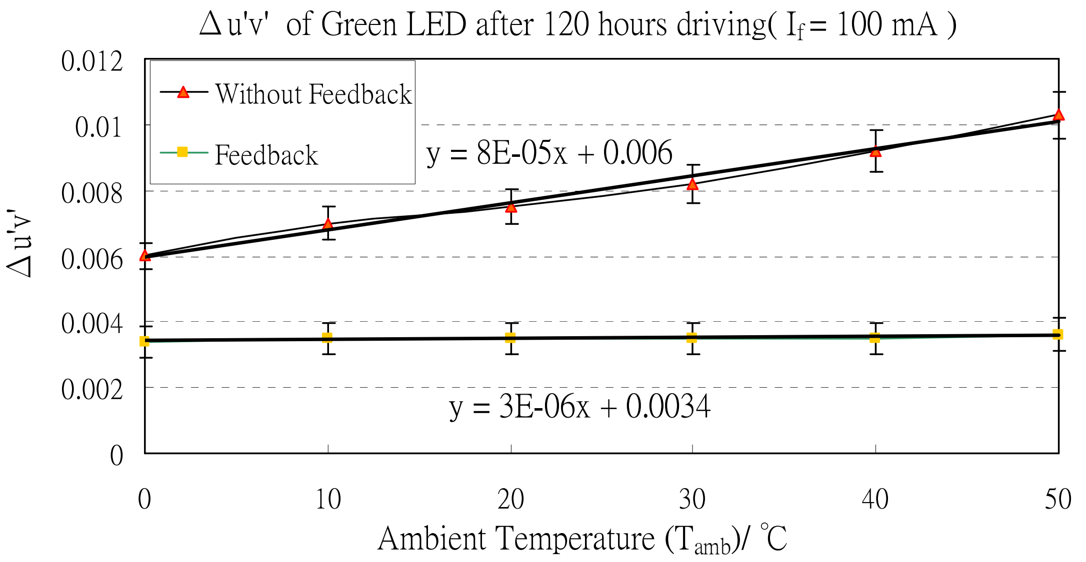


Fig. 4-17 Color difference of Green LED in relation to ambient temperature(I_f=100mA)

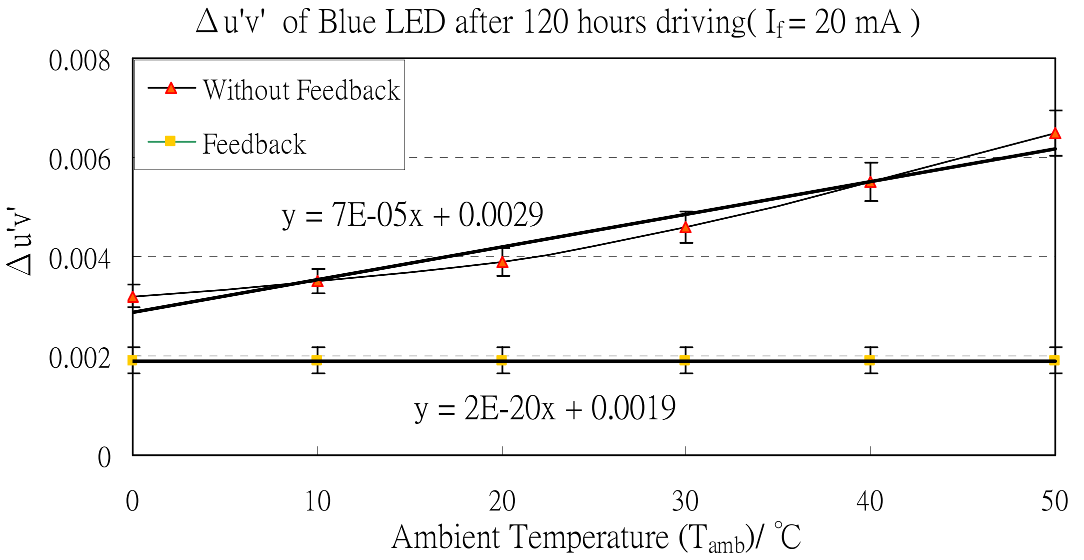


Fig. 4-18 Color difference of Blue LED in relation to ambient temperature (I_f=20mA)

