Color and Luminance Correction and Calibration System for LED Video Screens

Mohammad Al-Mulazem

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ABSTRACT

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Recent years have seen a surge in the popularity of Light emitting diode (LED) video screens, which have come to be a critical part of how the world of show business and corporate events are seen by their audiences. LED video screens are bright, visually attractive, can stand severe weather conditions, and consume far less power than CRT technology. In LED screens technology, pixels are composed of three primary LED colors: red, green, and blue (RGB). Using the primary colored LEDs provide the ability to generate variety of color hues, saturations and values. However, the RGB LEDs in the screen's pixels have different luminance and color due to the LEDs themselves. These differences seriously destroy the white balance of the LED pixels and modules, and make the picture color aberration, blotchy and patchy. To overcome these problems, different techniques and methodologies has been proposed in the literature. The main drawbacks of these techniques are the cost-effectiveness in the sense they provide mediocre resolution. In this thesis, a new and cost-effective methodology and technique is proposed to correct the color and the luminance of LED video screens while maintaining a high quality and high resolution image display. Also, a new developed algorithm is proposed to fit different color and brightness calibration purposes. The proposed algorithm is based on the CIE Commission Internationale de l'Eclairage standards. The technique and methodology have been implemented, in collaboration with LSI SACO Technologies Inc., using fully automated robotic spectrometer system and achieved the targeted goals.

CONCORDIA UNIVERSITY

School of Graduate Studies

This is to certify that the thesis prepared

By: **Mohammad Al-Mulazem**

Entitled: **Color and Luminance Correction and Calibration System for LED Video Screens**

and submitted in partial fulfillment of the requirements for the degree of

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complies with the regulations of this University and meets the accepted standards with respect to originality and quality.

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______________________ Dr. Amir G. Aghdam

______________________ Dr. Ibrahim G. Hassan

______________________ Dr. Luiz A.C. Lopes

______________________ Dr. Otmane Ait Mohamed

Approved by ______________________

Chair of the ECE Department

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Dean of Engineering

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This thesis is dedicated to

My Mother, My Father, My Wife

and

My Daughter Jana

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LIST OF NOMENCLATURE

English Notations:

P	Light relative spectral power, *no unit*
$\bar{x}, \bar{y}, \bar{z}$	CIE color matching function, *no unit*
XYZ	CIE Tristimulus value, *no unit*
x, y	CIE 1931 color coordinate, *no unit*
u', v'	CIE 1976 color coordinate, *no unit*
Yn	n Color Brightness, *nits*
C	Forward Current, *Amp*
K	Color Coefficient, *no unit*
F	Relative Weight, *no unit*

Greek Notations:

λ	Wavelength, *m*

LIST OF ACRONYMS

ASIC Application-Specific Integrated Circuit

CCD Charge-Coupled Device

CIE Commission Internationale de l'Eclairage

CPLD Complex Programmable Logic Device

CPU Central Processing Unit

CRT Cathode Ray Tube

DC Direct Current

EEPROM Electrically Erasable Programmable Read-Only Memory

FPGA Field Programmable Gate Array

GUI Graphical User Interface

IP Intellectual property

LED Light Emitting Diode

NTSC National Television System Committee

PWM Pulse Width Modulation

RGB Red, Green, Blue

SNR Signal to Noise Ratio

SPD Spectral Power Distribution

SPI Serial Peripheral Interface

UART Universal Asynchronous Receiver/Transmitter

W White

CHAPTER 1

Introduction

1.1 Motivation

In recent years, LED video screens achieved widespread usage and adoption in the consumer market. The growing demand of the LED video screens increased the number of suppliers and manufacturers in the market. Along with this rising demand comes an increasing need for higher quality products with competitive prices. This rapid growth created a lot of challenges and pressure on manufacturers to supply a cost-effective and high quality product.

Accordingly, the LED video screens industry is facing an ongoing problem with the non-uniformity of the color and luminance. This problem started to influence consumers' decision with the wide choices available in the market.

LED screen manufacturers are using two main techniques to handle non-uniformity issues. 1) Buying the LEDs from manufacturers in highly-binned lots, or 2) using a camera-based system that measures and calibrates the LED screen. Let's explore each of these methods in greater detail;

> **Binning**: This is the process of sorting the LEDs into bins according to luminance and color. The fact that LED manufacturers cannot control the manufacturing process to produce universally uniform LEDs, they can resort to the process of

binning. Binning is time-consuming and costly process and demands more time and higher cost for the best results. For example, Lumileds' Luxeon LEDs in a single bin nominally vary in light output by over a factor of two [18], and the peak wavelength spread of Nichia's LEDs is 10 nm for one bin [10].

Camera-based system: This system uses a highly sensitive camera connected to a computer with user software communicating with the screen. This solution is expensive, complicated, and sensitive to the environmental conditions of the system. These conditions include ambient temperature, ambient light intensity, as well as camera and screen position. Moreover, the periodical service and calibration of the camera has an effect on the results [11].

In this thesis, new correction and calibration techniques were proposed to deal with the non-uniformity problem in LED screens. Our proposed solution is cost-effective, simple and adaptive to environmental changes.

1.2 Uniformity Problems in LED video screens

The root cause of color and luminance uniformity problems in LED video screens is mainly due to dissimilarities in optical and physical characteristics of the LEDs themselves. Modern manufacturing processes for LEDs produce LEDs that vary greatly in both luminance and color. To further illustrate the problem, we can observe an example: when the same electrical current is applied to two blue LEDs produced as part of the same batch, the wavelength may vary by as much as 15-20 nanometers and the luminance may vary by as much as 50%. These differences are very noticeable to the naked eye and LEDs that vary by this much should not be used in the same video screen.

By contrast, Cathode Ray Tube (CRT) televisions rely on phosphors to produce luminance and color, where the phosphor in each pixel control is accomplished by electron beam, deflected by scanning system. Therefore pixels produce nearly the same luminance and color when hit with the same amount of energy from the cathode ray gun. The first line of pixels in Figure 1.1 below shows the Television Phosphors uniform color and luminance pixels.

LED screens, however, have two problems as mentioned above. First, the luminance of each LED varies widely even though they are driven by the same amount of current. The second line of pixels in Figure 1.1 below illustrates the LEDs first problem. Second problem, the colors of the LEDs are quite variable, as the third line of pixels in Figure 1.1 below illustrates this problem (non-uniform color pixels). When you add these two problems together, as shown in the forth line of pixels in Figure 1.1, you can see why achieving uniformity in an LED screen is so difficult.

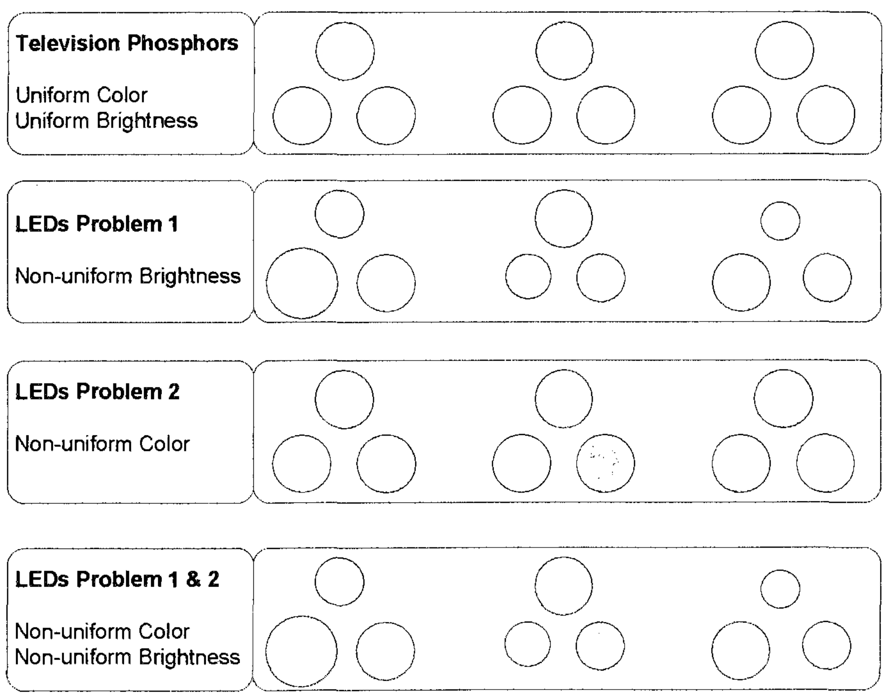


Figure 1.1: LED Pixels uniformity problem

Another cause of non-uniformity in LED screens is that the LEDs' characteristics get changed as they get slightly dimmer and slightly shifts the color because of the temperature and usage time. A study on thermal effects on RGB LED characteristics was reported in [1]. Figure 1.2 shows LED Luminance Decay with usage. The blue LEDs dim the most and the red LEDs dim the least, but the biggest problem is that individual LEDs dim differently over time [9]. So, even if an LED screen was perfectly uniform when it left the factory, it would lose its uniformity as the LEDs dim, and after approximately two to three years of usage it would begin to look quite non-uniform.

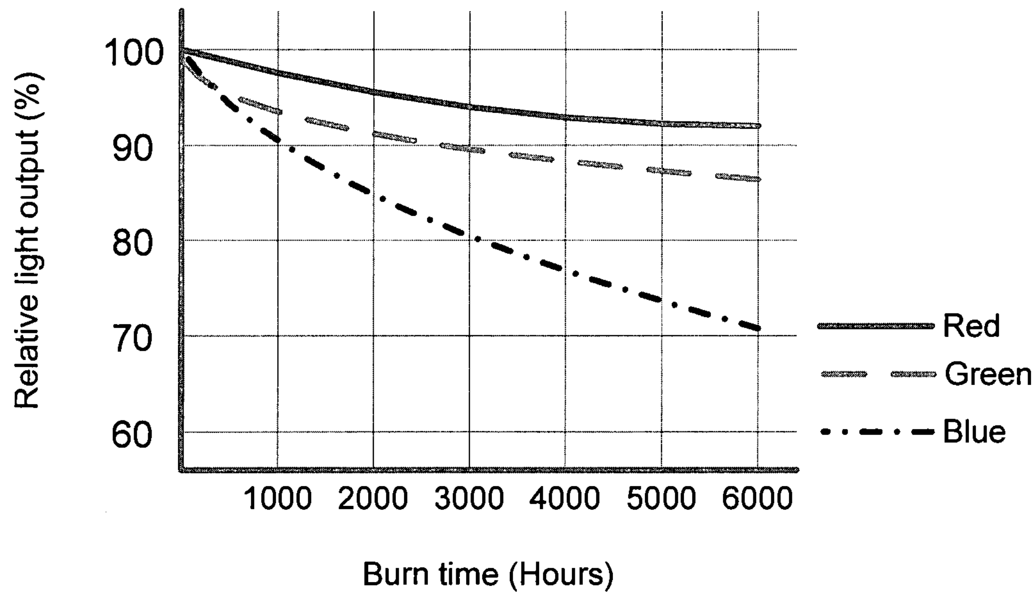


Figure 1.2: Red, Green and Blue LEDs luminance decay with usage

1.3 Proposed Solution

In this section a general description is provided for the color and luminance correction and calibration algorithm which is based on Dot Correction (Current Correction) and Pulse Width Modulation (PWM) correction methods.

1. Dot Correction (Current correction)

The luminance of LEDs is determined by the amount of DC current that flows through the P/N junction. More current produces a brighter LED. Unfortunately, however, adjusting the current will also change the color of the LEDs.

Although, this method will reduce the color difference and can be used to make sure that the modules all have the same luminance, but it cannot be used to correct the color differences. Furthermore, if two modules were the same color before adjusting the current, they would no longer be the same color after the adjustment.

2. Pulse Width Modulation (PWM) Correction

PWM is a widely used technique to control the luminance of LEDs [13]. It can be used to process the video signal and also to perform color uniformity correction. PWM is used instead of varying the current because changing the current of the LEDs would also change the colors as explained above, while PWM does not change the LED color when changing the brightness. PWM works by flashing the LEDs either fully on or fully off at a very high rate. The flashes are so fast that the human eye cannot notice them and the duration of the individual flashes (pulse width) determines the perceived luminance.

Video signal in a non-corrected system is turned into pulse widths by LED drivers to flash the LEDs. In a corrected system, the pulse widths are multiplied by correction coefficients before being sent to the LED drivers. Unfortunately, however, adjusting the PWM will cut a lot of the LED output video resolution.

Our proposed solution is to use both methods in conjunction to achieve uniformed color and Luminance LED screen with a high image resolution. In order to implement these methods, a Robotic Spectrometer system was used to measure and adjust the luminance and color of each displayed pixel.

The proposed methodology and algorithm were implemented and tested with successful results.

1.4 Related Work

In this section the related work is presented in the area of color and luminance calibration and correction systems for RGB LED pixels using various techniques and methodologies. Also, different theoretical algorithms will be shown for color mixture and rendering.

Since LED video screens and LED lighting systems became more and more popular, there is a need for an efficient and cost-effective design to fix the non-uniformity problem in the color and luminance of the LED screens and modules as it is now competitive requirement for LED screen manufacturers and owners who seek to deliver high image quality and resolution. For instance, the offered solution in [11] proposes a color and luminance correction and calibration using camera-based system. The camera uses several optics and filters for measuring each color. The solution measures the LEDs' colors and luminance data, then it analyses them using Windows based software. The software calculates the correction coefficients and sends them back to the display to perform the correction. The correction algorithm based on setting the current of the Red, Green and Blue LEDs at certain values, and then it uses the PWM method to calibrate and correct the LEDs colors and luminance. The correction algorithm is not published as this is a commercial solution. As it was discussed before, this kind of solution is sensitive to ambient temperature, light intensity, expensive and difficult to setup. The camera needs a periodic calibration to be done by the manufacturer as it has different optics and filters which are very hard to calibrate. Our proposed system uses an off-the-shelf spectrometer and diffuser which can be calibrated by the user directly. In addition it is easy to setup and run.

Another work has been presented in [28] for a robotic spectrometer system for LED display measurements. It is a developed technique for measuring the luminosity and operating characteristics of each LED in every pixel and stores them in a lookup table. The aim of this technique is to allow the system to adjust the output luminance of each LED based on the results of the lookup table. The provided technique is to be incorporated as part of each display and to be hidden at the back of the display when not in use, to facilitate periodic measurements in the field. This solution is not implemented and it will increase the cost of each LED screen as it adds an extra complication to the product. The proposed design in this thesis is to be implemented at the manufacturer place and it calibrates both luminance and color non-uniformity in the LED pixels.

In [1] [2], the authors provide an overview of the white color accuracy required, made of the red, green, and blue LEDs, in the general illumination market and the challenges to achieve the required achromatic point (white light). It also shows how the variation in lumen output and wavelength for nominally identical LEDs and the change in these parameters with temperature and time result in an unacceptably high variability in the color point of white light from RGB-LEDs. The work shows how they overcome these problems using a feedback control schemes which can be implemented in a practical LED lamp (or pixel). As for the work in [29], the authors provide color control implementation using a laboratory setup based on a rapid color control prototyping system which uses commercially available software and digital hardware amended by custom in-house developed hardware. Both works base their color control on PWM methodology. Our proposed technique bases its color and luminance control on both PWM and Current amplitudes methodologies, which gives more resolution on the gray level.

Several additive color mixing algorithms were introduced using the CIE color system. In [27] the author shows a linear color mixing procedure which depends on the brightness of the primary colors. It explains how adding two colors of light can be worked out as a weighted average of the CIE chromaticity coordinates for the two colors. The weighting factors involve the brightness parameters Y. This linear procedure is valid only if the colors are relatively close to each other in value. In [31] the author shows color mixtures procedures in CIE RGB and XYZ color spaces, in CIE xy Chromaticity Space, and in CIE u'v' Chromaticity Space. The procedures depend on the primary colors weighting factors. The weighting factors involve the brightness parameters. The procedures apply the center of gravity law. Our proposed algorithm is a new linear color mixing algorithm which depends only on calculating the weighting factors while the weighting factors are independent of the primary colors' brightnesses. The algorithm is based on Grassmann's laws of additive color mixture and it applies the center of gravity law.

1.5 Thesis Contribution

The contribution of this thesis is as follows:

- New correction and calibration algorithm and technique were developed to fit LED video screens and LED lighting products and applications.

- Cost-effective, efficient, and simple solution was provided to solve the non-uniformity of the color and luminance problem in LED screens.
- The resolution of the output video and the picture quality were improved for the calibrated LED screens.

1.6 Thesis Outline

This thesis is made up of 6 chapters. Chapter 2 provides an overview of the light definition and standards, where we introduce the CIE color spaces and definitions. In addition, it provides an overview of the LED screen technology and architecture. In Chapter 3, the color and luminance correction algorithm along with the developed methodologies are presented. Chapter 4 presents the color and luminance correction and calibration developed system and tools to implement the developed methodologies. In Chapter 5, experimental results are presented. Conclusions and future work are presented in chapter 6.

CHAPTER 2

Preliminaries

2.1 LED video screens

Nowadays, LED video screens represent the most competitive large-scale display technology. LED screen is like a giant television, but with one fundamental difference; instead of the picture being beamed from a cathode ray tube, each pixel is made up of a cluster of tiny LEDs. Each cluster has a red, green and blue LED, which light up accordingly to create the correct color. Figure 2.1 shows a picture of a LED screen.

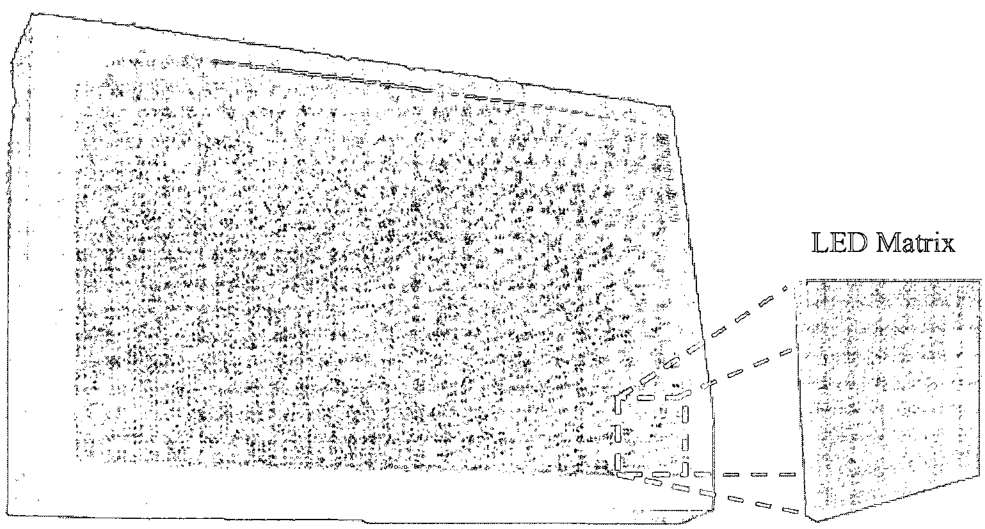


Figure 2.1: LED Video Screen and LED Matrix

Due to the large size of LED screens, a modular construction is used. This allows for flexibility of formats, shapes and transportability. Usually LED screens are composed by

LED matrices (See Figure 2.1) controlled by LED Drivers, Matrix controller (FPGAs, ASICs, CPLDs, ...) and CPUs (which are used for communication and configuration purposes). Figure 2.2 shows LED Matrix structure.

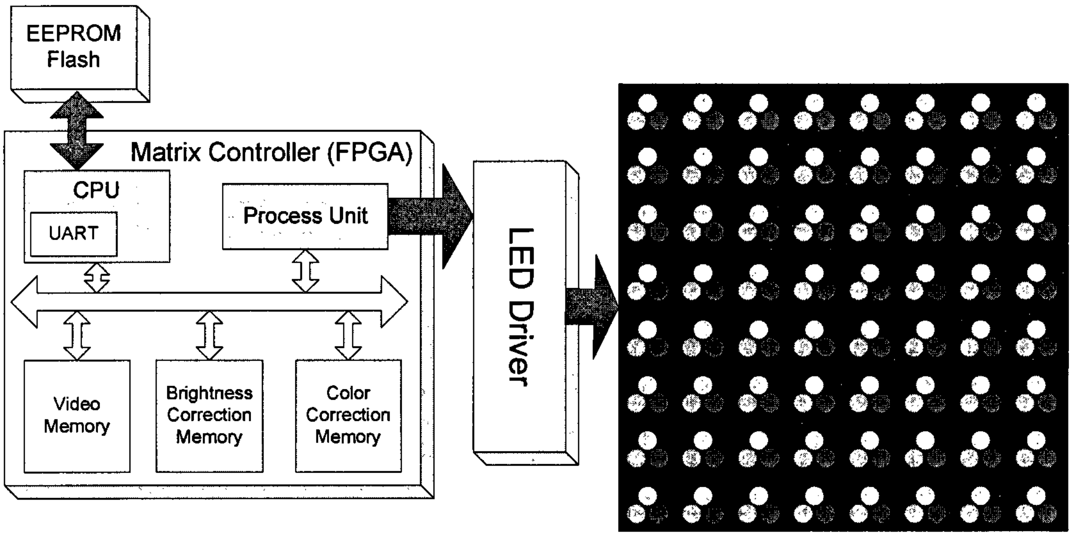


Figure 2.2: LED Matrix Structure

LED Matrices incorporate a set of LED pixels mounted on single board. They are available in different sizes and pitch resolutions. Size wise, typically LED Matrix is (16 x 16), (8 x 16) or (4 x 16) pixels. Pitch resolution varies between 3 to 30 mm.

2.1.1 LED Pixel

LED Pixels are composed of three primary colored LEDs: Red, Green, and Blue (RGB). Using the primary colors provide the ability to generate variety of color hues, saturations and values (Brightness). Figure 2.3 shows LED Matrix Pixels.

LED light is produced by the phenomenon of the electroluminescence. Optical quantities such as luminous intensity, peak and dominant wavelength or chromaticity coordinates, spectral width, deterioration factor or expected lifetime are used to assess the LED [17].