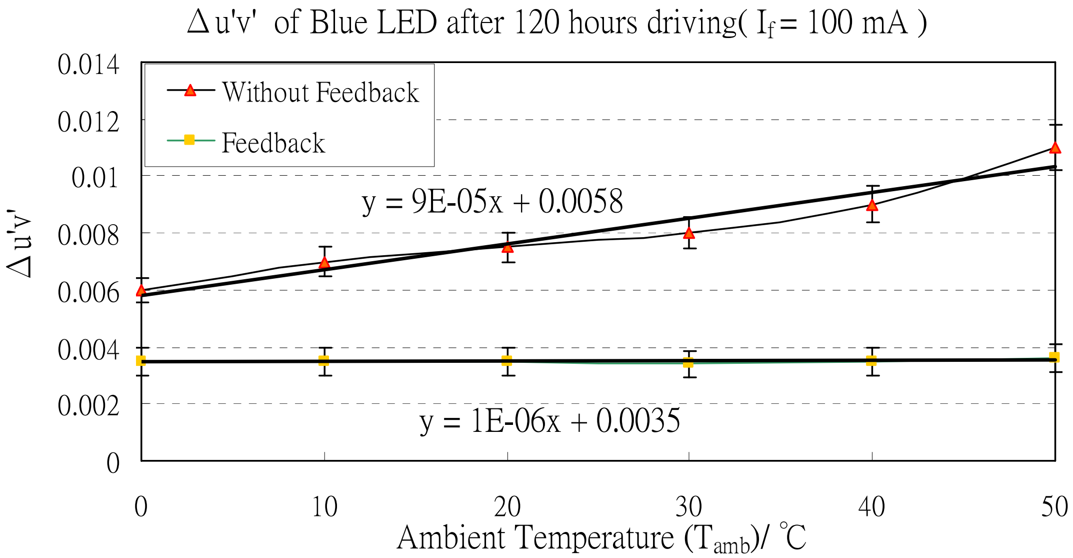


Fig. 4-19 Color difference of Blue LED in relation to ambient temperature(I_f=100mA)