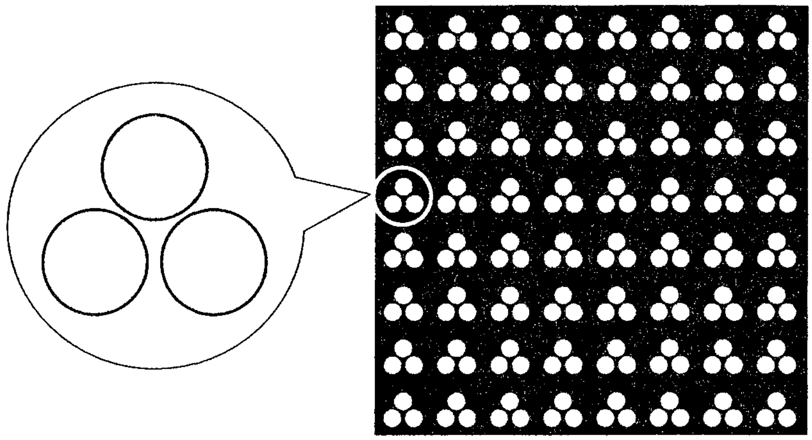


Figure 2.3: LED Matrix Pixel

2.1.2 Properties of LEDs

Optical prosperities of LEDs:

The radiation of a LED can be characterized by radiometric and spectroradiometric quantities. Visible light LED also requires photometric and colorimetric quantities to quantify its effect on the human eye. Consequently, radiometric, spectroradiometric, photometric and colorimetric quantities with their related units may all have to be used to characterize the optical radiation emitted by LED [15]. For the proposed algorithm in this thesis, Colorimetric quantities such as; luminosity (which represents the LED brightness) and chromaticity coordinates (which represents the LED color), were the only needed quantities to measure and calibrate the non-uniformity problems in the LEDs. Colorimetric quantities are determined from the LED spectral power distribution (SPD).

Typical single-color LEDs have quasi-monochromatic spectral distribution, with spectral bandwidth that are typically a few 10 nanometers wide, which is something between monochromatic spectral distribution (as emitted by laser) and broad-band spectral distribution (as found with white LED) [15]. Figure 2.4 shows the three different spectral distribution types.

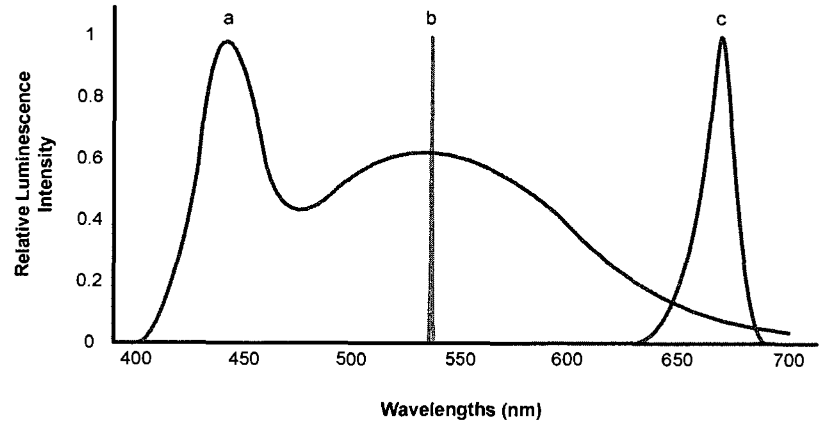


Figure 2.4: (a) Broad-band spectral, (b) monochromatic, (c) quasi-monochromatic.

The proposed technique in this thesis uses CCD-based Spectrometer to measure the LEDs spectral power distribution. As reported in [15], the spectral distribution can be measured with a spectrometer in four different methods: 1) irradiance mode, 2) total flux mode, 3) partial flux mode and 4) radiance mode. In irradiance mode, the spectral distribution of a LED is measured in one direction, whereas, in total flux mode, they are measured as an average of all directions. The partial flux mode is in between. The radiance mode measures the spectral radiance of the LED surface, using an imaging optic with the photometer.

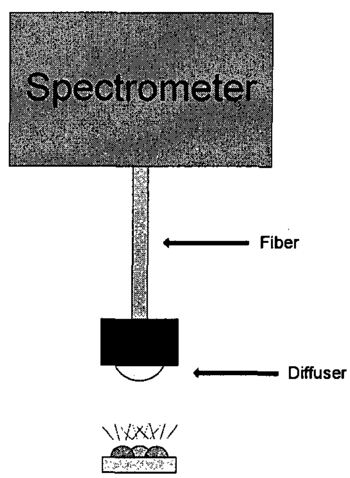


Figure 2.5: Irradiance Mode

The proposed technique in this thesis uses the irradiance mode since all LEDs are placed and soldered to the LED matrix board. Figure 2.5 shows the irradiance mode method.

Electrical characteristics of LEDs:

LEDs normally need a DC current source applied in a forward bias direction in order to operate and generate the illumination. Changing the amount of the current applied through the LED P/N junction results in; 1) variation of the luminous intensity (Brightness), as shown in figure 2.6, and 2) Shift of the chromaticity coordinated (Color), as shown in figure 2.7.

The relation between the LED *forward current* and *relative luminosity* is not linear as it is shown in figure 2.6. This nonlinear relation usually varies from one LED to other, even if they have the same color and from the same batch. In another word, there is no unique mathematical formula that can represent the nonlinear relation between the LEDs' current and luminosity. To overcome this problem, a new calibration model was proposed in this thesis, based on the linear iteration technique.

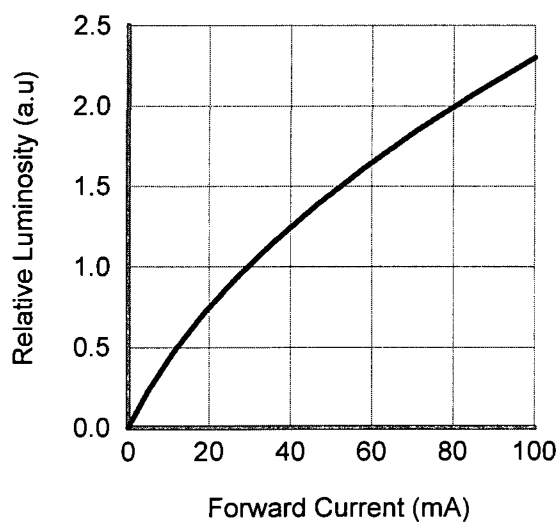


Figure 2.6: Forward current vs. Relative Luminosity graph for Blue LED

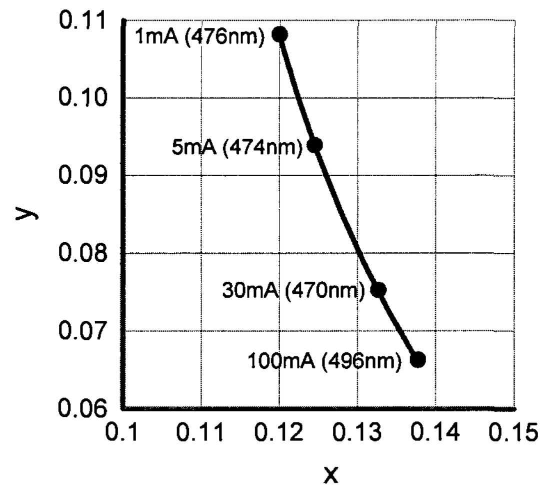


Figure 2.7: Forward current vs. Chromaticity Coordinates graph for Blue LED.

2.1.3 LED Driver

LED Driver is a self-contained power supply that has digitally controlled outputs, which provide regulated current sources that match the electrical characteristics of the LEDs. Figure 2.8 shows an illustrative 3-channel LED Driver Block Diagram. For more detailed information about LED drivers check the data sheets in [19, 20].

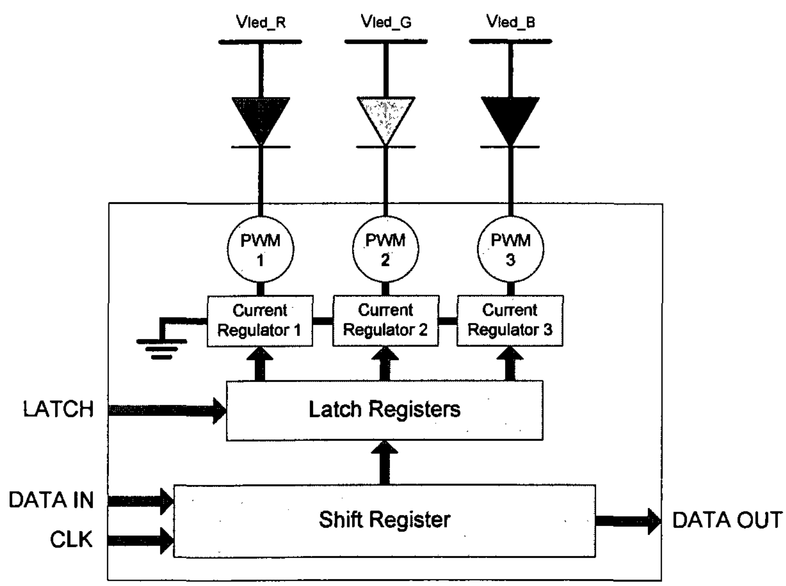


Figure 2.8: Illustrative 3-channel LED Driver Block Diagram

As illustrated in figure 2.8, usually LED Driver control the LED brightness through two stages; 1) Analog control (current regulator), and 2) Pulse Width Modulation (PWM). In analog control stage, LED Driver sets the maximum DC current that can pass through the LED, Whereas, PWM is used for dimming the brightness of LED, where the brightness of LED is in proportion to the PWM driving duty ratio.

In LED displays, PWM driving is able to incorporate the grayscale characteristics with high precision and display images with high resolution. Analog control was more explained in section 2.1.2, while PWM will be more illustrated in the following section. Figure 2.9 shows an illustrative diagram for LED brightness control stages.

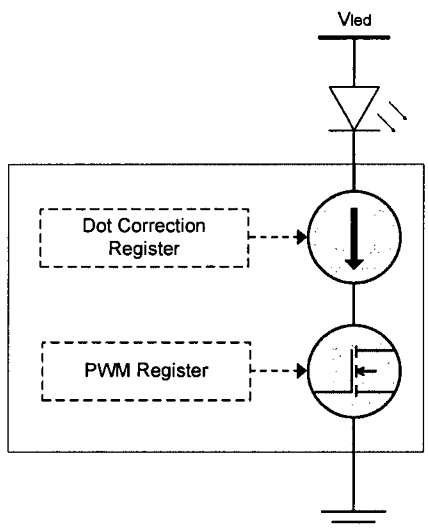


Figure 2.9: Illustrative diagram for LED brightness control stages

2.1.4 PWM Dimming

PWM is the most common way for LED dimming [13]. PWM dimming is achieved by applying full current to the LED at a reduced cycle. Accordingly, for 20% brightness, full current is applied at 20% duty cycle; and for 80% brightness, full current is applied at 80% duty cycle. Therefore, the brightness of LED is controlled only by how long the

LED is turned which does not affect the light color. PWM is illustrated in figure 2.10.

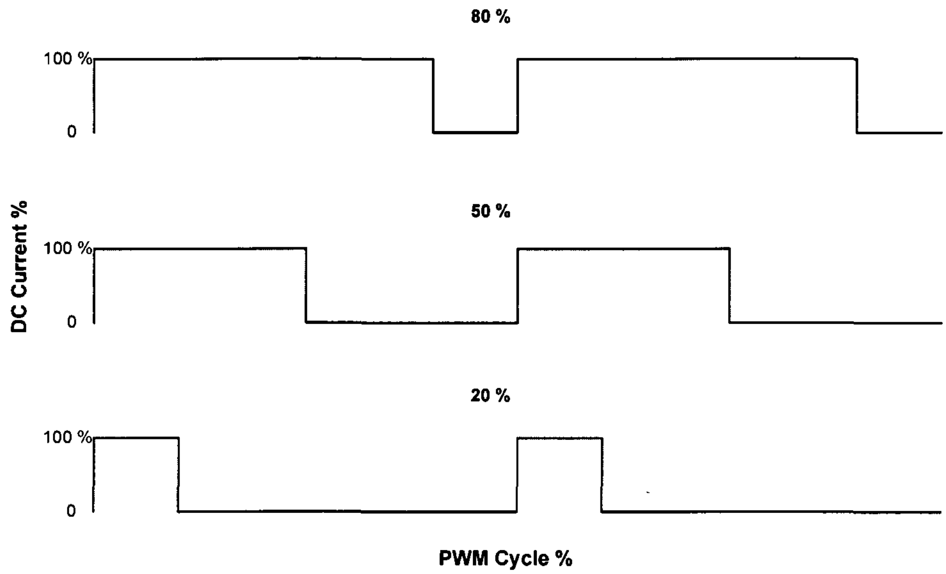


Figure 2.10: Pulse Width Modulation

2.1.5 Matrix Controller

The LED Matrix controller is the main component of the video signal processing, mapping, and outputting. Usually matrix controllers are designed and synthesized using a field programmable gate array (FPGA), complex programmable logic device (CPLD), or application-specific integrated circuit (ASIC). LSI SACO Technologies uses FPGAs for designing LED matrix controllers. Current FPGAs have large variety of high performance IP cores (processors, intellectual functional logics and etc...) as well as high speed memories and much more. These features facilitate the implementation of LED Matrix controller in FPGAs. Figure 2.11 shows an illustrative block diagram of LED Matrix Controller.

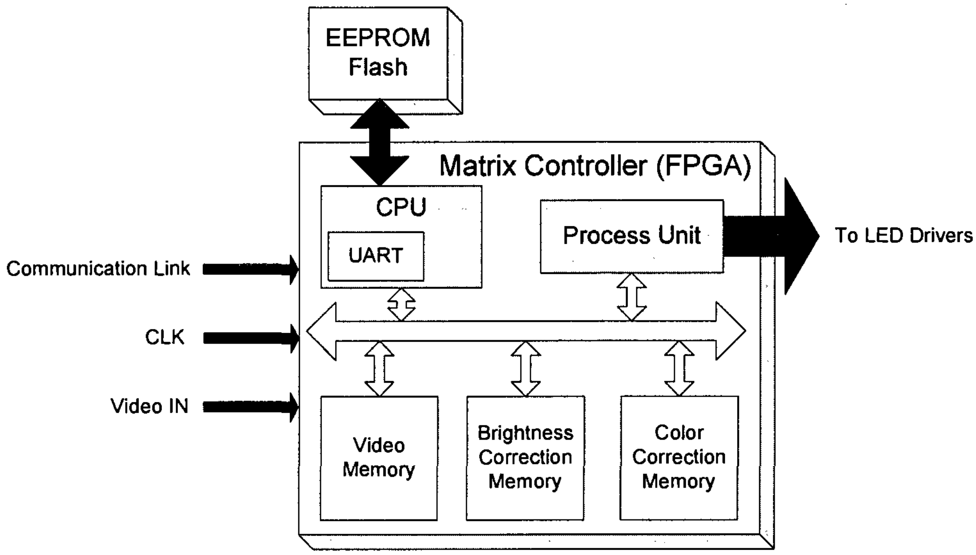


Figure 2.11: Illustrative block diagram of LED matrix controller

EEPROM Flash: is used to store the FPGA binary file, the matrix configuration data, and the correction coefficients data. The FPGA binary file is an encoded data file which contains the raw bits that need to be stored inside the FPGA to program the chip. The Matrix configuration data contain information about the size of the matrix, the video memory mapping, and other more matrix details. The correction coefficients data are used to correct the LED pixels brightness and color data (Usually. They are set to default values when the LED matrix is not calibrated). In the next chapter, the matrix calibration process will be explained more in details along with how to assign the coefficients values.

CPU: is the main microcontroller unit that controls all the communication links between the FPGA, EEPROM Flash, and the external systems to the LED Matrix. The CPU loads, from the EEPROM, the stored matrix configuration data to the FPGA, and it loads the correction coefficients and values to the brightness correction memory and the color correction memory. CPU uses Universal Asynchronous Receiver/Transmitter (UART) interface to communicate with the external systems, and Serial Peripheral

Interface (SPI) bus to communicate with the EEPROM flash.

Process Unit: is the main component inside the matrix controller where all the data calculations are performed. It grabs all the pixels data from the memories, processes them, calculates the brightness and color of each LED, builds the data string, and then sends them to the LED Driver. In the next chapter, the calculation process of the LED color and brightness data will be explained more in details.

2.2 Light and Color

Light is electromagnetic radiant energy. The region of the electromagnetic spectrum that can be perceived by human vision is called visible light. Visible light, as well as other types of electromagnetic energy, is measured and described by its wavelengths in nanometer (nm) which approximately ranges from 380 nm to 780 nm. Figure 2.12 shows the visible part of the spectrum.

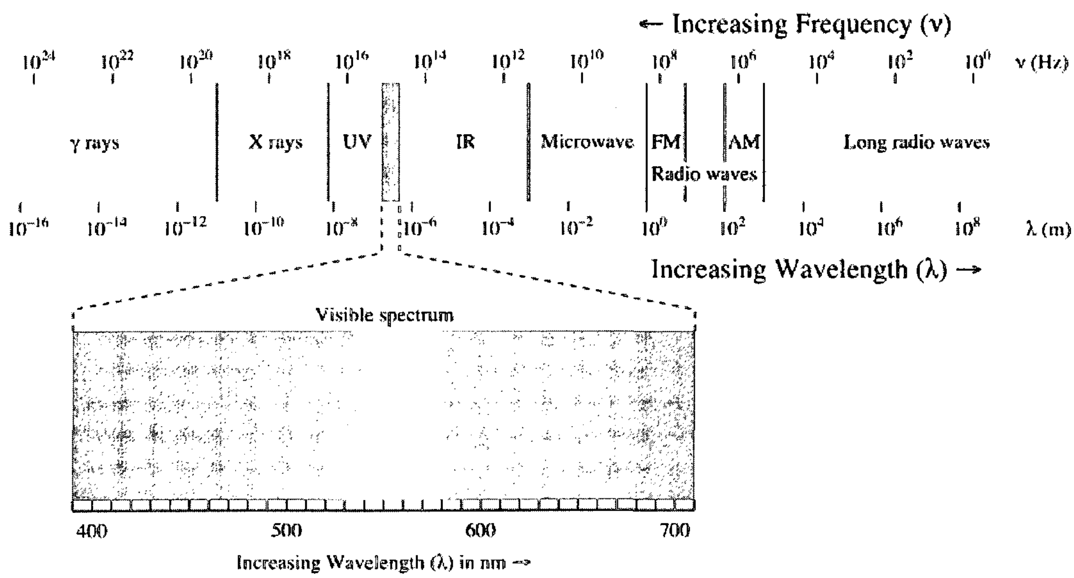


Figure 2.12: Visible spectrums. (Figure from http://www.wikimedia.org)

Color is the visual sensation (or the perceptual result) of incident visible light upon the human's eye retina. The visible light radiance (or physical power) is expressed in a *spectral power distribution* (SPD).

A SPD describes the power of the light at each wavelength in the visible spectrum. The SPD contains all the basic physical data about the light and serves as the starting point for quantitative analyses of color. Both the luminance and the chromaticity of a color may be derived from the SPD to precisely describe the color in the CIE color system. Usually a SPD can be obtained and determined by using spectrometer. In this thesis, SPD is defined as a function P(λ). Figure 2.13 shows the SPD for a white LED.

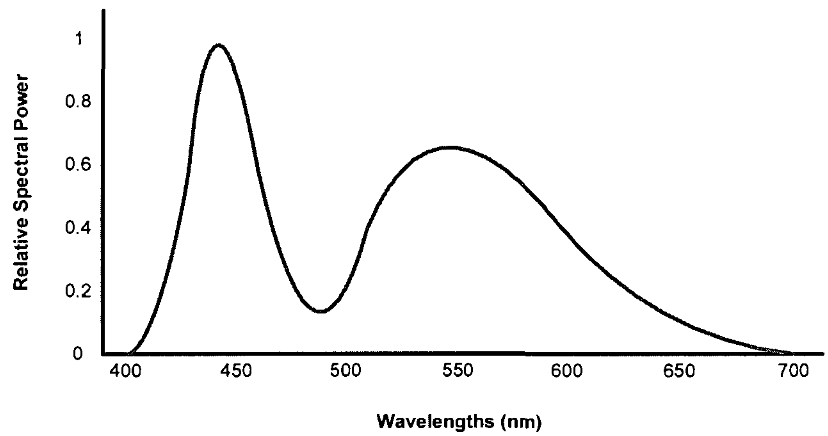


Figure 2.13: Spectral Power Distribution (SPD) for white LED

Isaac Newton said, "Indeed rays, properly expressed, are not colored." Spectral power distributions (SPDs) exist in the physical world, but color exists only in the eye and the brain.

2.2.1 Color Perception and Color Space

The human retina contains two groups of sensors, the rods and the cones. As for the cones, it has three types of color photoreceptor cone cells, which respond to incident radiation with different spectral response curves. On the other hand, rods are effective only at extremely low light intensities. The signals from these color sensitive cells (cones), together with those from the rods, are combined in the brain to give several different "sensations" of the color.

As humans, we may define these sensations in term of its attributes of brightness, Hue, colorfulness, lightness, chroma, and saturation which have been defined by the Commission Internationale de L'Éclairage (CIE) [22] and Hunt's book "Measuring Colour" [21] as follows:

- *Brightness*: "the attribute of a visual sensation according to which an area appears to emit more or less light" [22].
- *Hue*: "the attribute of a visual sensation according to which an area appears to be similar to one of the perceived colors, red, yellow, green and blue, or a combination of two of them" [22].
- *Colorfulness*: "the human sensation according to which an area appears to exhibit more or less of its hue" [21].
- *Lightness*: "the sensation of an area's brightness relative to a reference white in the scene" [21].
- *Chroma*: "the colorfulness of an area relative to the brightness of a reference white" [21].
- *Saturation*: "the colorfulness of an area judged in proportion to its brightness" [22].