4.7 White Light analysis

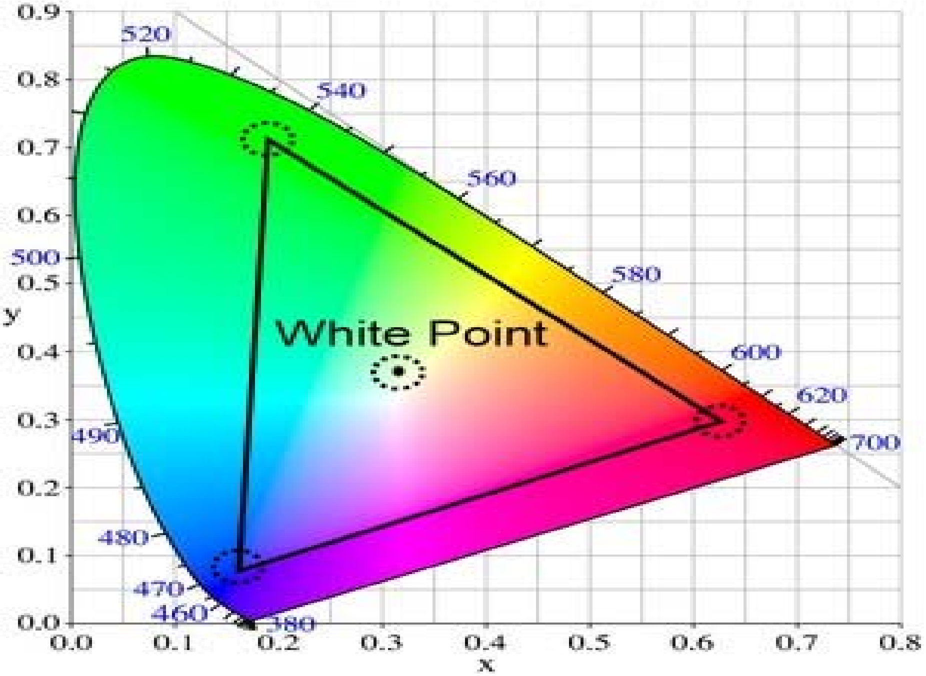


Fig. 4-20 Simulation of White Point Color Difference

White light can be generated by combining blue, red, and green light. Therefore, after taking the color difference variation of red, green, and blue LEDs as 0.005 into consideration, the maximum variation range of white point can be obtained as 0.005. The color difference variation range is shown in dotted line in Fig. 4-19.

4.8 Δu'v' VS. Resolution Bits

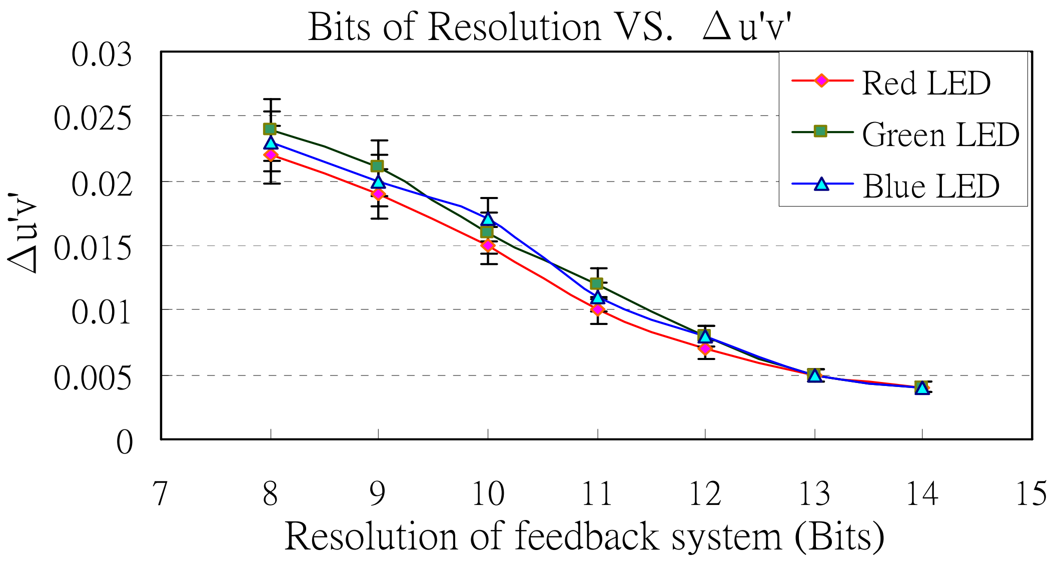


Fig. 4-21 Color difference Δu'v' of RGB LEDs at different Resolution bits

When the least significant bit of Analog to Digital or Digital to Analog conversion is neglected, the relationship between resolution digits and color difference Δu'v' can be obtained in Fig. 4-20. It is found that 13 bits is required for recursive approach to make color difference Δu'v' within 0.005. Besides, 14 bits resolution bits can make Δu'v' within 0.004. Whereas the recursive current unit is 2.4 μA for 13 bits resolution, and 1.2 μA for 14 bits under 20 mA driving current. The calculation is listed below.

$$20\ (\text{mA}) \div 2^{13} = 2.4\ (\mu\text{A})$$

$$20\ (\text{mA}) \div 2^{14} = 1.2\ (\mu\text{A}) \qquad \text{Eq. (4-4)}$$

Consequently, the color differences of RGB LEDs with feedback control system are dominated by LED driving currents and resolution bits.

4.9 Summary

In order to examine the reliability and accuracy of recursive feedback control system, ambient temperature dependency and aging condition of LED were simulated by applying 100 mA driving current. Besides, relationship between resolution bits and color difference was also investigated. 14 bits Recursive Approach Feedback Control System makes Color difference Δu’v’ be kept within 0.004 under aging simulation of 6000 hours usage. Moreover, 13 bits Resolution Digits is necessary for Recursive approach to make Δu’v’ within 0.005 in LED light output feedback control. 2.4 μA recursive current (13 bits) contributes to 0.005 of color difference Δu’v’. Since this feedback control system is initially designed for 14 bits, 1.2 μA recursive current (14 bits) can further approach 0.004 of color difference Δu’v’ of LEDs. Moreover, when feedback control system is applied, ambient temperature ranges from 0 °C to 50 °C is independent to LED’s color difference. Besides, led driving current is the key for feedback control system to restrict LED’s color difference. The higher the driving current is, the larger the LED’s color difference will be. Consequently, small current driven LEDs are preferable for this feedback control system.

Chapter 5

Conclusions and Future works

5.1 Conclusions

LED lighting has the ability to change the color and dimming level instantaneously in addition to many other advantages such as long lifetime [29][30]. They therefore have great potential in many applications such as LCD backlighting, and video projection. However, LED still has some issues to be resolved. The major issues to be tackled are the control and maintenance of LED light output. We utilized a recursive approach method to deal with color shift of LED after longtime usage. Our feedback control system possesses some features and advantages listed below.

1. A 14 bits RGB LEDs light output feedback control system has been realized and verified. Finally, we proved that feedback control system is independent to ambient temperature ranges from 0 °C to 50 °C.
2. We have demonstrated that 14 bits Recursive Approach Feedback Control System makes LEDs color difference (Δu'v') of Red, Green, and Blue LEDs within 0.005 under aging simulation of 10291, 16537, and 9667 hours usage and white point is in 0.005 color difference variation range. Such performance is competitive to the 5000 hours lifetime standard of 5.7 inch TFT LCD with white light LED backlight. [10]
3. Instead of using many mathematic transformations as prior art mentioned in section 1.3, this feedback control system provide an illustration to resolve LED color shift issue in accurate current control domain. Moreover, this feedback control system has simpler system configuration than prior art and features comparable

performance on reducing color difference of LED at the expense of high accuracy of recursive current unit control and instrument cost.

4. 13 bits resolution is proved necessary for this system to keep Δu'v' within 0.005, the just noticeable difference of human. The process steps of 13 bits resolution are half of that of 14 bits resolution because recursive current of 13 bits is twice as big as that of 14 bits.

In order to simplify the system configuration, it is trade-off between cost and performance after all. In order to optimize the balance of cost and performance, it is necessary to find the relationship between minimum controllable color difference and corresponding resolution bits of feedback control system. Therefore, by determining desired minimum color difference, the resolution bits of feedback control system can be known. Afterward appropriate and applicable electronic devices can be found and utilized.

5.2 Future works

In this thesis, the light output of 5mm RGB Lamp LEDs is stabilized within just noticeable difference. Moreover, it is proved that its lifetime is competitive to commercial TFT LCD backlight. Besides, this thesis has set an example and rules to design a feedback control system.

In order to maintain the brightness and raise the contrast ratio of LED backlight, local dimming is a popular method to utilize. Obviously, the heat dissipation of LED is a critical issue needed to be resolve. Therefore, the LED arrangement and heat dissipation mechanism design is a following research topic. On the other hand, the circuit design and data processing for local dimming and sensor signal of feedback control system is of great importance as well.

Reference

[1] HTTP://www.ausairpower.net/OSR-0398.html

[2] G. Harbers et al., “High performance LCD backlighting using high intensity red, green, and blue light emitting diodes”, SID’01, pp. 702-706, (2001).

[3] HTTP://campaign.hncb.com.tw/intranet/monthly/mon046/04604.pdf

[4] S. Muthu et al., “Red, green and blue LED based white light generation: issues and control”, 37th Annual IEEEIAS meeting 2002, vol. 1, pp. 327 –333, (2002).

[5] S. Muthu et al., “Red, green and blue LED-based white light source: implementation challenges and control design”, Proc. IEEE ISA’03, vol. 1, pp. 515-522, (2003).

[6] S. Muthu et al., “Red, green and blue LEDs for white light illumination”, IEEE, journal on selected topics in quantum electronics, vol. 8, no. 2, pp. 333-338, (2002).