On the other hand, color systems (or models) interpret these sensations using color space which is a method by which they can specify, create and visualize color. The CIE has defined a color system that classifies any colored light in the visible spectrum according to the visual sensations mentioned above. A color is thus usually specified using three co-ordinates, or parameters. These parameters describe the position of the color within the color space being used. They do not tell us what the color is, that depends on what color space is being used.

2.3 CIE Color system

The International Commission on Illumination - also known as the CIE from its French title, the Commission Internationale de l'Eclairage - is an international organization, located in Vienna, which worked in the first half of the 20th century developing a method for systematically measuring color in relation to the wavelengths they contain. This system became known as the CIE color system (or model). The model was originally developed based on the trichromatic theory of color perception. The theory describes the way three separate lights, red, green and blue, can match any visible color – based on the fact of the eye's use of three different types of color sensitive photoreceptors cells (cones) as was explained in section 2.2. These three photoreceptors respond differently to different wavelengths of visible light.

The CIE had measured this differential response of the three cones in the eye, by matching spectral colors to specific mixtures of the three colored lights, to define the CIE color matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$.

The SPD of a color is cascaded with these matching functions, over the visual range from 380 to 780 nm, to produce three CIE tri-stimulus values X, Y, and Z, which are the building blocks from which many color specifications are made. These tri-stimulus values are used to get the color CIE chromaticity coordinates (x, y), and the luminous which is represented by the CIE Y parameter.

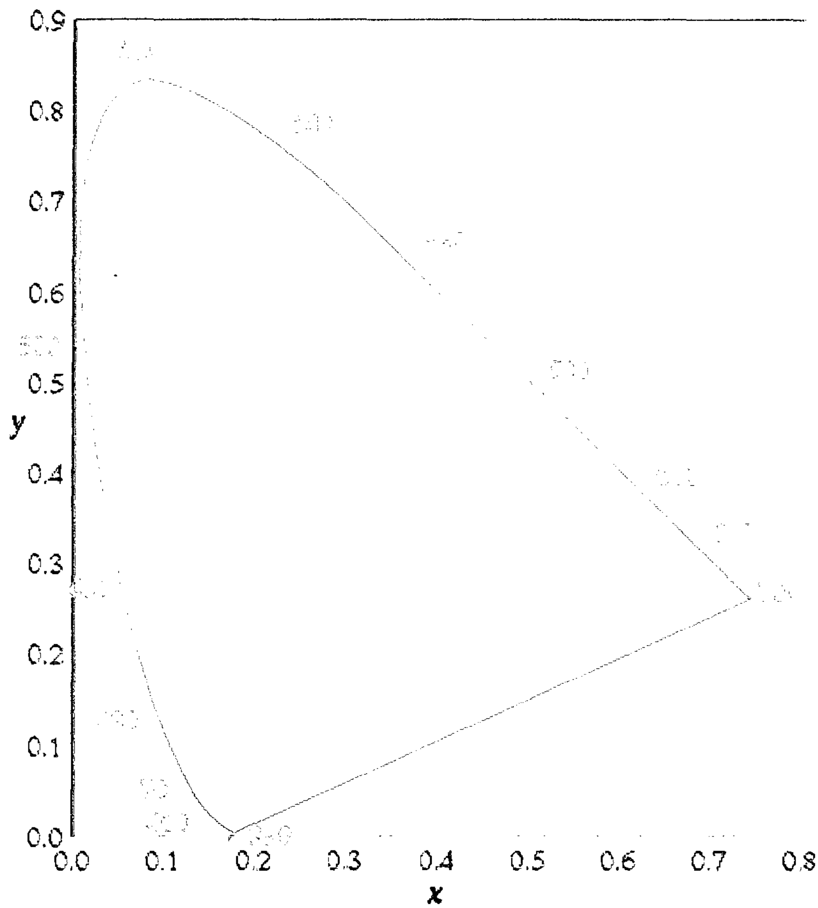


Figure 2.14: CIE 1931 Chromaticity Diagram.
(Figure from http://www.wikimedia.org)

Accordingly, the CIE defined the three-dimensional color space CIE XYZ which is the basis for all CIE color management systems. This color space contains all perceivable colors which many of them cannot be shown on monitors or printed. In 1931, the CIE introduced the CIE 1931 *xy* chromaticity diagram (figure 2.14) which shows a special projection of the CIE XYZ color space.

2.3.1 CIE color matching functions

The CIE color matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ (Figure 2.15) characterize the relationship between SPD and color. They can be understood as weight factors. In 1931, the CIE standardized these functions and specified them as table of measurements at wavelength intervals, frequently 1 nm or 5 nm, through the visual range. Appendix A lists the CIE 1931 color matching functions' measurements at 5 nm interval.

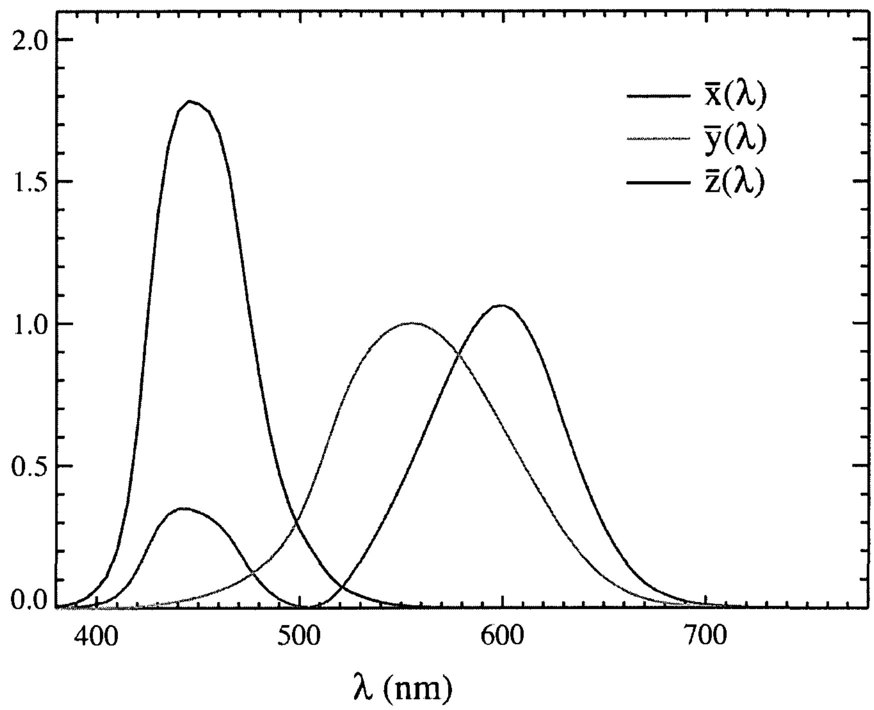


Figure 2.15: CIE color matching functions.
(Figure from http://www.wikimedia.org)

2.3.2 CIE XYZ tristimulus

The CIE XYZ tristimulus values for light are obtained by multiplying at each wavelength the light SPD (P(λ)) by that of each of the CIE color matching functions ($\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$) and integrating each set of products over the wavelength range corresponding to the entire visible spectrum 380 nm to 780 nm.

$$X = \int_{380}^{780} \bar{x}(\lambda)P(\lambda)d\lambda \quad \text{2.1 (a)}$$

$$Y = \int_{380}^{780} \bar{y}(\lambda)P(\lambda)d\lambda \quad \text{2.1 (b)}$$

$$Z = \int_{380}^{780} \bar{z}(\lambda)P(\lambda)d\lambda \quad \text{2.1 (c)}$$

The integration may be carried out by numerical summation at wavelength intervals, $\Delta\lambda$, equal to 1 nm, 5 nm, or 10 nm.

$$X = \Delta\lambda \sum_{\lambda=380}^{780} \bar{x}(\lambda)P(\lambda) \quad \text{2.2 (a)}$$

$$Y = \Delta\lambda \sum_{\lambda=380}^{780} \bar{y}(\lambda)P(\lambda) \quad \text{2.2 (b)}$$

$$Z = \Delta\lambda \sum_{\lambda=380}^{780} \bar{z}(\lambda)P(\lambda) \quad \text{2.2 (c)}$$

The CIE Y value represents the luminance of the measured light source. Due to the nonlinearities in the human visual system, this measurement is roughly correlated, with but not equal to, the perceived brightness of the light source. In color and brightness correction, we are usually interested only in relative luminosities so we can ignore absolute values of Y and simply scale luminosities between user-defined minimum and maximum brightnesses.

2.3.3 CIE 1931 chromaticity coordinates

The CIE 1931 chromaticity coordinates (x, y, z) are calculated from the tristimulus values X, Y and Z as follows:

$$x = \frac{X}{X+Y+Z} \qquad \text{2.3 (a)}$$

$$y = \frac{Y}{X+Y+Z} \qquad \text{2.3 (b)}$$

$$z = \frac{Z}{X+Y+Z} \qquad \text{2.3 (c)}$$

The third coordinate, is redundant since,

$$x + y + z = 1 \Rightarrow z = 1 - x - y \qquad \text{2.4}$$

Therefore, it is sufficient to quote (x, y) only.

2.3.4 CIE 1976 *u'v'*

Although CIE 1931 *xy* chromaticity diagram has been widely used, it suffers from a serious disadvantage: the distribution of the color on it is very non-uniform. Beginning in the 1940s, MacAdam and his co-workers derived a body of date on the uncertainty with which a match of colored lights could be made using a visual colorimeter [32, 33]. MacAdam's experiment measured standard deviations about 25 chromaticities for a single observer [32]. The resulting ellipses, shown on Figure 2.16, are known as MacAdam ellipses and are still used in evaluating models of color discrimination. Each of MacAdam ellipses was based on a serious of matches constrained in define directions about a color center. Each circle represents the standard observer deviation of a match from the center of the ellipses.

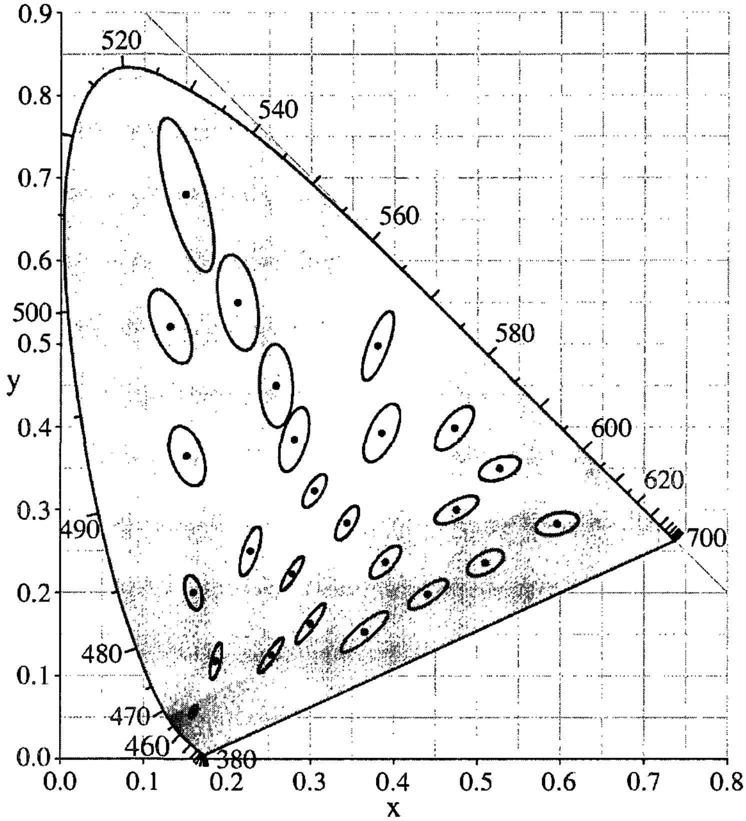


Figure 2.16: MacAdam ellipses. The axes of plotted ellipses are 10 times their actual lengths. (Figure from http://www.wikimedia.org)

CIE 1976 Y$u'v'$ is a linear transformation of the CIE XYZ (or CIE 1931 Yxy), in an attempt to produce a chromaticity diagrams in which a vector of unit magnitude (difference between two points representing two colors) is equally visible at all colors. The parameter Y is unchanged from XYZ (or Yxy). The distribution of the color difference non-uniformity is reduced considerably.

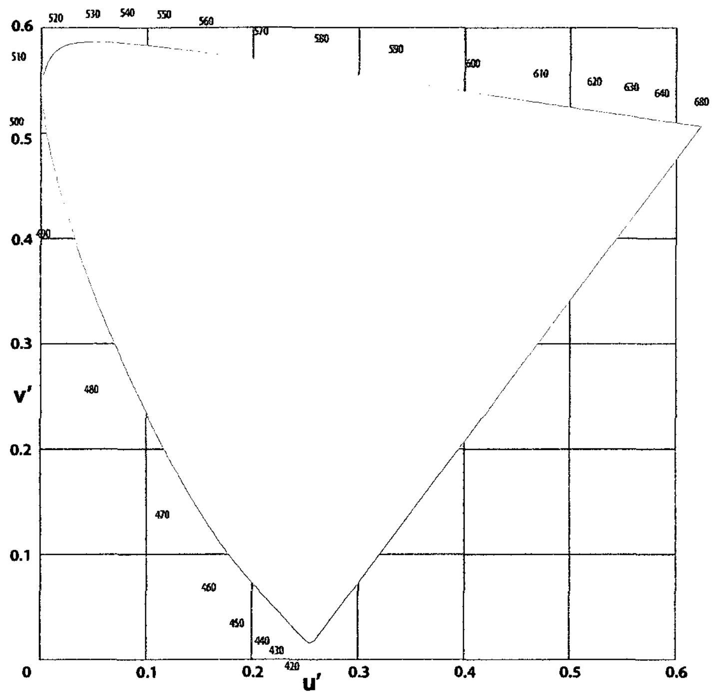


Figure 2.17: 1976 CIE *u'v'* chromaticity diagram.

(Figure from http://www.wikimedia.org)

The chromaticity diagram shown in Figure 2.17 is known as CIE 1976 uniform chromaticity diagram or CIE 1976 UCS diagram, commonly referred to as CIE $u'v'$ chromaticity diagram. It is obtained as:

$$u' = \frac{4x}{-2x+12y+3} \quad \text{2.5(a)}$$

$$v' = \frac{9y}{-2x+12y+3} \quad \text{2.5(b)}$$

The CIE $u'v'$ diagram is useful for showing the relationships between colors whenever the interest lays in their discriminability. Both chromaticity diagrams, CIE xy and CIE $u'v'$, have the property that additive mixture of colors are represented by points lying on the straight line joining the points representing the constituent colors.

2.4 Color Gamut

A color gamut is the set of possible colors a device can reproduce within a color space. The color chromaticity and the brightness of the primary colors (the red, the green and the blue) determine the color gamut of the device.

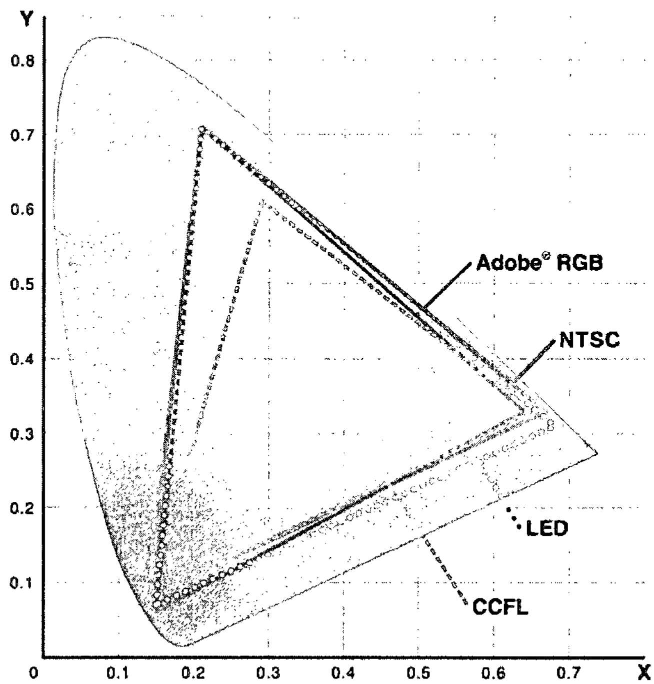


Figure 2.18: Color Gamuts. It shows the color gamut for: Adobe RGB, NTSC (National Television System Committee), CCFL (Cold cathode fluorescent lamps), and LEDs in general. (Picture from http://www.nec-lcd.com)

Often the gamut will be represented in only two dimensions, for example on a CIE *xy* chromaticity diagram. Figure 2.18 shows an example of the color gamut for different systems.

2.5 Additive Color Mixture

2.5.1 Grassmann's Laws of additive color mixture

In 1953 the German mathematician Hermann Günther Grassmann discovered and introduced laws concerned with the results of mixing colored lights. Simple explanation for the laws was illustrated in [26], "Any color (source C) can be matched by a linear combination of three other colors (primaries e.g. RGB), provided that none of those three can be matched by a combination of the other two. This is fundamental to colorimetry and Grassman's first law of color mixture. So a color C can be matched by Rc units of red, Gc units of green and Bc units of blue. The units can be measured in any form that quantifies light power.

$$C = Rc\,(R) + Gc\,(G) + Bc\,(B) \quad \ldots\ldots\ldots\ldots\ldots \quad 2.6$$

A mixture of any two colors (sources C1 and C2) can be matched by linearly adding together the mixtures of any three other colors that individually match the two source colors. This is Grassman's second law of color mixture. It can be extended to any number of source colors.

$$C3(C3) = C1(C1) + C2(C2) = [R1 + R2](R) + [G1 + G2](G) + [B1 + B2](B) \ldots. 2.7$$

Color matching persists at all luminances. This is Grassman's third law. It fails at very low light levels where rod cell vision (scoptopic) takes over from cone cell vision (photopic).

$$kC3[C3] = kC1[C1] + kC2[C2] \quad \ldots\ldots\ldots\ldots\ldots \quad 2.8$$

The symbols in square brackets are the names of the colors, and not numerical values. The equality sign should not be used to signify an identity; in colorimetry it means a color matching, the color on one side of the equality looks the same as the color on the other side.

These laws govern all aspects of additive color work, but they apply only signals in the "linear-light" domain. They can be extended into subtractive color work."

2.5.2 Newton's 'Centre of Gravity' Law of additive color mixing

As quoted from Byrne and Hilbert book "Reading on Color: The philosophy of color" [36], "Newton claims that if the colors of the spectrum are arranged in a circle, with white in the centre, then if you know the colors of the component spectral lights out of which a compound light is composed, then you can predict the color of the mixture. If you consider the points on the color circle representing the spectral lights in the mixture, and assign to each of them a weight proportional to the intensity of light of that kind, then the centre of gravity of the resultant figure will represent the color of the mixture of lights, as illustrated in figure 2.19"

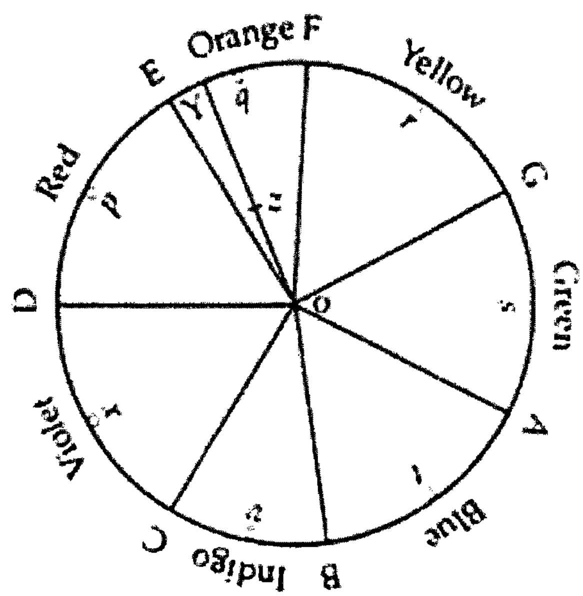


Figure 2.19: Newton's color wheel

"Newton's color wheel (Figure 2.19): to predict the color of mixtures of light. The circumference *DEFGABCD* represents "the whole Series of Colors from one end of the Sun's colored Image to the other." Let *p, q, r, s, t, v, x* be the "Centers of Gravity of the Arches" *DE, EF, FG, GA, AB, BC* and *CD*, respectively; "and about those Centers of Gravity let Circles proportional to the Number of Rays of each Color in the given Mixture be described." "Find the common Center of Gravity of all those Circles, *p, q, r, s, t, v, x*. Let that Center be *Z*; and from the Center of the Circle *ADF*, through *Z* to the Circumference, drawing the Right Line *OY*, the place of the Point *Y* in the Circumference shall show the Color arising from the Composition of all the Colors in the given Mixture." The ratio of *OZ* to the radius of the circle gives the relative saturation of the color. (From Newton, Opticks, 154-5.)".

2.5.3 Additive Color Mixing with CIE

The result of adding two colors of light can be worked out as a weighted average of the CIE chromaticity coordinates for two colors [27]. The weighting factors involve the brightness parameters Y. If the coordinates of the two colors are;

x_1, y_1 with brightness Y_1 x_2, y_2 with brightness Y_2

then the additive mixture color coordinates are;

$$x_3 = \frac{Y_1}{Y_1 + Y_2} x_1 + \frac{Y_2}{Y_1 + Y_2} x_2 \,, \quad y_3 = \frac{Y_1}{Y_1 + Y_2} y_1 + \frac{Y_2}{Y_1 + Y_2} y_2 \quad \text{.......} \; 2.9$$

"This linear procedure is valid only if Y1 and Y2 are reasonably close to each other in value". "They say that each of the resulting chromaticity coordinates (say, x3) is the average of the respective coordinates of the components (x1 and x2) weighted according to their relative contributions to the total luminance. This is sometimes called the "Center of Gravity"" Quoted from [27].