[7] US patent 6,507,159, “Controlling method and system for RGB based LED luminary”.

[8] US patent application 20020195541 A1, “Method and system for controlling a light source”.

[9] N. Mohan et al., “Power electronics: Converters, Applications and Design”, 2nd Edition, John Wiley & Sons, New York, (2003).

[10]http://www.ecntaiwanmag.com/article-6766-5000%E5%B0%8F%E6%99%82%E5%A3%BD%E5%91%BD%E7%9A%84TFTLCD%E6%A8%A1%E7%B5%84-Asia.html

[11] R. Jackson et al., “Computer Generated Color: A Practical Guide to Presentation and Display”, 2nd Edition, John Wiley & Sons, New York, (1993).

[12] G.. Wyszecki et al., “Color Science: Concepts and methods, quantitative data and formulae”, 2nd Edition, John Wiley & Sons, New York, (1982).

[13] D. Malacara, “Color Vision and Colorimetry: Theory and Applications”, SPIE Press, Bellingham, Washington, (2002).

[14] S. Robinson et al., “Polychromatic optical feedback: control, stability, and dimming”, Proceedings of Solid State Lighting VI, SPIE vol. 6337, 633714 (2006).

[15] Wien, “CIE. Colorimetry”, 3rd Edition, Commission Internationale de l’Eclairage, Austria, (2004).

[16] HTTP://www.eedesign.com.tw/article/forum/fo1158.htm

[17] D.L MacAdam, “Color Measurements: Theme and Variations”, 2nd Edition, Springer, New York, (1985).

[18] HTTP://www.datasheetsite.com/datasheet/S9032

[19] HTTP://www.sitikorea.com/DD313.pdf

[20] HTTP://www.siti.com.tw/product/spec/LED/DM413.pdf

[21] R.S. West et al., “LED backlight for large area LCD TV’s”, IDW'03, pp. 657-660, (2003).

[22] HTTP://hk.cgan.net/book/books/print/packcolor/link/2-2.htm

[23] Y. Gu et al., “spectral and luminous efficacy change of high-power LEDs under different dimming methods”, Sixth International Conference on Solid State Lighting, Proceedings of SPIE 6337, 63370J. (2006).

[24] D. L. Barton et al., “Life tests and failure mechanisms of GaN/AlGaN/InGaN light-emitting diodes”, Proc. SPIE, v 3279, pp.17 (1998).

[25] D. Kececioglu et al., “The Arrhenius, Eyring, inverse power law and Combination models in accelerated testing”, Reliability Engineering, (1983).

[26] 劉熙娟，溫岩，朱紹龍, “白光LED的使用壽命的定義和測試方法” ,光源與照明, 2001年04期

[27]O. Pursiainen et al., “Identification of aging mechanisms in the optical and electrical characteristics of light-emitting diodes” [J].Appl.Phys.Lett., (2001)

[28] Raimund Zach, "Color Stabilization of RGB LEDs in an LED Backlighting Example", OSRAM Opto Semiconductors, Application Note, (2004).

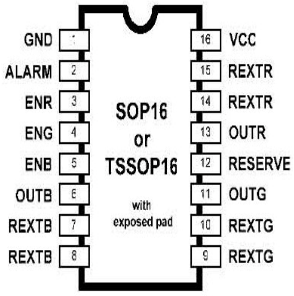
[29] M.G. Craford, "LED's challenge the incandescents", IEEE Circuits and Devices Mag., vol. 8, pp. 24-29, (1992).

[30] S.A.Steigerwald et al., "Illumination with solid state lighting technology", IEEE journal on selected topics in quantum electronics, vol. 8, pp. 316-317, (2002).

Appendix

(A) Pin Connection and Description of LED Driver, DD313

Pin Connection

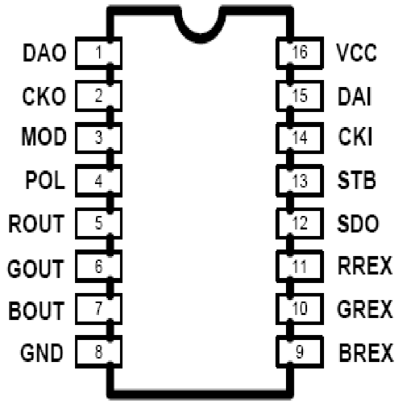


Pin Description

PIN No.	PIN NAME	FUNCTION
SOP16/TSSOP16: 1 QFN16: 3	GND	Ground terminal.
SOP16/TSSOP16: 2,12 QFN16: 4	ALARM	Output open drain terminal: (connected to a pull-high resistor) '**H**' for normal conditions, '**L**' for LED open or chip overheated.
SOP16/TSSOP16: 3,4,5 QFN16: 5,6,7	ENR,G,B	Output current enable terminal.
SOP16/TSSOP16: 6,11,13 QFN16: 8,13,15	OUTB,G,R	Sink constant current outputs (open-drain).
SOP16/TSSOP16: 7,8,9,10,14,15 QFN16: 9,10,11,12,16,1	REXTB[*1] REXTG[*1] REXTR[*1]	External resistors connected between REXT and GND for driver current value setting.
SOP16/TSSOP16: 16 QFN16: 2	VCC	Power supply terminal.

(B) Pin Connection and Description of PWM Generator

Pin Connection



Pin Description

PIN No.	PIN NAME	FUNCTION
1	DAO	Serial data output terminal.
2	CKO	Clock output terminal.
3	MOD	Input mode selection: '**H**' for 13bits/5byte mode, '**L**' for 14bits/4byte mode, '**Floating**'[*1] for 8bits/3byte mode.
4	POL	PWM current output polarity selection: '**H**' for positive polarity, '**L**' for negative polarity.
5~7	R(G、B)OUT	Sink constant current outputs (open-drain).
8	GND	Ground terminal.
9~11	R(G、B)REX	External resistors connected between REXTR(G、B) and GND for driver current value setting.
12	SDO	Serial data output trigger mode selection: '**H**' means data is shifted out on synchronization to falling edge of CKO, '**L**' means data is shifted out on synchronization to rising edge of CKO.
13	STB	Input terminal of data strobe: '**H**' means data is latched, '**L**' means data on shift register goes through latch (level latch).
14	CKI	Synchronous clock input terminal for serial data transfer. Data is sampled at the rising edge of CKI.
15	DAI	Serial data input terminal.
16	VCC	Power supply terminal.