2.6 PWM Correction Methodology

Pulse Width Modulation (PWM) is mainly used for light dimming as was explained in section 2.1.4. In this section, another use for the PWM will be explained as a correction methodology for LED lighting products.

PWM correction has proven to be the best method for correcting uniformity problems in LED screens and LED lighting systems. The methodology works by modifying the pulse widths for each pixel to compensate for the brightness variations of LEDs. By adjusting the brightness of the individual LEDs in an LED screen pixel, the color of the LED pixel can be selectively adjusted to a target color. In an uncorrected LED screen, the video signal is turned directly into pulse widths by the LED drivers to flash the LEDs. In a corrected system, the video signal is multiplied by correction coefficients by the LED matrix controller before it is sent to the LED drivers. The correction coefficients are computed for every color in the LED pixel in such a way as to correct the luminance and the color coordinates. The computation process will be explained in chapter 3.

The PWM correction methodology is applied to each color LED in each pixel in the LED screen. The concept behind the correction methodology is to light up the three tristimulus colors (RGB) with a certain amounts to create the target color. To illustrate the methodology further more, the following example is given;

Example 2.1:

Assume that we have LED pixel with the following RGB color and luminance;

Y_r = 110 nits, u'_r = 0.52, v'_r = 0.54

Y_g = 200 nits, u'_g = 0.09, v'_g = 0.58

Y_b = 60 nits, u'_b = 0.15, v'_b = 0.21

And we wish to correct the red color to the following target color and luminance;

Target luminance: 105 nits

Target color coordinates: u'_{r_t} = 0.49, v'_{r_t} = 0.51

The system will compute the red, green and blue coefficients which needed to correct the red according to the target color and luminance;

Let's assume for R = 90% the G = 1.5%, and the B = 5%

Total Brightness = (0.9 x 110) + (0.015 x 200) + (0.05 x 60) = 105 nits

Accordingly, the red signal was reduced by a factor of 0.9 and some green and blue was added to achieve the desired targets. Figure 2.20 shows the red coefficients before and after the correction.

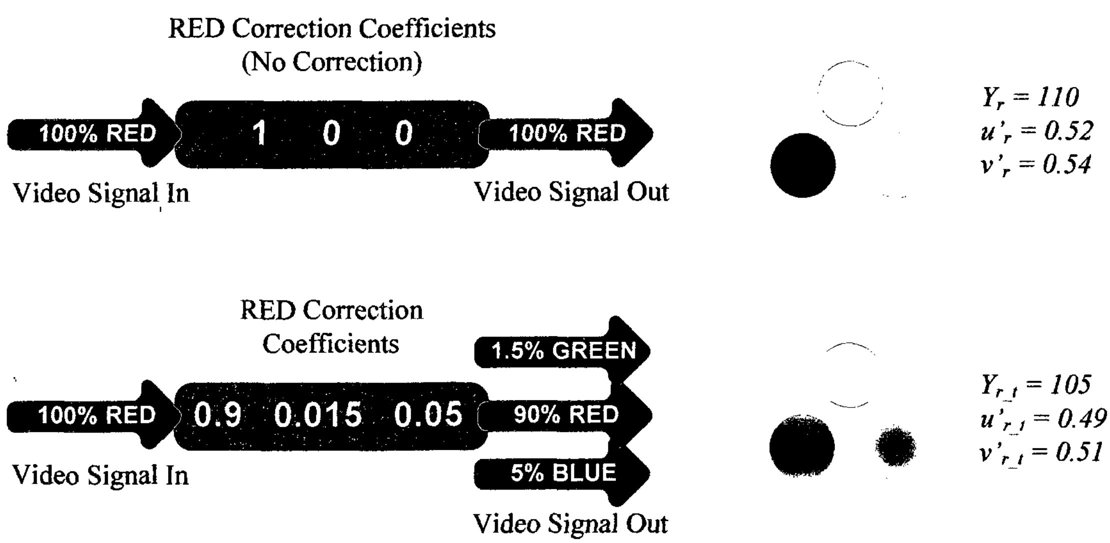


Figure 2.20: Red coefficients before and after correction

The previous example just showed the sequence to correct one color in one pixel of the LED screen. To correct the complete LED screen, this process must be applied to each color (Red, Green, and Blue) for each pixel in the LED screen. Therefore, the final correction coefficients will be a 3x3 matrix for each pixel as shown in figure 2.21 below. The Coefficients will be stored in the LED matrix controller where they will be multiplied by the video signal stream when video is being displayed on the screen.

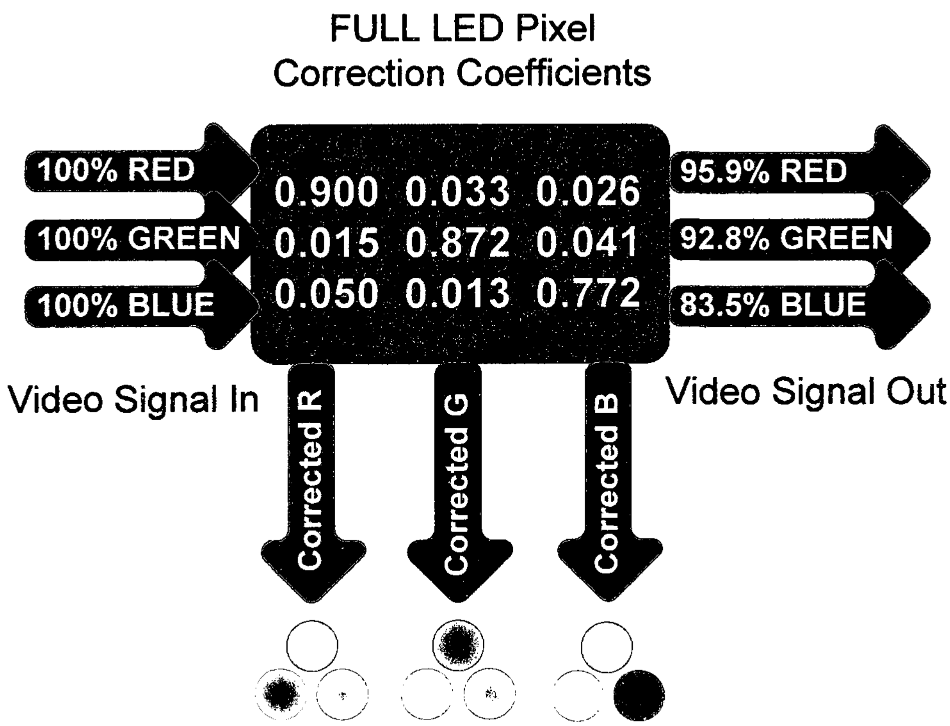


Figure 2.21: Full LED pixel correction coefficients

CHAPTER 3

Correction and Calibration Algorithms

3.1 Introduction

In this Chapter, the color and luminance correction and calibration algorithms will be presented. The Correction algorithm deals mainly with the color non-uniformity problem of the LED pixels, while the Calibration deals with their luminance variation problem. The algorithms are based on the Current and PWM correction methods where they use the CIE color systems to measure, calibrate, and correct the LEDs colors and Luminances.

3.2 Luminance Calibration Algorithm

The proposed luminance calibration algorithm and process is based on the *Dot Correction* (Current Correction) methodology based on controlling the current passing through each LED in each pixel individually. Since the relation between the LED *forward current* and *relative luminosity* is not linear, as was discussed in section 2.1.2, the calibration process is implemented based on the linear iteration technique.

The proposed algorithm has two inputs and one output. The inputs are represented by the default current value ($C_{defualt}$) and the target luminance (Y_{target}) for the LED, while the output is represented by the target current (C_{target}). The algorithm consists of two main steps which will be explained in the following calibration process for red LED in a target pixel. The green and blue LEDs luminance calibration process is identical to the red LED calibration process.

Red LED calibration process:

First, the luminance (Y_r) and chromaticity coordinates (u'_r, v'_r) are measured for the fully saturated red LED. The chromaticity coordinates (u'_r, v'_r) are not used for the luminance calibration process, but they are measured for the color correction algorithm which will be explained in the next section. The luminance and chromaticity coordinates measuring procedure is illustrated briefly in the following steps along with the drawings in figure 3.1;

1. The red LED is lighted up.
2. The RED light SPD is acquired using Spectrometer (Explained in the Chapter 4).
3. The CIE XYZ tristimulus values are calculated, where the Y parameter represents the red LED luminance (Y_r).
4. The (x_r , y_r) chromaticity coordinates are calculated from the XYZ tristimulus values.
5. Finally, the (u'_r, v'_r) chromaticity coordinates are calculated from the (x_r , y_r) coordinates.

Then, the target current is calculated based on the assumption that the relation between the *forward current* versus the *luminance* is linear, therefore the target luminance is calculated according to the following equation;

$$C_{\text{target}} = \frac{Y_{\text{target}} \times C_r}{Y_r} \qquad 3.1$$

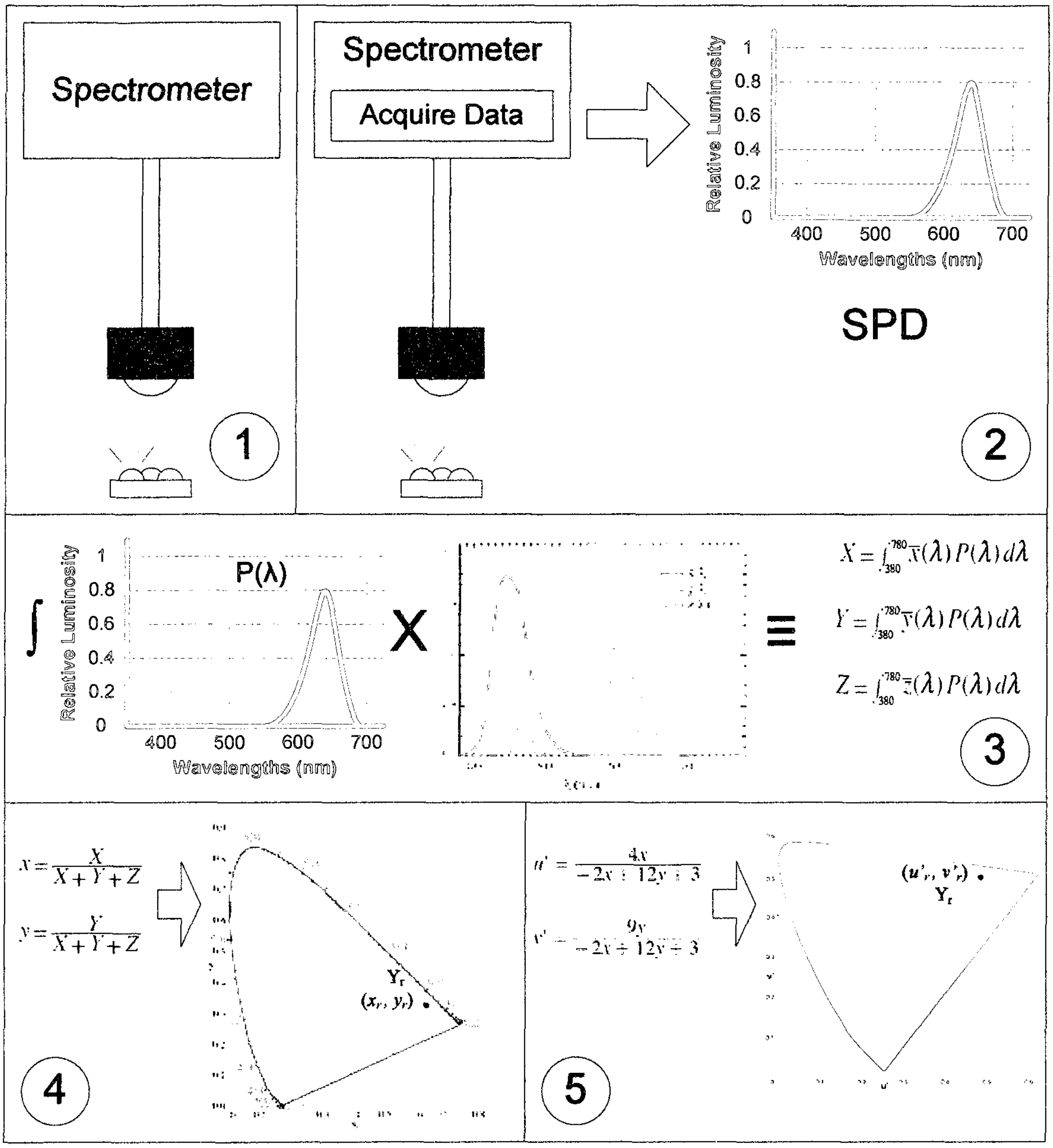


Figure 3.1: Luminance and Color Coordinates measuring procedure for red LED.

Where,

C_{target}: is the target Current

Y_{target}: is the target luminance

C_r : is the present passing Current

Y_r : is the present luminance.

Since the luminance-current relation is not linear, the algorithm uses the *iteration technique* to achieve the target luminance. The iteration technique runs the two steps mentioned above (The Luminance and Color Coordinates measuring, and Target current calculation) at every iteration turn. The following example will illustrate and explain the iteration process;

<u>*Example*</u>: Assume that the Target Luminance (Y_{target}) for a LED is 60, the present Current (C_1) is 1, and the *Current* vs. *Luminosity* curve as shown in figure 3.2.

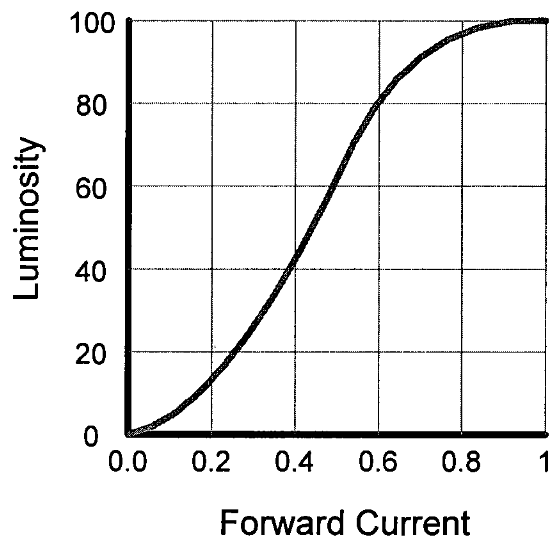


Figure 3.2: Current vs. Luminosity (Example)

To achieve the target luminance, the algorithm will go through the following steps:

1. It lights the LED with the default current (C_1) and Measures the current luminance (Y_1). It uses the point (C_1, Y_1) and (C_0, Y_0) to create the assumed linear relation line between the current and luminance (Figure 3.3).

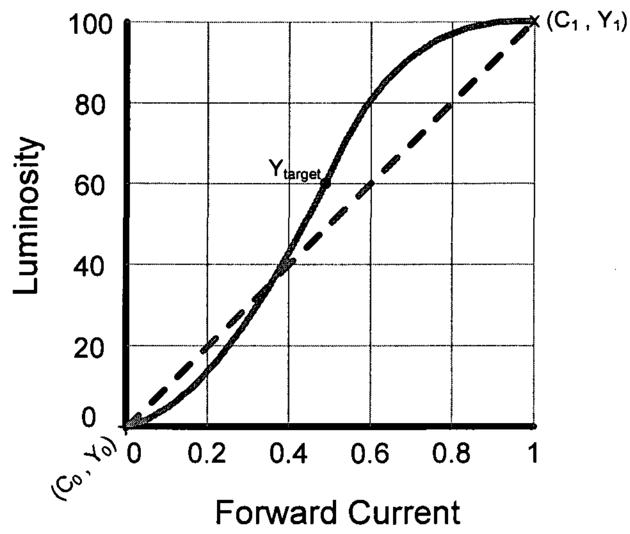


Figure 3.3: Light and measure (C_1, Y_1)

2. It calculates the new current value (C_2) using equation 3.1, and uploads it to the LED in order to measure the new luminance (Y_2) (Figure 3.4).

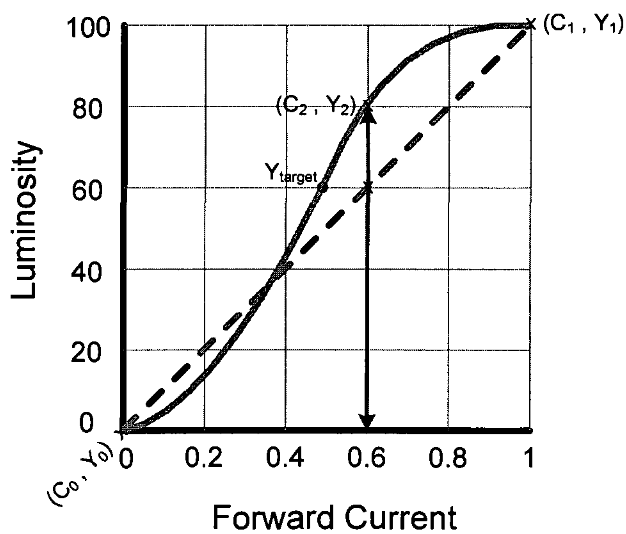


Figure 3.4: Light and measure (C_2, Y_2)

3. Since ($Y_2 > Y_{target}$), it uses the point (C_2, Y_2) and (C_0, Y_0) to create the new linear line. Then it calculates the new current (C_3) and uploads it to the LED to measure the new luminance (Y_3) (Figure 3.5).

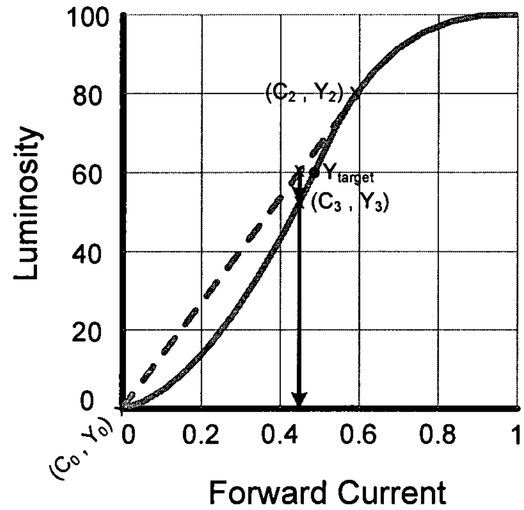


Figure 3.5: Light and measure (C_3, Y_3)

4. Since ($Y_3 < Y_{target}$), it uses the point (C_2, Y_2) and (C_3, Y_3) to create the linear line. Then it calculates the new current and uploads it to the LED to measure the new luminance. If the new luminance equals to the target luminance (Y_{target}) then the new current will represent the target current (C_{target}) (Figure 3.6).

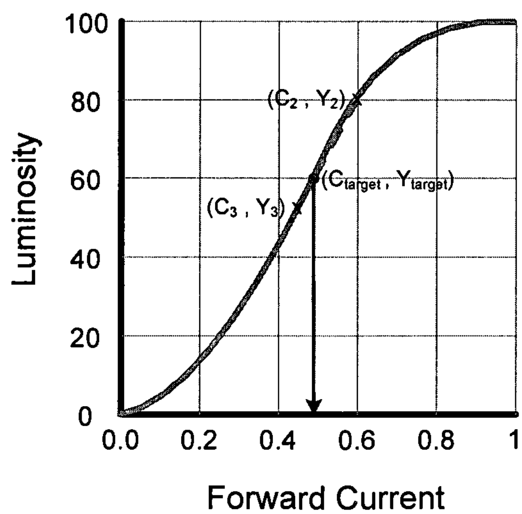


Figure 3.6: Light and measure (C_{target}, Y_{target})

Figure 3.7 shows the luminance calibration algorithm flowchart.

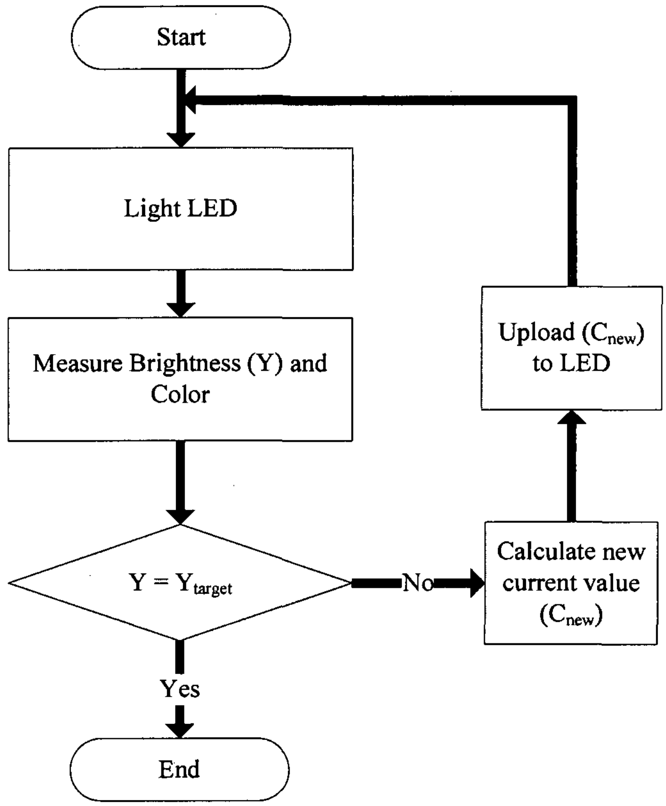


Figure 3.7: Luminance calibration process flowchart

The same procedure is done for the green and the blue LEDs to have at the end of the process the luminance and color for each LED in the pixel (Figure 3.8).