(C) Recursive Program of Central Processor

```
{
module run(rst,osc,clk,r1,g1,b1,out1,out2,stb,r2,g2,b2,glin,adc);
input   rst,osc;
input [7:0]r1,g1,b1,r2,g2,b2,glin;
output clk,out1,out2,stb,adc;
wire [5:0]gl;
wire   [6:0]counts;
count_1   thecount_1      (rst,osc,counts);
clkd        theclkd          (rst,osc,counts,clk);
rgb          thergb
(rst,osc,counts,r1,g1,b1,out1,out2,r2,g2,b2,gl,glin);
stbdat     thestbdat       (rst,osc,counts,stb);
trig   gtlu            (rst,osc,adc);
endmodule
//-------count-----------------------------------------------------------------------
module count_1(rst,osc,counts);
input   rst,osc;
output [6:0]counts;
reg      [6:0]counts;
always@(posedge osc or negedge rst)
begin
     if(!rst)counts=0;
     else if(counts <'d66) counts=counts+1;
```

```
    else counts=0;
end
endmodule
//-------clk---------------------------------------------------------------------------
module clkd(rst,osc,counts,clk);
input   rst,osc;
input [6:0]counts;
output clk;
reg       clk;
always@(posedge osc or negedge rst)
begin
    if(!rst)clk=0;
    else if((counts=='d0)||((counts
<'d67)&&((counts%2)==1))||(counts>='d66))clk=0;
    else clk=1;
end
endmodule
//-------rgb---------------------------------------------------------------------------
module rgb(rst,osc,counts,r1,g1,b1,out1,out2,r2,g2,b2,gl,glin);
input   rst,osc;
input [6:0]counts;
input [7:0]r1,g1,b1,r2,g2,b2,glin;
output [5:0]gl;
reg [5:0]gl;
output out1,out2;
reg out1,out2;
```

```
always@(posedge osc or negedge rst)
begin
   if(!rst)begin out1=0; out2=0; end
   else
   begin
   gl=glin/4;
   if(counts<'d1)begin out1=0; out2=0; end
   if(counts=='d1)out1=r1[7];     if(counts=='d3)out1=r1[6];
if(counts=='d5)out1=r1[5];     if(counts=='d7)out1=r1[4];
   if(counts=='d9)out1=r1[3];     if(counts=='d11)out1=r1[2];
if(counts=='d13)out1=r1[1];   if(counts=='d15)out1=r1[0];
   if(counts=='d17)out1=g1[7];   if(counts=='d19)out1=g1[6];
if(counts=='d21)out1=g1[5];   if(counts=='d23)out1=g1[4];
   if(counts=='d25)out1=g1[3];   if(counts=='d27)out1=g1[2];
if(counts=='d29)out1=g1[1];   if(counts=='d31)out1=g1[0];
   if(counts=='d33)out1=b1[7];   if(counts=='d35)out1=b1[6];
if(counts=='d37)out1=b1[5];   if(counts=='d39)out1=b1[4];
   if(counts=='d41)out1=b1[3];   if(counts=='d43)out1=b1[2];
if(counts=='d45)out1=b1[1];   if(counts=='d47)out1=b1[0];
   if(counts=='d49)out1=1;          if(counts=='d51)out1=1;
if(counts=='d53)out1=gl[5];   if(counts=='d55)out1=gl[4];
   if(counts=='d57)out1=gl[3];   if(counts=='d59)out1=gl[2];
if(counts=='d61)out1=gl[1];   if(counts=='d63)out1=gl[0];

   if(counts=='d1)out2=r2[7];     if(counts=='d3)out2=r2[6];
if(counts=='d5)out2=r2[5];     if(counts=='d7)out2=r2[4];
```

```
   if(counts=='d9)out2=r2[3];      if(counts=='d11)out2=r2[2];
if(counts=='d13)out2=r2[1];    if(counts=='d15)out2=r2[0];
   if(counts=='d17)out2=g2[7];    if(counts=='d19)out2=g2[6];
if(counts=='d21)out2=g2[5];    if(counts=='d23)out2=g2[4];
   if(counts=='d25)out2=g2[3];    if(counts=='d27)out2=g2[2];
if(counts=='d29)out2=g2[1];    if(counts=='d31)out2=g2[0];
   if(counts=='d33)out2=b2[7];    if(counts=='d35)out2=b2[6];
if(counts=='d37)out2=b2[5];    if(counts=='d39)out2=b2[4];
   if(counts=='d41)out2=b2[3];    if(counts=='d43)out2=b2[2];
if(counts=='d45)out2=b2[1];    if(counts=='d47)out2=b2[0];
   if(counts=='d49)out2=1;           if(counts=='d51)out2=1;
if(counts=='d53)out2=gl[5];    if(counts=='d55)out2=gl[4];
   if(counts=='d57)out2=gl[3];    if(counts=='d59)out2=gl[2];
if(counts=='d61)out2=gl[1];    if(counts=='d63)out2=gl[0];


      end
   end
endmodule
//-------stb-------------------------------------------------------------------------
module stbdat(rst,osc,counts,stb);
input    rst,osc;
input [6:0]counts;
output stb;
reg stb;
always@(posedge osc or negedge rst)
begin
```

```
    if(!rst)stb=1;
    else
    begin
      if(counts>='d65)stb=0;
      else stb=1;
    end
end
endmodule
//-------adc---------------------------------------------------------------------------
module trig(rst,osc,adc);
input    rst,osc;
output adc;
reg adc;
reg stop;
always@(posedge osc or negedge rst)
begin
    if(!rst)begin adc=0; stop=0;end
    else
    begin
      if(stop<1)begin adc=1; stop=stop+1; end
      else adc=0;
    end
end
endmodule
}
```