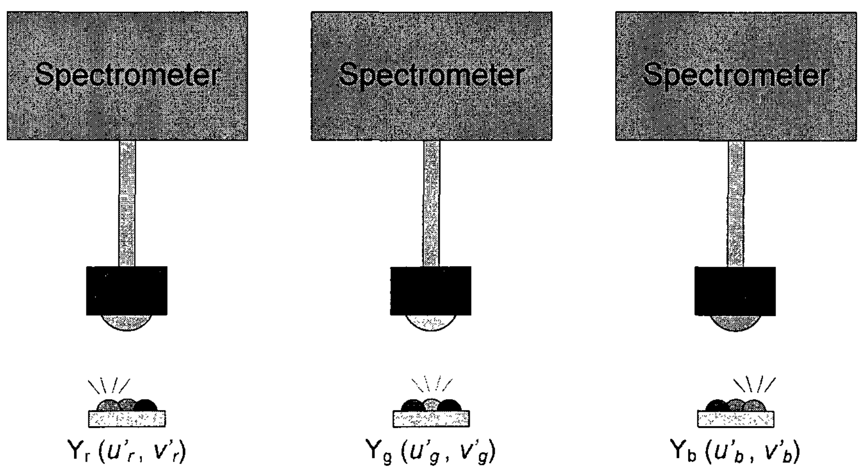


Figure 3.8: RGB LEDs luminance and color values

3.3 Color Correction Algorithm

The purpose of the color correction algorithm, as was discussed in chapter 1, is to solve the color non-uniformity problem in the LED screen's pixels. To achieve this purpose, the color correction algorithm shifts every color in each individual pixel to one target chromaticity coordinates. Therefore, all measured greens' chromaticity coordinates will be shifted to one target green chromaticity coordinate (G_{target}), measured reds to a target red (R_{target}), and measured blues to a target blue (B_{target}). The target white (W_{target}) will be achieved by determining the right luminance values for the target colors (R_{target}, G_{target}, and B_{target}). Figure 3.9 illustrates the color correction concept.

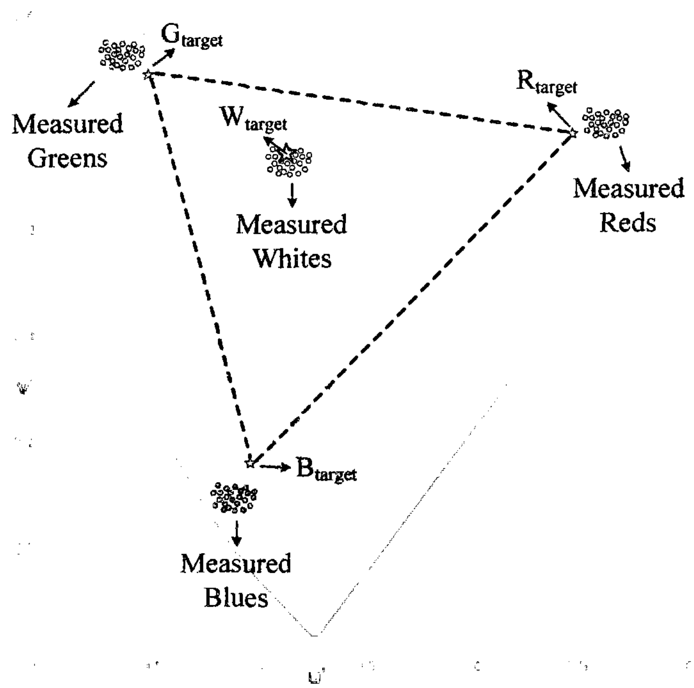


Figure 3.9: RGB LEDs luminance and color values

The proposed color correction algorithm is based on Grassman's laws of color mixture. If two colors **A** and **B** are represented by points as shown in figure 3.10, then the additive mixture of the two colors is represented by a new point **C** lying on the line joining **A** and **B**. The position of **C** on the line depends on the forces exerted by **A** and **B** (F_A and F_B), where these forces represent the relative luminance weights of **A** and **B**. It is also at the center of gravity of each luminance weights. Hence the results are referred as the Center of Gravity Law of Color Mixture which was announced by Isaac Newton.

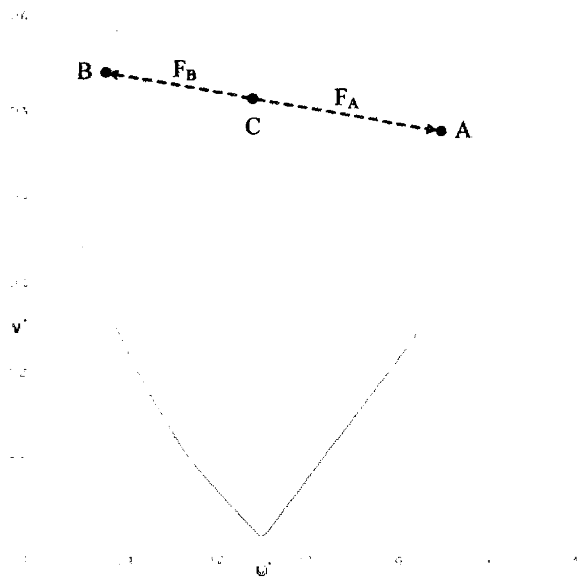


Figure 3.10: The color C can be matched by an additive mixture of the colors A & B.

The same concept applies when we have three colors **R**, **G**, and **B** represented by points as shown in figure 3.11 then the additive mixture of the three colors is represented by a new point **W**. The position of **W** depends on the relative luminance weights of **R**, **G**, and **B** (The forces exerted by **R**, **G**, and **B** (F_R, F_G, and F_B)).

Accordingly, we conclude that the luminance weights are the main factors (forces) to determine the color mixture point and not the luminance values themselves. Therefore the proposed algorithm runs several steps to determine these factors and uses them to calculate the correction coefficients. The coefficients will be uploaded to the LED matrix board to perform the color correction (Color Rendering).

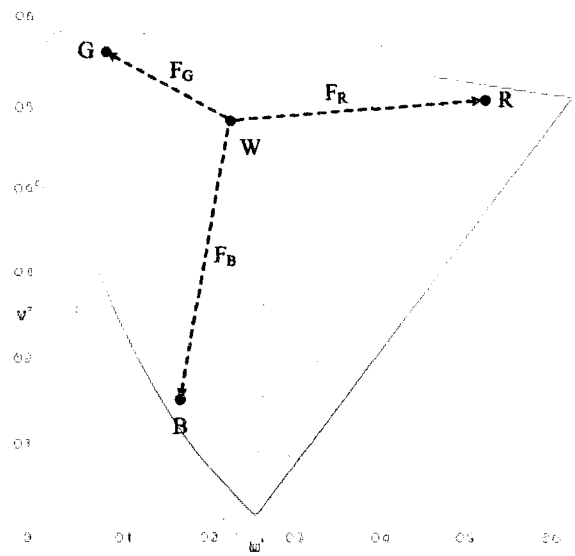


Figure 3.11: The color W can be matched by an additive mixture of the colors R, G, and B.

The algorithm utilizes the PWM correction methodology to implement the correction process. In the following, we will explain the main vision of the color correction algorithm, and later in this chapter we will explain different ways to implement the algorithm according to the user available information and needs.

Algorithm inputs and outputs:

The algorithm has 14 inputs and 9 outputs. The inputs are represented by,

- Red LED chromaticity coordinates (u'_r, v'_r), and luminance (Y_r)
- Green LED chromaticity coordinates (u'_g, v'_g), and luminance (Y_g)
- Blue LED chromaticity coordinates (u'_b, v'_b), and luminance (Y_b)
- White pixel chromaticity coordinates (u'_w, v'_w), and luminance (Y_w)
- Target Red chromaticity coordinates (u'_{r_t}, v'_{r_t}), and luminance (Y_{r_t})
- Target Green chromaticity coordinates (u'_{g_t}, v'_{g_t}), and luminance (Y_{g_t})
- Target Blue chromaticity coordinates (u'_{b_t}, v'_{b_t}), and luminance (Y_{b_t})

The first eight inputs are measured and calculated in advance, and the last six inputs should be provided by the user.

The outputs are represented by

- The red coefficients (K_{rr}, K_{rg}, and K_{rb})
- The green coefficients (K_{gr}, K_{gg}, and K_{gb})
- The blue coefficients (K_{br}, K_{bg}, and K_{bb})

Where K_{rr} represents the coefficient for the amount of row red in the target red, the K_{rg} is the coefficient for the amount of row red in the target green; the K_{rb} is the coefficient for the amount of row red in the target blue, and so on for the rest of the coefficients. The formula for adjusting the video signal to each LED pixel is given by the following equations;

$$\begin{aligned} R_{out} &= K_{rr} + K_{rg} + K_{rb} \\ G_{out} &= K_{gr} + K_{gg} + K_{gb} \\ B_{out} &= K_{br} + K_{bg} + K_{bb} \end{aligned} \qquad \text{3.2}$$

Algorithm Steps

The following steps show the correction algorithm procedure for one pixel which applies for the rest of the pixels in the LED matrix board. The procedure assumes that all the target coordinates are inside the measured pixel Gamut, while later in this section we will explain how the proposed algorithm deals with the out of gamut coordinates. It also assumes that the pixels passed through the luminance calibration algorithm.

1. The color coordinates and luminance are measured for the saturated red (Y_r (u'_r, v'_r)), green (Y_g (u'_g, v'_g)), blue (Y_b (u'_b, v'_b)), and white (Y_w (u'_w, v'_w)) (Figure 3.12).

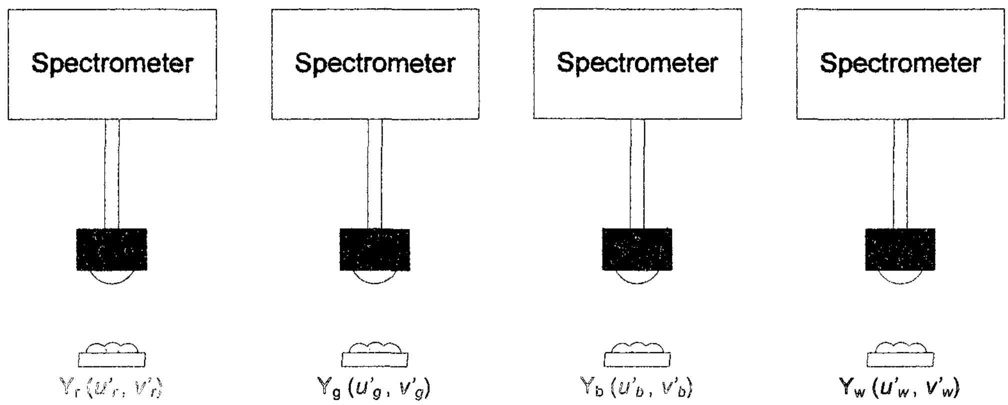


Figure 3.12: Saturated red, green, blue, and white measuring.

2. The red, green, and blue luminance weights (F_R, F_G, and F_B) are calculated based on the measured white color and on the fact that the sum of the luminance weights equals to one (Figure 3.13).

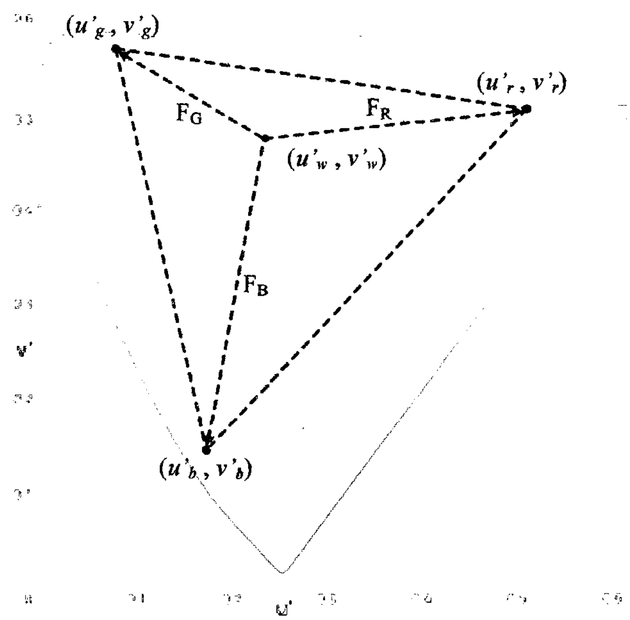
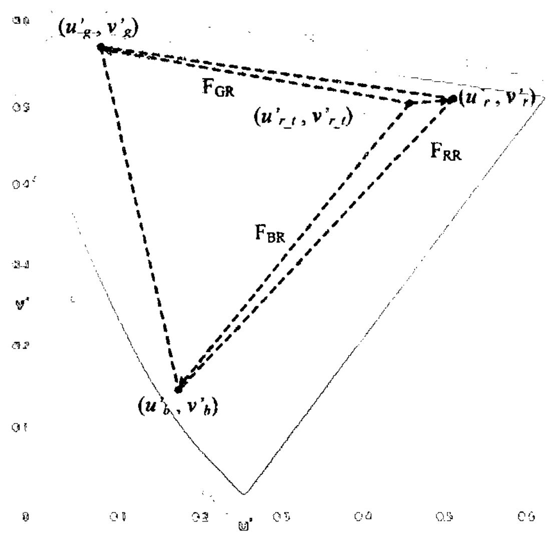
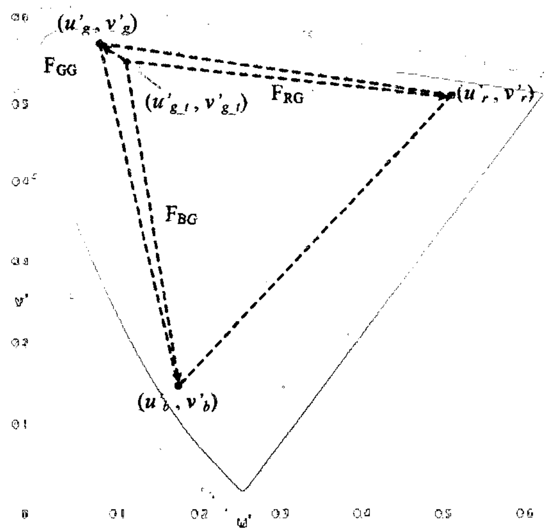


Figure 3.13: Red, green and blue luminance weights (F_R, F_G, and F_B).

3. The sub luminance weights are calculated for each color individually based on the target color.





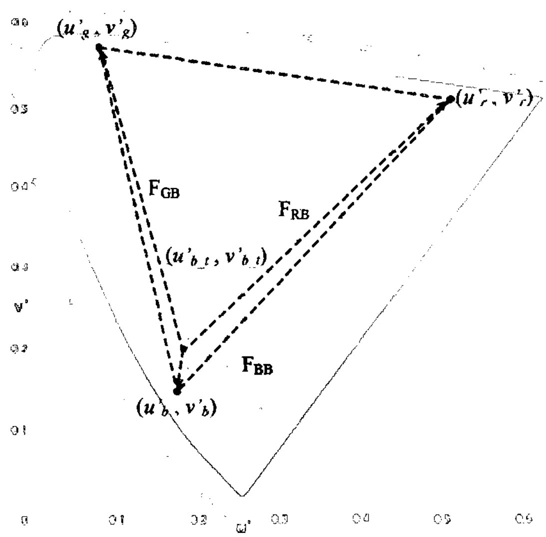


Figure 3.14: Sub-luminance weights for target red, green and blue.

The calculated sub luminance weights are illustrated in figure 3.14 and listed as follows;

- For target red : F_{RR}, F_{GR}, and F_{BR}
- For target green : F_{RG}, F_{GG}, and F_{BG}
- For target Blue : F_{RB}, F_{GB}, and F_{BB}

4. The weights from step 2 with each set of the sub weights from step 3 are combined to compute the coefficients for each color. The red coefficients (K_{rr}, K_{rg}, and K_{rb}), the green coefficients (K_{gr}, K_{gg}, and K_{gb}), and the blue coefficients (K_{br}, K_{bg}, and K_{bb}).
5. The algorithm checks the Luminance of each LED to determine whether the coefficients of each set are sufficient to light up each color as the target luminance (Y_{r_t}, Y_{g_t}, Y_{b_t}) or not. If the target luminance is not achieved with these calculated coefficients, the algorithm calculates the error percentage and multiplies it with the coefficients.
6. The algorithm runs *coefficients unity check* function to assure that the sum of each set of coefficients does not exceed one.

$$\begin{aligned} K_{rr} + K_{rg} + K_{rb} &\leq 1 \\ K_{gr} + K_{gg} + K_{gb} &\leq 1 \\ K_{br} + K_{bg} + K_{bb} &\leq 1 \end{aligned} \qquad \text{3.3}$$

If any set of the coefficients exceeds one, the algorithm calculates the error percentage and multiplies it with the luminance for that color LED. The luminance calibration algorithm will be run again to re-calibrate that LED individually. The error percentage is also used to set the sum of those coefficients at unity value.

7. Finally, the algorithm uploads and stores the computed 3x3 matrix of correction coefficients, for that pixel, to the LED Matrix controller. Figure 3.15 shows the 3x3 correction coefficients for full LED pixel.

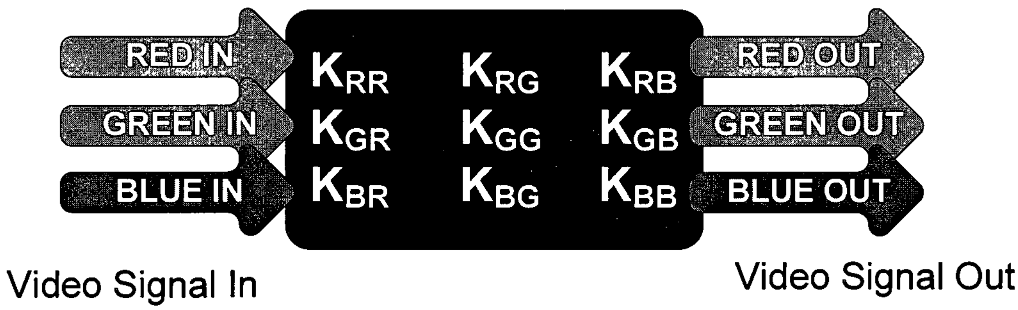


Figure 3.15: Full LED pixel correction coefficients

Out of Gamut

The algorithm runs *Out of Gamut check* function to determine if any of the target colors is out of the pixel gamut. This check is applied between steps 2 and 3 in the algorithm steps mentioned above. If any of the colors out of the pixel gamut, new target chromaticities coordinates are calculated for that target color depending on the region where the original target chromaticity coordinates fall. As shown in figure 3.16, if the target coordinates for the blue color (u'_{b_t} , v'_{b_t}) fall in "Region 1", the algorithm calculates the new coordinates $(u'_{b\_t}, v'_{b\_t})_{New}$ to be on the line connecting the green and blue coordinates; if the target coordinates fall in "Region 3", the algorithm calculates the new value to be on the line connecting the red and blue coordinates; and if the target coordinates fall in "Region 2", the algorithm keeps the measured coordinates to be the target coordinates.

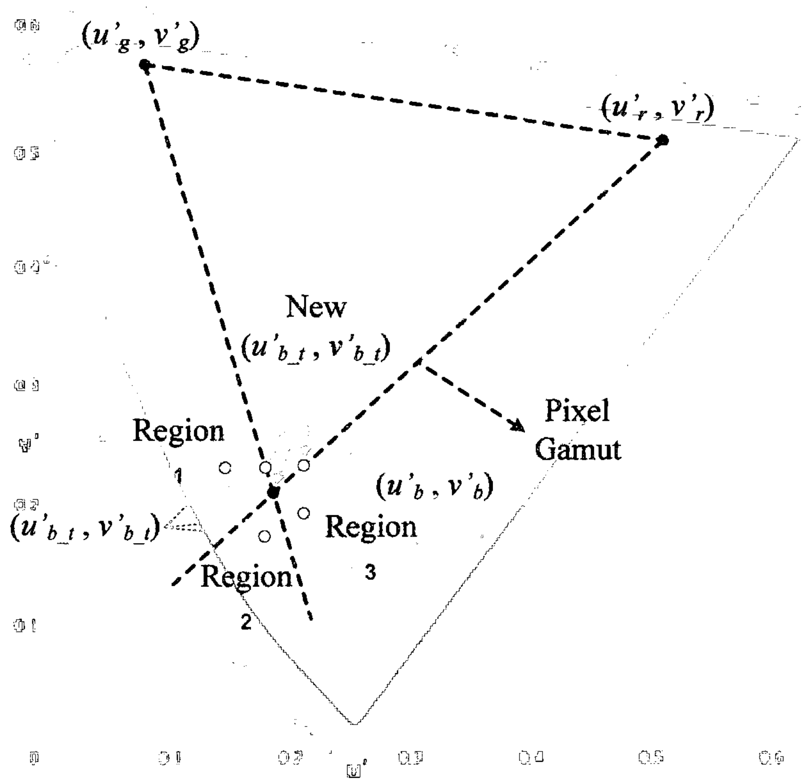


Figure 3.16: Out of Gamut function

Figure 3.17 shows the color correction flowchart.

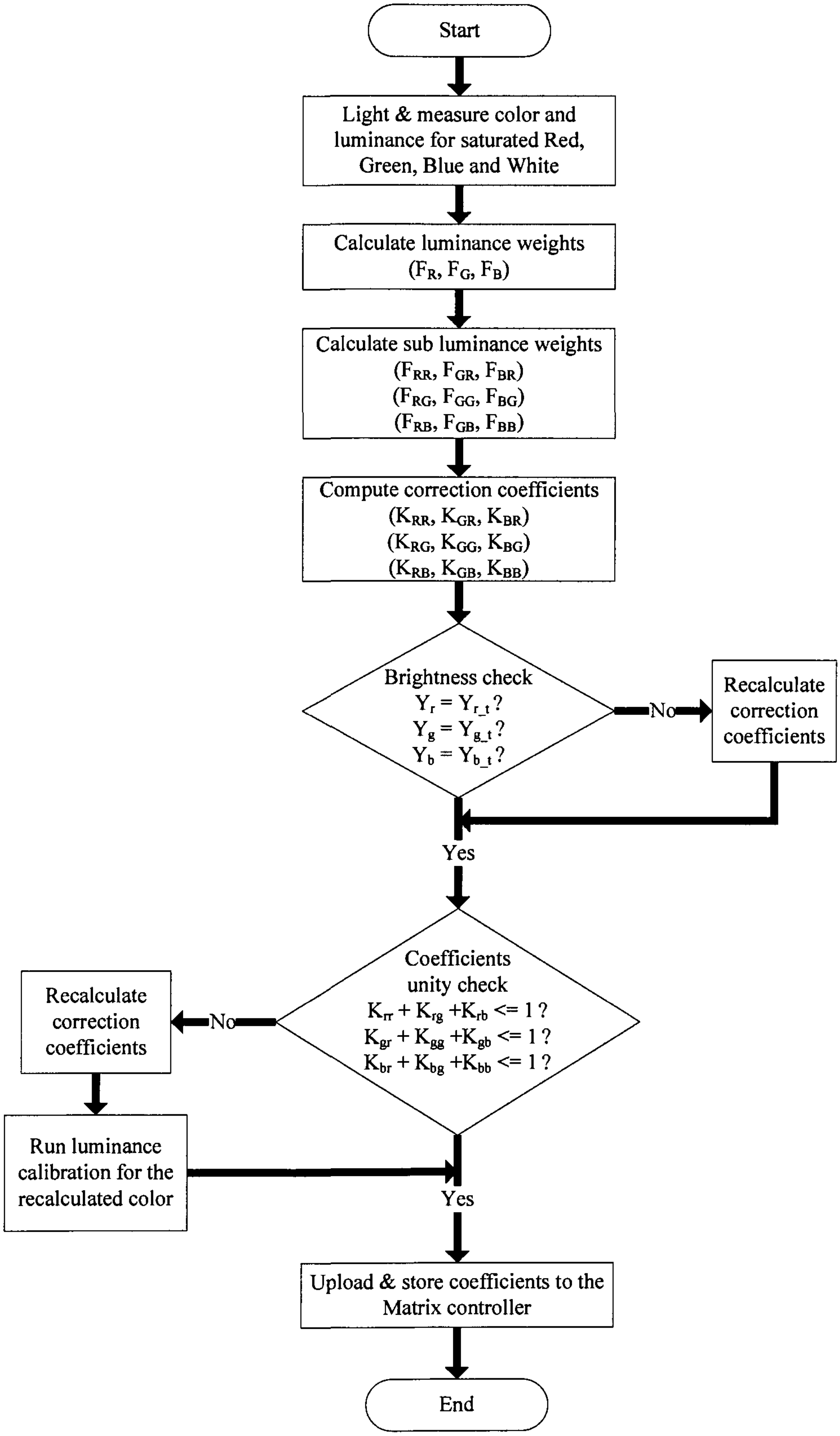


Figure 3.17: Color Correction algorithm flowchart

3.4 Proposed Methodologies

Based on the algorithm mentioned in section 3.3, the following proposed methodologies were developed to fit different users needs and according to the available inputs that can be provided to the algorithm to perform the correction;

- RGBW Color and W Luminance methodology
- RGB Color and Luminance methodology
- W Color and Luminance methodology
- RGB Luminance methodology
- Achromatic Point methodology

Some of these methodologies' ideas are used by other industrial solutions available in the market, like the *RGB Color and Luminance* methodology and the *RGB Luminance* methodology. The *RGB Color and Luminance* methodology could provide a mediocre resolution if the user didn't choose a suitable Luminance values to the algorithm to calibrate and correct the colors. The *RGBW color and W Luminance* is developed to calculate the needed Luminance values to the correction algorithm, which over come the mediocre resolution that can be caused by the user. Later in this chapter, in the *Image Quality and Resolution* section, the possible cause of mediocre resolution in corrected and calibrated LED screens will be explained and discussed.

The methodologies can be useful for different user needs and can fit different conditions. The following sub-sections will explain the methodologies' algorithms along with the possible uses.

3.4.1 RGBW Color and W Luminance

The color and luminance correction can be performed based on the information available for the target chromaticity coordinates for the red, green, blue and white (RGBW) colors and the target White luminance. This proposed methodology computes the suitable luminance values for the red, green, and blue and then performs the same calibration and correction process mentioned in the previous section 3.3.

In order to calculate these luminances, the methodology's algorithm runs several steps as follows;

1. The pixel LEDs are lighted up and measured with fully saturated red, green, blue, and white. Then the algorithm computes the luminance weights for the RGB colors (F_R, F_G and F_B) (As mentioned in step 2 in the color correction algorithm section 3.3).
2. The algorithm calculates the weights for the RGB targets (F_{R_t}, F_{G_t} and F_{B_t}) according to the target white (W_{target}) (Figure 3.18).
3. It computes the sub luminance weights for each color individually (As mentioned in step 3 in the color correction algorithm section 3.3).

- For target red: F_{RR}, F_{GR}, and F_{BR}
- For target green: F_{RG}, F_{GG}, and F_{BG}
- For target blue: F_{RB}, F_{GB}, and F_{BB}

4. The red components (R_c), the green components (G_c) and the blue components (B_c) are calculated as follows;

$$\begin{aligned} R_c &= F_{rr} + F_{rg} + F_{rb} \\ G_c &= F_{gr} + F_{gg} + F_{gb} \\ B_c &= F_{br} + F_{bg} + F_{bb} \end{aligned} \qquad 3.4$$

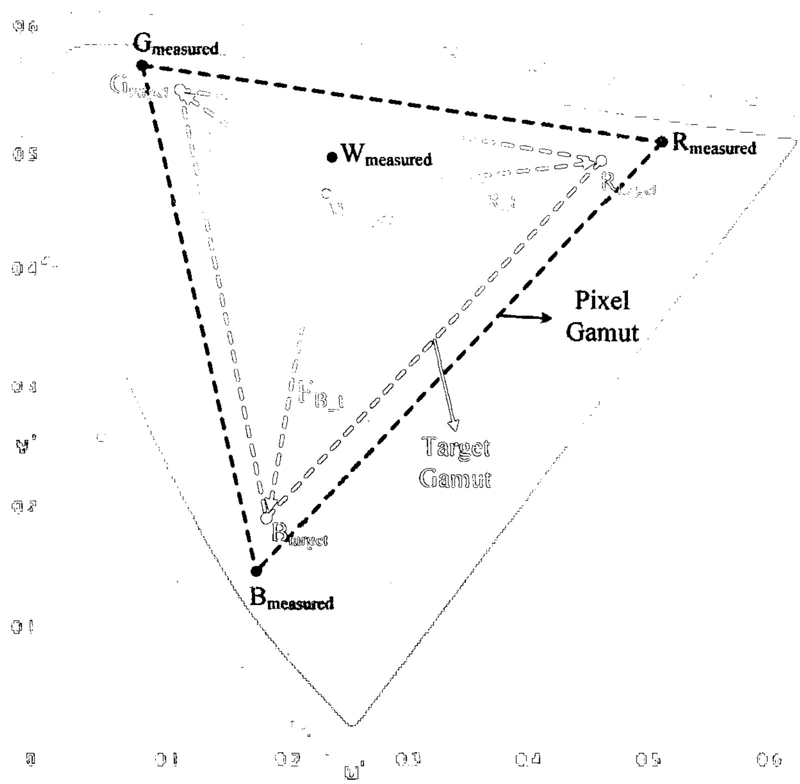


Figure 3.18: (F_{R_t}, F_{G_t} and F_{B_t}) according to (W_{target})

5. The target luminance for each color (Y_{R_t}, Y_{G_t} and Y_{B_t}) are then computed from the measured luminance weights (F_R, F_G and F_B), the target luminance weights (F_{R_t}, F_{G_t} and F_{B_t}), and the color components (R_c, G_c and B_c). The target white luminance should equal to the sum of the RGB target luminancees,

$$Y_{w\_t} = Y_{R\_t} + Y_{G\_t} + Y_{B\_t} \quad \text{3.5}$$

Otherwise, the RGB target luminancees will be scaled to fulfill the white target luminance.

6. The luminance calibration algorithm and the color correction algorithm will run, as was explained in the previous two sections 3.2 and 3.3, to perform the correction.

This kind of methodology is useful when the user wants to calibrate LED matrix for the first time. Another useful need for this methodology arises when there is LED matrix that has different LED patches.

3.4.2 W Luminance and Color

Another methodology is proposed here where the user can provide the target luminance and chromaticity coordinates for the white color. This methodology does not shift any of the primary colors; it just calculates and calibrates their luminances in order to compute the correction coefficients for the target white. The methodology's algorithm steps are explained as follows;

1. The algorithm lights and measures the saturated red, green, blue, and white, then it computes the luminance weights for the RGB colors (F_R, F_G and F_B) (Figure 3.19).

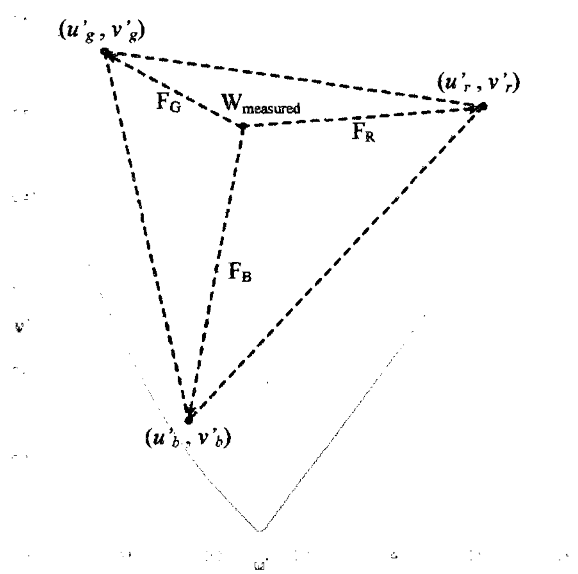


Figure 3.19: F_R, F_G and F_B according to $W_{measured}$

2. The sub luminance weights (F_{RR}, F_{GG}, and F_{BB}) are then calculated for the target white (W_{target}) (Figure 3.20).

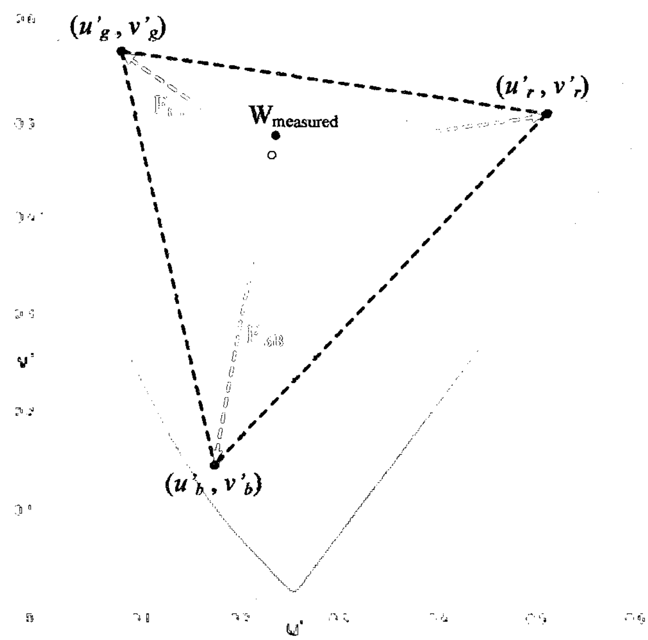


Figure 3.20: (F_{RR}, F_{GG} and F_{BB}) according to (W_{target})

3. The target luminances for each color (Y_{R_t}, Y_{G_t} and Y_{B_t}) are then computed from the measured luminance weights (F_R, F_G and F_B) and the sub luminance weights (F_{RR}, F_{GG} and F_{BB}).
4. The luminance calibration algorithm will run as was explained in section 3.2.
5. The algorithm recalculates the luminance weights (F_R, F_G and F_B) and the sub luminance weights (F_{RR}, F_{GG} and F_{BB}) in order to calculate the correction coefficients (K_{rr}, K_{gg}, and K_{bb}).
6. The algorithm checks the Luminance of each LED to determine whether the coefficients are sufficient to light up the white color according to the target luminance or not. If the target luminance is not achieved with these calculated

coefficients, the algorithm calculates the error percentage and multiplies it with the coefficients.

7. The algorithm runs *coefficients unity check* function to assure that each coefficient does not exceed one.

$$K_{rr} \leq 1$$
$$K_{gg} \leq 1 \quad \text{.......} \quad 3.6$$
$$K_{bb} \leq 1$$

If any coefficient exceeds one, the algorithm calculates the error percentage, then it multiplies it with the luminance for that color LED, and then it runs the luminance calibration algorithm to re-calibrate that LED individually. The error percentage is also used to recalculate the coefficient at unity value.

8. Finally, the algorithm uploads and stores the computed correction coefficients, for that pixel, to the LED Matrix controller. Figure 3.21 shows the 3x3 Matrix for the pixel.

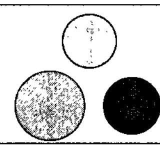
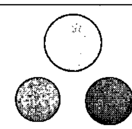
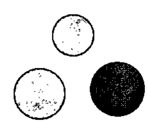
Figure 3.21: LED pixel correction coefficients for W color and luminance methodology

This methodology is useful when the user is interested for calibrated white LED screen. This kind of LED screens is usually favorable for advertisements, dasher boards, text ribbons, and general billboards.

3.4.3 RGB Color and Luminance

In this methodology, the user assigns the default luminance for all the Pixel LEDs in the LED screen to perform the luminance calibration algorithm (Section 3.2), then it runs the same color correction algorithm (section 3.3) to perform the color and luminance correction.

The criteria for how to determine a proper luminance values depends on the maximum required luminance value for the LED color in the LED matrix. For example, to assign the default luminance for the Red LEDs, the user has to determine the maximum that each target color needs Red to achieve the target color coordinates and luminances. To illustrate the criteria further more, assume that we have the following three pixels with the following default color coordinates and luminances;

			
R Default Color Coordinates	(0.540 , 0.505)	(0.490 , 0.510)	(0.520 , 0.500)
G Default Color Coordinates	(0.067 , 0.562)	(0.075 , 0.558)	(0.080 , 0.546)
B Default Color Coordinates	(0.140 , 0.185)	(0.115 , 0.210)	(0.129 , 0.177)
R Default Luminance	80	50	65
G Default Luminance	140	165	125
B Default Luminance	38	40	43

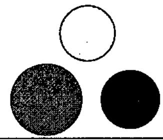
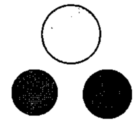
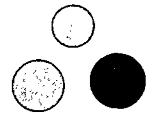
The target color coordinates and luminances are as follows;

R target color coordinates : (0.480 , 0.500) Target Luminance: 45

G target color coordinates : (0.090 , 0.540) Target Luminance: 120

B target color coordinates : (0.190 , 0.275) Target Luminance: 30

Also, let's assume that we need the following amount of RGB for each pixel to achieve the target colors and luminances mentioned above;

			
Total Red	45	48	40
Total Green	115	121	117
Total Blue	31	27	34

Accordingly, the user can not assign luminance value for the Red LEDs less than 48, for the Green LEDs less than 121, and for the Blue LEDs less than 34.

The procedure for how to get these values can be performed in two ways, 1) try and error, or 2) Run the *RGBW color and W luminance* methodology. The Try and Error is time consuming and not so accurate. On the other hand, the user can run the *RGBW color and W luminance* methodology for one LED matrix board to extract the maximum luminance needed for each color LEDs.

The main disadvantage of having one fixed luminance for each color LEDs, is that may cause mediocre image resolution. On the other hand, this methodology has faster process than the *RGBW color and W luminance* methodology. It is also more useful when target LED matrices need to be calibrated to match another sample calibrated LED matrix, where in this case the algorithm has to measure the sample matrix and applies the measured values to the other non-calibrated LED matrices. The user can rely on this methodology when the used LEDs in the LED matrices are all from the same manufactured patch.

3.4.4 RGB Luminance

The RGB luminance methodology uses only the Luminance Calibration process which calibrates the pixels LEDs to target luminances without performing any color correction. This methodology reduces the non-uniformity problems in the LED screens, but it does not solve it.

This process can be useful for LED lighting products as they are usually apart and do not need accurate color calibration. It is also used for LED screens when a fast calibration is needed.

3.4.5 Achromatic Point

The achromatic point methodology was developed for LED lighting products, as this methodology calibrate the white achromatic point with the maximum possible luminance. The methodology is similar to that *White luminance and color algorithm* with one main difference that it does not calibrate the luminance.

The methodology's algorithm is performed in few steps as follows;

1. The algorithm lights and measures the pixel with fully saturated red, green, blue, and white, then it computes the luminance weights for the RGB colors (F_R, F_G and F_B).
2. The sub luminance weights (F_{RR}, F_{GG}, and F_{BB}) are calculated for the target white.
3. The luminance weights (F_R, F_G and F_B) and the sub luminance weights (F_{RR}, F_{GG} and F_{BB}) are used to calculate the correction coefficients (K_{rr}, K_{gg}, and K_{bb}).

4. Finally, the algorithm uploads and stores the computed correction coefficients, for that pixel, to the LED Matrix controller.

3.5 Image Quality and Resolution

LED video screen image quality and resolution influence the consumers' decision with the wide choices available in the market. The image quality can be solved through the color correction and calibration process, but it is not usually necessary to have high resolution associate with the correction process, and that all depends on the algorithm and the methodology used to correct and calibrate the LED screens. In this section, the Image Quality and Resolution provided by the methodologies, *RGB color and Luminance* and *RGBW Color and W Luminance,* will be discussed.

To illustrate how each of the two mentioned methodologies influence the Resolution of the image, assume that we have LED pixel with the following default RGB color and luminance;

$Y_r = 140$ nits, $(u'_r = 0.52, v'_r = 0.54)$

$Y_g = 230$ nits, $(u'_g = 0.09, v'_g = 0.58)$

$Y_b = 60$ nits, $(u'_b = 0.15, v'_b = 0.21)$

And we wish to correct the pixel colors as the following;

Red target color coordinates : (0.490, 0.510) Target luminance: 90 nits

Green target color coordinates : (0.100, 0.550) Target luminance: 170 nits

Blue target color coordinates : (0.180, 0.270) Target luminance: 30 nits

The *RGBW color and W luminance methodology* will proceed as the following;

First, it calculates the proper luminance for each LED individually and then it will run the Luminance Calibration Process. The new calculated luminance (assumption) will be as the following;

$Y_r = 98$ nits

$Y_g = 176$ nits

$Y_b = 32$ nits

Then, the algorithm calculates the coefficients to correct the color and luminance and uploads them.

Total Luminance R = $(0.925 \times 98)_R + (0.011 \times 176)_G + (0.075 \times 32)_B = 95$ nits

Total Luminance G = $(0.009 \times 98)_R + (0.948 \times 176)_G + (0.068 \times 32)_B = 170$ nits

Total Luminance B = $(0.029 \times 98)_R + (0.007 \times 176)_G + (0.810 \times 32)_B = 30$ nits

The calculated coefficients will be as the following (Figure 3.22);

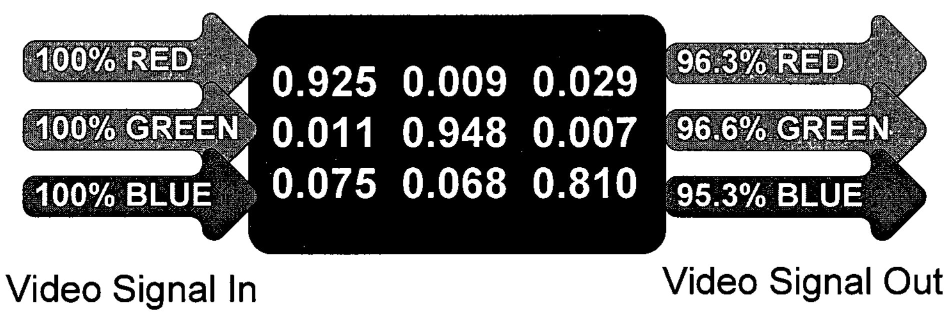


Figure 3.22: LED pixel correction coefficients for RGBW color and W luminance methodology example

For the *RGB color and luminance* methodology will proceed as the following;

First, the user is going to assign one default luminance value for each LED color for the LED pixels in the LED screen. Assume that the assigned luminance values are as the following;

$Y_r = 115$ nits

$Y_g = 205$ nits

$Y_b = 40$ nits

Then, the algorithm will run the Luminance Calibration Process and calculates the coefficients to correct the color and luminance and uploads them.

Total Luminance R = $(0.753 \times 115)_R + (0.024 \times 205)_G + (0.088 \times 40)_B = 95$ nits

Total Luminance G = $(0.071 \times 115)_R + (0.787 \times 205)_G + (0.012 \times 40)_B = 170$ nits

Total Luminance B = $(0.014 \times 115)_R + (0.009 \times 205)_G + (0.665 \times 40)_B = 30$ nits

The calculated coefficients will be as the following (Figure 3.23);

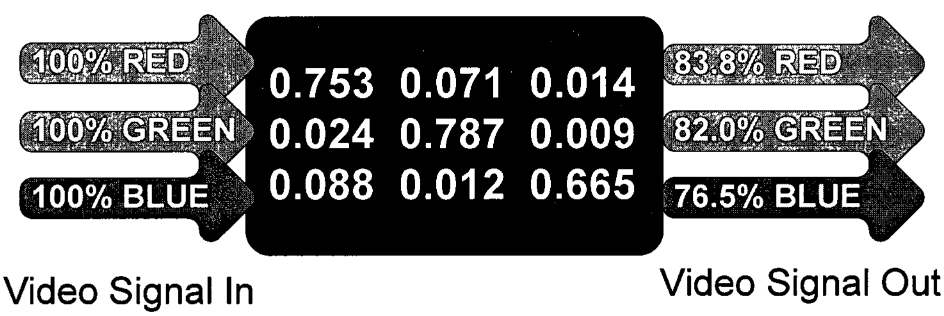


Figure 3.23: LED pixel correction coefficients for RGB color and luminance methodology example

Reviewing the results out of the two methodologies example mentioned above, the *RGBW color and W Luminance* methodology shows higher efficiency and resolution for the corrected pixel as shown in table 3.1.

The *RGB Color and Luminance* methodology can provide a better resolution if the determined luminance values were closer to the ones provided by the *RGBW Color and W Luminance* methodology.

	RGBW Color & W Luminance		RGB Color & Luminance	
	Coefficients	**Total Usage**	**Coefficients**	**Total Usage**
Red	**0.925**	**96.3**	**0.753**	**83.8**
Green	**0.948**	**96.6**	**0.787**	**82.0**
Blue	**0.81**	**95.3**	**0.665**	**76.5**

Table 3.1: Methodologies efficiencies

3.6 Summary

In this chapter, the proposed algorithm and methodologies were discussed for the color and luminance correction. The purpose of the color and luminance correction and the target we want to achieve were illustrated. Also, the different developed methodologies and the differences between them were described. Finally, the image quality and resolution difference between the proposed methodology and the methodology used in the market solutions were compared.

CHAPTER 4

Correction and Calibration Experimental Setup

4.1 Introduction

A LED Screen Correction and Calibration System is developed for measuring and correcting the color and luminance of each LED in every pixel, in a LED video screen, and stores the correction data in lookup tables in the LED matrix memory. The system is an integrated hardware and software solution where it uses; 1) robotic spectrometer head, to precisely measure the chromaticity and luminance of each LED in a target LED Matrix, and 2) Windows based graphical user interface (GUI) application software, to calculate the correction coefficients and factors for each pixel based on the measured data.

4.2 System Description

The proposed Correction and Calibration System consists of three components:

- *Robotic Spectrometer system* which uses off-the-shelf Robot (JR2500 by Janome) and Spectrometer (SPM-002-A by Photon Control).
- *Correction Software* which is developed using VB.net.
- *Matrix Controller* which provides full control over the LED matrix (see section 2.1.5 for more details).

The system can be used to calibrate different LED matrix sizes with up to 16x16 / 28 mm pitch. It has precision correction with pixel-to-pixel luminance corrected to +/- 3%

and pixel-to-pixel color corrected to +/- 0.005 Δ $u'v'$.

4.2.1 Robotic Spectrometer system

The used *robot* is an off-the-shelf JR2500 by Janome (figure 4.1). The robot has the following specifications:

- **Range of operation:** (X, Y axis) 510 mm x 510 mm, (Z axis) 150 mm
- **Speed:** 8 ~ 800 mm/sec
- **Movement Accuracy:** 0.001 mm
- **Interface:** RS232

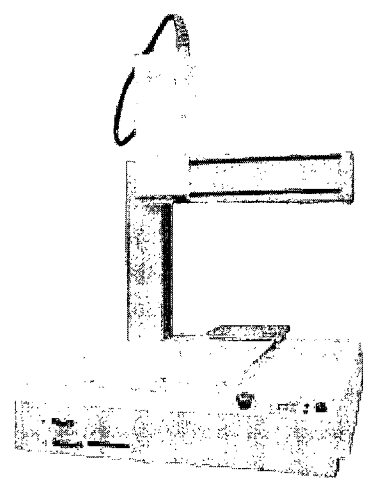


Figure 4.1: Robot JR2500 by Janome.

The *spectrometer* is an off-the-shelf SPM-002-A by Photon Control (Figure 4.2). It uses a mirror based optical system, flat grating and a 64 mm focal length mirror to achieve high resolution design. The spectrometer is CCD-based with the following specifications:

- **Spectral Range (nm):** 400 - 700
- **CCD Pixels:** 3648
- **A/D Resolution:** 12-bit
- **Integration time:** 10 μsec to 65 sec

- **Interface:** USB 2.0

Figure 4.2: Spectrometer SPM-002-A by Photon Control

A cosine receptor (diffuser) is used and attached to the spectrometer fiber head to collect and diffuse the input light. The receptor provides accurate absolute intensity when multiple lights are to be measured at the same time.

Figure 4.3 shows the light measuring path inside the spectrometer. The spectrometer measures the light's spectral power frequently according to the set integration time (Exposure time), for the wavelength range 400 nm to 700 nm, and stores the data on a lookup table memory. The stored data represents the SPD which is used to determine the light's color and luminance.

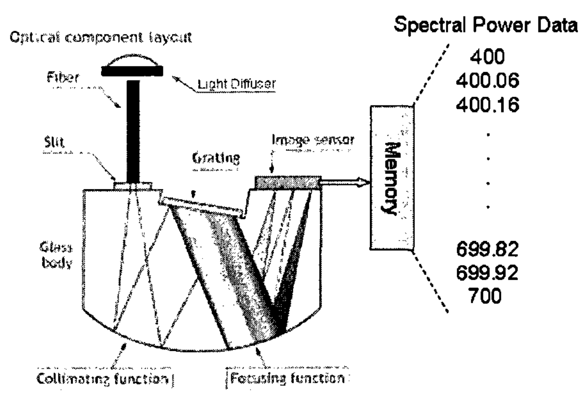


Figure 4.3: Light measuring path inside the spectrometer.
(Optical layout drawing from http://www.hamamatsu.com)

The receptor along with the spectrometer fiber is attached with a custom fitting to the robot Z-axis arm, and the LED Matrix is placed with a custom base on the robot X-axis base. Figure 4.4 shows a picture of the robotic spectrometer system.

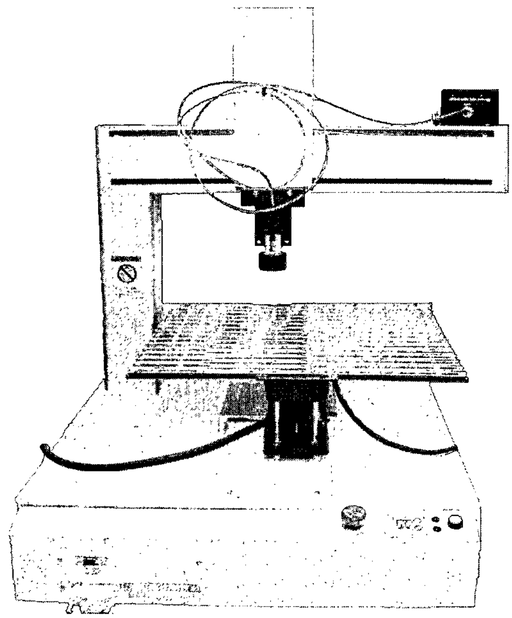


Figure 4.4: Robotic Spectrometer system

4.2.2 Correction Software

The robot, the spectrometer, and the LED matrix controller interfaces communicate with the correction software which in turn is controlling all over the system to run the correction process.

The Software is built out of several classes (figure 4.5) which represent a set of objects. Each of the hardware components (The robot, the spectrometer, and the matrix controller) has one control class that works as software driver. These drivers are responsible for communication link initialization, hardware initialization, and building, sending, receiving and checking commands. As for the other classes, there is a class responsible for the CIE chromaticity coordinates and luminance calculations, other classes are available for each LED matrix type which has the matrix type, size, pitch, position, memory map, and the communication commands.

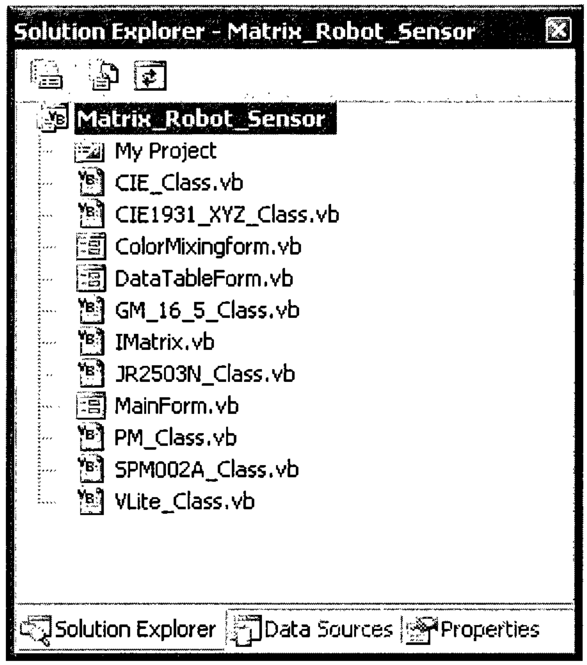


Figure 4.5: Software classes

Figure 4.6 shows the software *Main* window. Clicking the Auto Connect (Auto Disconnect) button makes the software to search, communicate, and connect (disconnect) with the system hardware automatically without the need to specify the communication port numbers. The user has to select the type of the LED Matrix from the LED Matrix combo list. Clicking the initialize button will; 1) Create the LED Matrix object and load the Matrix configuration data, 2) power on and initialize the robot, 3) initialize the Matrix controller, and 4) set the spectrometer exposure time. The robot status, the matrix controller status, and the spectrometer status descriptions are always briefly shown at the bottom of the software window. As it is shown in the main tab, the software can run different correction algorithms based on the available correction information and the user need. The algorithms were explained in the previous chapter.

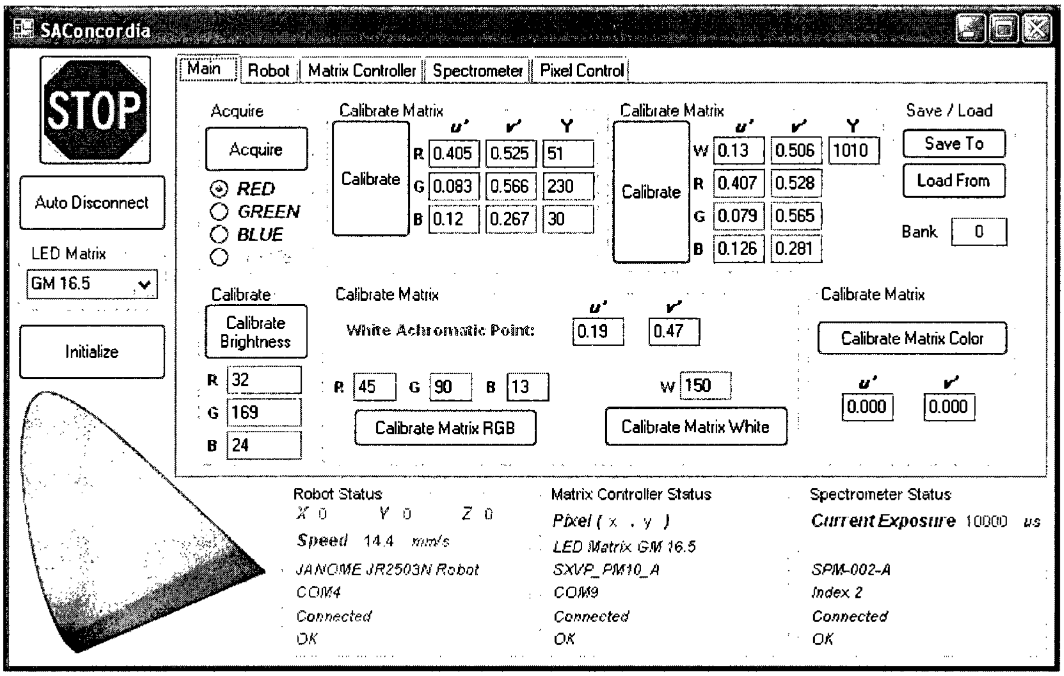


Figure 4.6: Software main page

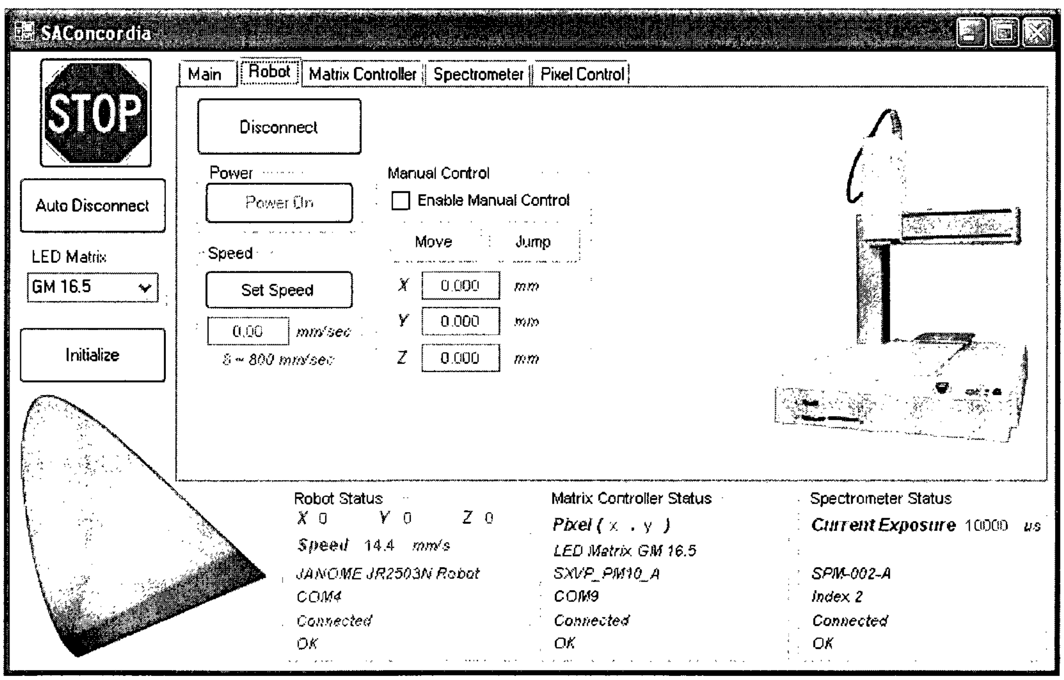


Figure 4.7: Software Robot tab

In the software *Robot* tab (Figure 4.7) the user can control the robot individually. This feature is useful when the user needs to add a new LED matrix type to the system where it allows moving the robot arms over the LED matrix (0, 0) pixel to get the robot starting coordinates.

Figure 4.8 shows the software *Matrix Controller* tab. Under this tab, the user can control the LED matrix individually. It allows the user to select between the different correction memories which are introduced as follows; 1) Default (No correction), 2) Dot correction (only the dot correction factors are uploaded), 3) Coefficients (only the PWM coefficients are uploaded), or 4) DC + Coef (run both correction coefficients and factors). The user can also set the default Dot correction (Current correction) values for the matrix LEDs and to switch between video mode and test pattern mode.

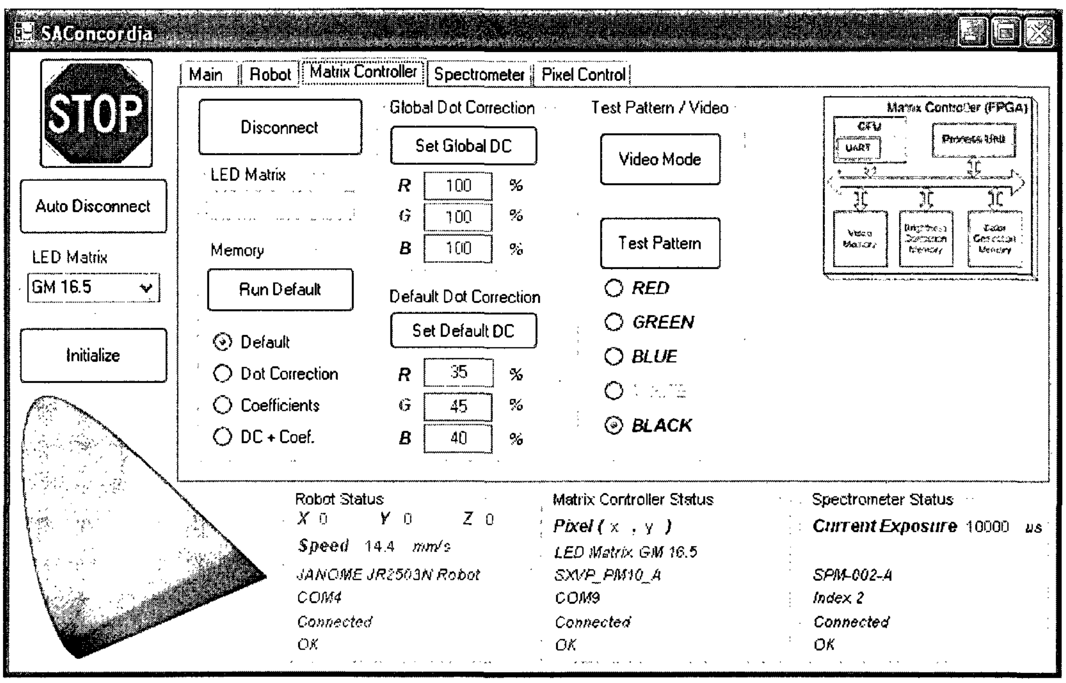


Figure 4.8: Software Matrix Controller tab

Under the software *Spectrometer* tab (figure 4.9), the user can control the spectrometer exposure time and run different functions associate to it. The exposure time (in μs) is the time during which light falls on the CCD array between readout cycles.

Adjusting this parameter changes the overall sensitivity of the instrument, as changing the exposure does for a camera.

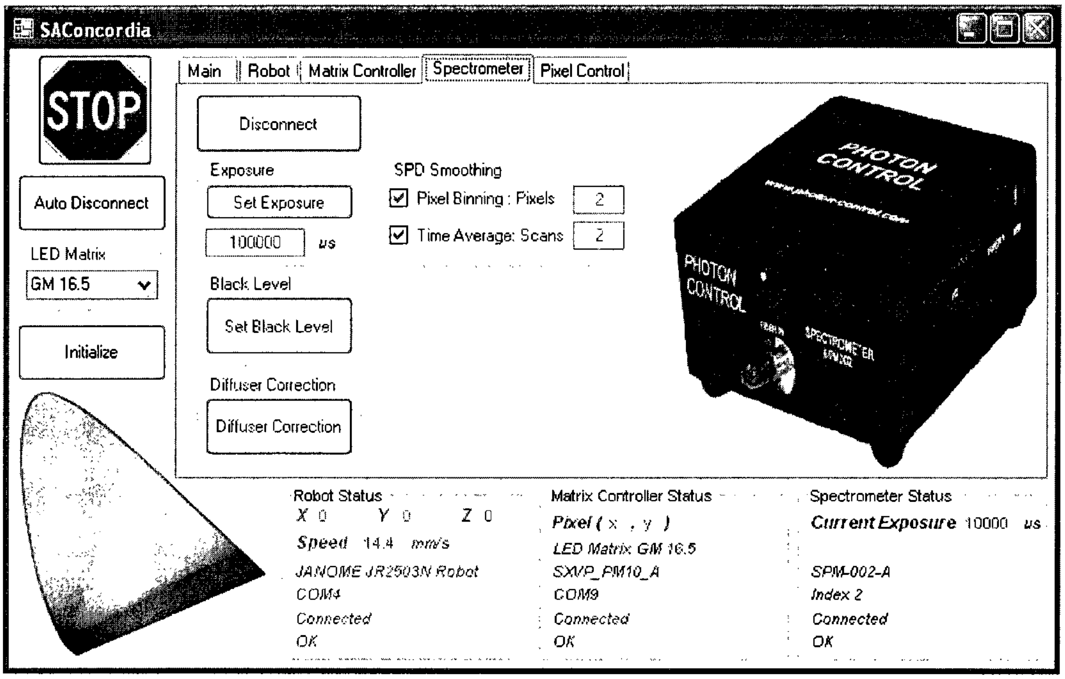


Figure 4.9: Software Spectrometer tab

Other features, such as Pixel Binning, Time Average, Black Level measurement, and Diffuser Correction, were developed and implemented for the correction process to have accurate readings and higher signal-to-noise ratio (SNR). The following are brief descriptions for each of these features;

- *Pixel Binning*: is a technique that averages across spectral data. This technique averages a group of adjacent detector elements. A value of 5, for example, averages each data point with 5 points to its left and 5 points to its right. The greater this value, the smoother the data and the higher the SNR. If the value entered is too high, a loss in spectral resolution will result. The SNR will improve by the square root of the number of pixels averaged.

- *Time Average*: Sets the number of discrete spectral acquisitions that are accumulated by the spectrometer before the software calculates the light chromaticity and luminance. The higher the value, the better the SNR. Very large scan numbers can be averaged, but this can easily cause total data collection times to approach 5 – 10 minutes and longer.
- *Black Level*: The black level reference is taken with the light source off. The Black Level function stores a background scan which will be subtracted from subsequent data scans for computing irradiance. The CCD sensor array is an integrating sensor; that is, charge is accumulated continuously in each of the CCD pixels until removed during a readout cycle. The charge desired is that due to the optical signal under observation. However, other sources also cause charge to accumulate between readout cycles, acting as a background or pedestal signal which varies slightly from pixel to pixel. There are three primary sources for dark signal: detector dark current, light scattered within the instrument, and ambient light in the test area. Usually the most important of these is detector dark current, which can be very significant for integration times of 300 mSec and longer. Every time the integration period is changed, a new Black Level must be taken.
- *Diffuser Correction*: It is a function to calibrate the spectrometer data with the use of a diffuser. It measures a white reference light without the existence of the diffuser, and stores the spectral power amplitudes at each wavelength in a look up table. The software asks the user to mount the diffuser to measure the reference light again and to compare both results to produce the diffuser correction table.

The diffuser correction table will be multiplied by the spectrometer spectral data to retrieve the correct SPD.

Figure 4.10 shows the software *Pixel Control* tab where the user can control each pixel individually. The pixel control tab allows controlling the robotic spectrometer to go over selected pixel, assign the current and PWM percentage for each LED in a pixel, acquire pixel luminance and chromaticity data, and to calibrate pixel color and luminance individually.

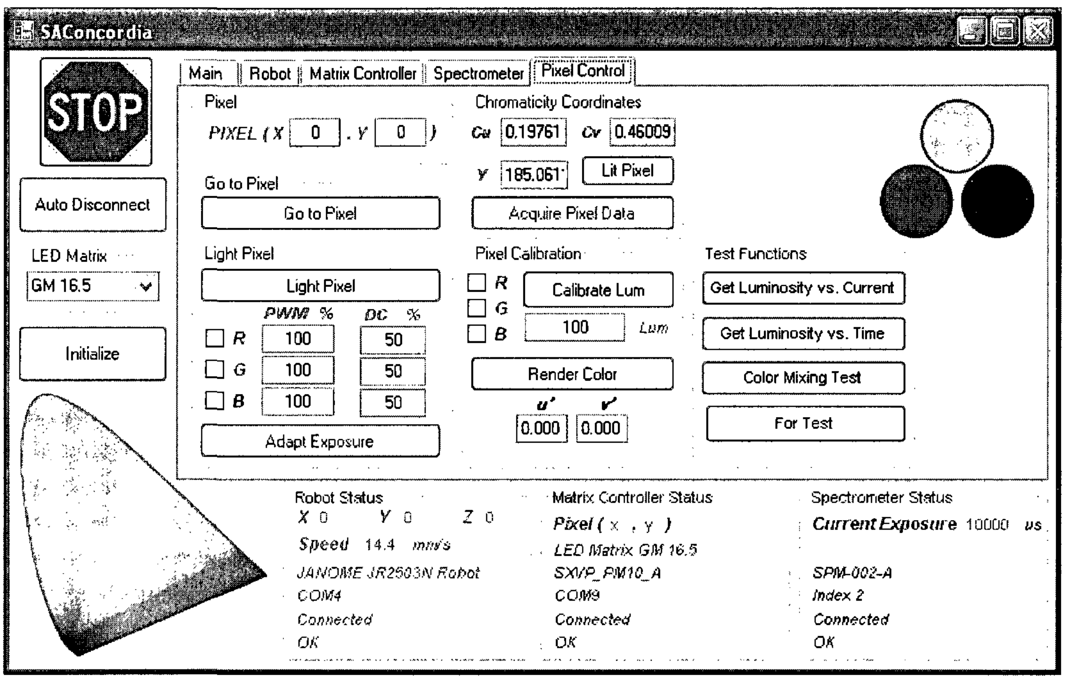


Figure 4.10: Software Pixel Control tab

Several functions were developed and implemented under this tab, such as Adapt exposure function, LED color vs. current test function, LED luminance vs. time and vs. current test functions, and other test functions to check the color mixing behavior and to test the speed of the developed algorithm. The following is a brief description for the Adapt exposure function;

Adapt Exposure function was developed to calibrate the spectrometer CCD exposure time where the light spectral peak fall within certain level, which can be defined by the user, to get accurate color and luminance readings. The function locates and finds the spectral peak through the spectral power data and uses it to adjust the spectrometer exposure time (Fig 4.11). Without setting the right exposure time, the system could have poor readings as the exposure time can be very high where the CCD is going to be over exposed or very low where the CCD is under exposed.

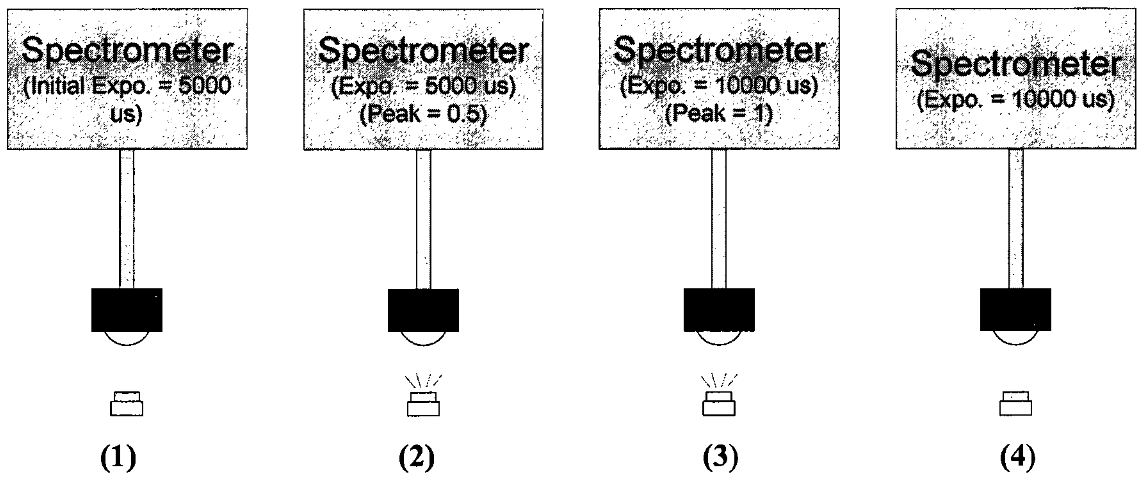


Figure 4.11: Illustrative example for adapting exposure steps

Figure 4.12 shows an illustrative example for the different CCD exposure time.

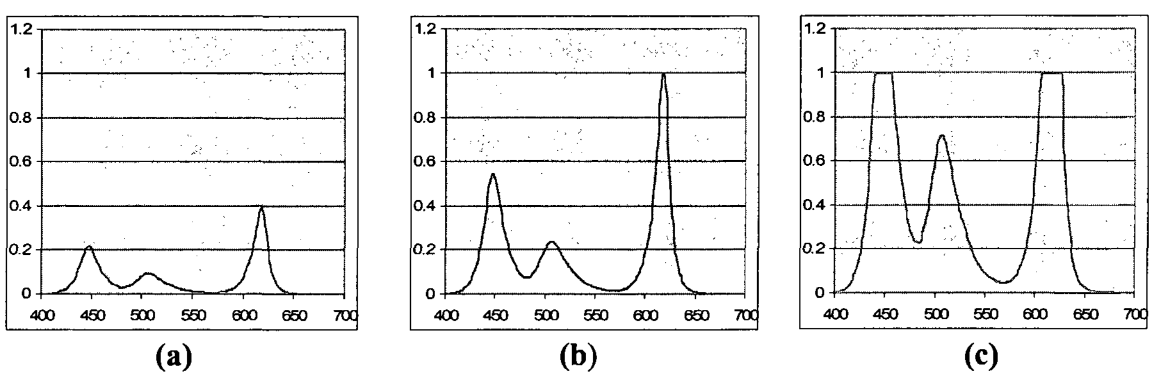


Figure 4.12: CCD different exposure timing;

(a) Low Exposure, (b) good exposure, (c)over exposed

4.3 Color and Luminance Correction and Calibration Process

The proposed color and luminance correction methodology consists of several software and hardware steps. These steps are arranged in the following sequence:

First, system initialization; where the software searches, connects, and resets the system's hardware components. Second, the user has to select the LED Matrix type which allows the software to generate and load the matrix board configurations (size, pitch, memory map, and starting coordinates). Third, the robotic spectrometer head moves over the first pixel (*0, 0*), which will be used as a reference light, to set the spectrometer exposure time using the *Adapt Exposure* function. (Note: we used the first pixel as a reference light for research and development purposes only. The reference light should be a separate unit). Fourth, the software runs the Luminance calibration process where it calibrates the luminance for each LED (Red, Green, and Blue) individually and generates the luminance calibration factors. Fifth, the software runs the color correction algorithm to compute a 3x3 matrix of correction functions for the pixel. Sixth, the system stores the coefficients and factors in the matrix controller. Finally, the robot spectrometer head moves to the next pixel to run the luminance and color correction algorithm again. Figure 4.13 shows a flowchart for the proposed methodology.

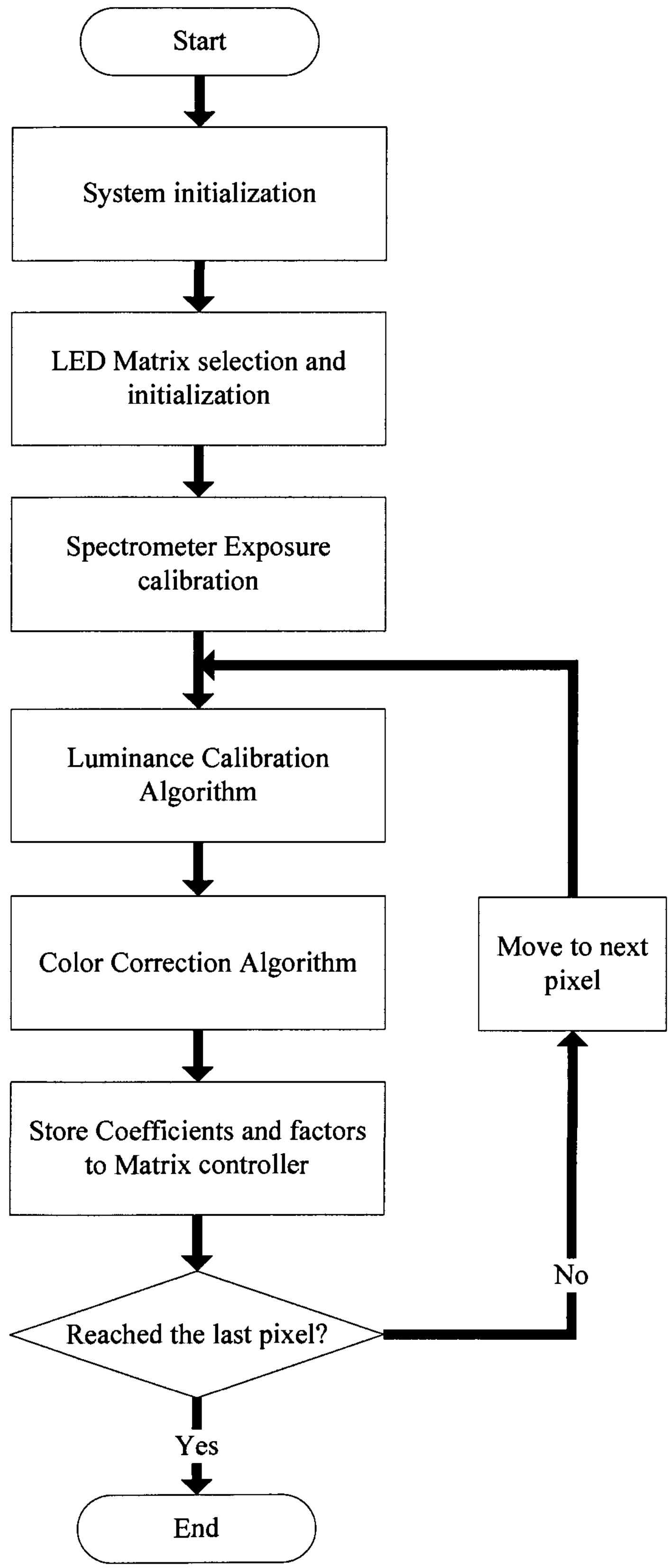


Figure 4.13: Proposed Methodology Flowchart

4.4 Summary

In this chapter, we described in details the developed color and luminance correction and calibration experimental system components, structure, and integration along with the over all specifications and the application software to implement and test our proposed algorithms and technique.

CHAPTER 5

Experimental Results

5.1 Experiments Set Up

The following experiments are designed in order to verify the functionality of the proposed algorithms. A 16x16 / 16.5mm pitch LED matrix board is used; each pixel consists of surface mount device (SMD) RGB LEDs. LEDs are driven by LED drivers with a maximum current set for each color LED in each pixel as the following;

- Red max. current = 40 mA
- Green max. current = 40 mA
- Blue max. current = 40 mA

The default current is set for each color LED in each pixel as the following;

- Red default current = 25%
- Green default current = 29%
- Blue default current = 28%

The spectrometer exposure time was fixed to 200 ms.

Since each board has a large amount of pixels (256 pixels), the experiments will show a sample results of 16 measured, calibrated, and corrected pixels. The experiments will illustrate the results of the following three methodologies;

- RGBW Color and W Brightness

- RGB Color and Brightness
- RGB Brightness

Each experiment will provide a table with the default values for the color coordinates and luminance for each LED in each pixel associated with the calibrated current and luminance values, and the corrected color coordinates and luminance values. The experiments will also provide a table for the correction coefficients associate with the usage efficiency for the calibrated LEDs. The coefficients with the usage efficiency will show the different in the resolution between the different methodologies used for the correction. Several diagrams will be provided as well to show the position of the measured data and the corrected data for each color.

5.2 RGBW Color and W luminance Experiment

For this experiment we had the following target color coordinates and luminance;

White target color coordinates : u' = 0.175, v' = 0.490. Target luminance: 230.

Red target color coordinates : u' = 0.485, v' = 0.500

Green target color coordinates : u' = 0.090, v' = 0.560

Blue target color coordinates : u' = 0.150, v' = 0.250

Table 5.1 shows the results for the default, calibrated, and corrected data. Table 5.2 shows a summary for the minimum, maximum, and average values for each color. Table 5.3 shows the coefficients for each pixel and the used percentage from each calibrated LED. Table 5.4 shows a summary for the maximum, minimum, and average usage efficiency for the proposed methodology.

		Default			Calibrated		Corrected		
Pixel	Color	u'	v'	Y	Current %	Y	u'	v'	Y
0	R	0.516	0.522	60.6	21.1	48.7	0.483	0.501	43.2
	G	0.064	0.576	414.1	8.9	168.5	0.090	0.560	161.6
	B	0.130	0.206	48.5	14.8	20.7	0.154	0.252	22.6
	W	0.128	0.488	525.9			0.173	0.489	229.4
1	R	0.521	0.521	58.0	22.3	56.0	0.482	0.500	47.9
	G	0.066	0.577	395.8	10.3	165.3	0.090	0.560	162.7
	B	0.140	0.183	68.0	9.0	19.9	0.152	0.250	22.2
	W	0.134	0.447	526.6			0.178	0.490	234.1
2	R	0.521	0.522	65.8	19.9	52.9	0.481	0.500	46.8
	G	0.063	0.577	416.7	10.1	169.1	0.090	0.560	161.3
	B	0.150	0.163	44.1	15.8	18.4	0.152	0.250	24.2
	W	0.137	0.471	530.9			0.180	0.490	233.9
3	R	0.522	0.522	59.5	20.7	48.9	0.483	0.499	43.2
	G	0.062	0.576	393.2	10.2	160.3	0.090	0.560	162.4
	B	0.123	0.215	49.7	14.7	26.2	0.151	0.254	24.3
	W	0.128	0.489	508.2			0.174	0.490	231.1
4	R	0.521	0.522	61.6	20.4	49.7	0.480	0.499	44.7
	G	0.063	0.575	382.9	10.3	163.5	0.091	0.559	164.7
	B	0.126	0.211	48.8	14.9	25.2	0.152	0.250	24.1
	W	0.131	0.486	497.7			0.174	0.490	234.9
5	R	0.522	0.522	62.6	20.3	50.8	0.484	0.501	47.4
	G	0.068	0.577	394.9	9.1	167.1	0.089	0.561	160.1
	B	0.130	0.201	55.4	11.1	23.7	0.152	0.249	23.8
	W	0.135	0.475	517.7			0.180	0.495	232.4
6	R	0.522	0.522	69.8	19.1	51.6	0.485	0.502	47.3
	G	0.065	0.576	403.0	10.2	169.7	0.088	0.562	159.9
	B	0.134	0.196	74.7	6.8	22.7	0.152	0.250	22.3
	W	0.138	0.451	553.0			0.180	0.496	232.2

Table 5.1: Default, Calibrated, and Corrected Color coordinates and Luminance [RGBW Color and W Luminance]

		Default			Calibrated		Corrected		
Pixel	**Color**	***u'***	***v'***	**Y**	**Current %**	**Y**	***u'***	***v'***	**Y**
7	**R**	0.521	0.521	64.9	18.8	47.7	0.485	0.501	43.0
	G	0.071	0.576	397.9	9.0	166.7	0.089	0.560	158.9
	B	0.132	0.198	54.7	11.2	23.7	0.151	0.251	24.0
	W	0.138	0.475	522.1			0.177	0.494	233.7
8	**R**	0.522	0.522	63.6	19.3	46.5	0.483	0.500	44.2
	G	0.072	0.573	367.4	10.1	166.2	0.089	0.561	158.9
	B	0.132	0.198	53.6	11.8	23.4	0.150	0.249	24.2
	W	0.142	0.469	489.1			0.176	0.492	230.5
9	**R**	0.520	0.522	62.3	20.3	50.0	0.485	0.502	45.8
	G	0.067	0.574	395.1	8.9	169.8	0.088	0.561	159.9
	B	0.135	0.195	77.4	7.0	23.5	0.151	0.249	23.2
	W	0.135	0.444	540.6			0.178	0.494	231.3
10	**R**	0.521	0.522	64.1	20.4	51.6	0.483	0.501	46.0
	G	0.064	0.575	424.2	8.7	179.7	0.089	0.560	159.4
	B	0.131	0.200	52.5	11.7	22.8	0.151	0.249	23.6
	W	0.130	0.482	544.7			0.178	0.494	231.8
11	**R**	0.521	0.521	63.2	19.0	49.8	0.483	0.501	43.5
	G	0.066	0.576	405.0	9.1	169.2	0.089	0.561	163.2
	B	0.115	0.232	48.2	13.0	23.0	0.150	0.255	22.1
	W	0.130	0.501	521.1			0.173	0.488	230.1
12	**R**	0.521	0.522	64.8	20.2	52.5	0.484	0.501	48.8
	G	0.065	0.574	387.1	9.2	167.4	0.088	0.561	156.5
	B	0.148	0.168	48.5	11.6	22.8	0.151	0.252	24.7
	W	0.140	0.461	505.1			0.182	0.494	231.0
13	**R**	0.519	0.522	61.1	21.7	50.1	0.482	0.503	47.7
	G	0.068	0.577	374.5	9.4	162.9	0.089	0.561	154.8
	B	0.151	0.164	35.7	17.1	22.9	0.154	0.254	23.8
	W	0.141	0.479	474.4			0.182	0.495	228.9

Table 5.1: Default, Calibrated, and Corrected Color coordinates and Luminance [RGBW Color and W Luminance] (Continued)

		Default			Calibrated		Corrected		
Pixel	Color	*u'*	*v'*	Y	Current %	Y	*u'*	*v'*	Y
14	R	0.521	0.522	60.5	19.7	49.4	0.483	0.499	43.1
	G	0.065	0.575	377.9	10.3	168.3	0.088	0.561	161.9
	B	0.116	0.230	47.1	13.7	24.4	0.149	0.256	22.6
	W	0.131	0.497	492.6			0.173	0.488	229.7
15	R	0.522	0.522	62.3	20.2	50.0	0.485	0.502	44.4
	G	0.069	0.573	355.9	10.5	171.0	0.090	0.561	161.7
	B	0.112	0.238	48.0	14.2	24.2	0.152	0.257	22.7
	W	0.137	0.495	471.9			0.175	0.488	229.6

Table 5.1: Default, Calibrated, and Corrected Color coordinates and Luminance [RGBW Color and W Luminance] (Continued)

		Default					Corrected		
	Color	*u'*	*v'*	Y			*u'*	*v'*	Y
Min	R	0.516	0.521	58.0			0.480	0.499	43.0
	G	0.062	0.573	355.9			0.088	0.559	154.8
	B	0.112	0.163	35.7			0.149	0.249	22.1
	W	0.128	0.444	471.9			0.173	0.488	228.9
Max	R	0.522	0.522	69.8			0.485	0.503	48.8
	G	0.072	0.577	424.2			0.091	0.562	164.7
	B	0.151	0.238	77.4			0.154	0.257	24.7
	W	0.142	0.501	553.0			0.182	0.496	234.9
Avg	R	0.521	0.522	62.8			0.484	0.501	45.4
	G	0.066	0.575	392.9			0.089	0.561	160.5
	B	0.132	0.200	53.4			0.151	0.252	23.4
	W	0.135	0.476	513.8			0.177	0.492	231.5

Table 5.2: Minimum, Maximum, and Average Color coordinates and Luminance [RGBW Color and W Luminance]

Pixel	Coefficients						Usage %
0	**RR**	**0.825**	**RG**	0.081	**RB**	0.077	98.2
	GR	0.011	**GG**	**0.922**	**GB**	0.012	94.5
	BR	0.061	**BG**	0.107	**BB**	**0.811**	97.9
1	**RR**	**0.817**	**RG**	0.062	**RB**	0.061	93.9
	GR	0.009	**GG**	**0.950**	**GB**	0.022	98.1
	BR	0.031	**BG**	0.110	**BB**	**0.763**	90.5
2	**RR**	**0.836**	**RG**	0.074	**RB**	0.051	96.1
	GR	0.010	**GG**	**0.921**	**GB**	0.039	97.1
	BR	0.044	**BG**	0.084	**BB**	**0.809**	93.7
3	**RR**	**0.811**	**RG**	0.100	**RB**	0.078	99.0
	GR	0.012	**GG**	**0.961**	**GB**	0.002	97.6
	BR	0.060	**BG**	0.127	**BB**	**0.766**	95.3
4	**RR**	**0.832**	**RG**	0.066	**RB**	0.073	97.0
	GR	0.011	**GG**	**0.968**	**GB**	0.009	98.8
	BR	0.062	**BG**	0.127	**BB**	**0.753**	94.2
5	**RR**	**0.856**	**RG**	0.060	**RB**	0.070	98.6
	GR	0.014	**GG**	**0.922**	**GB**	0.014	95.0
	BR	0.062	**BG**	0.126	**BB**	**0.756**	94.4
6	**RR**	**0.847**	**RG**	0.076	**RB**	0.067	99.0
	GR	0.013	**GG**	**0.902**	**GB**	0.006	92.1
	BR	0.064	**BG**	0.131	**BB**	**0.784**	98.0

Table 5.3: Coefficients and usage efficiency [RGBW Color and W Luminance]

Pixel	Coefficients						Usage %
7	**RR**	**0.876**	**RG**	0.039	**RB**	0.072	98.8
	GR	0.014	**GG**	**0.934**	**GB**	0.016	96.4
	BR	0.058	**BG**	0.121	**BB**	**0.754**	93.4
8	**RR**	**0.868**	**RG**	0.041	**RB**	0.064	97.4
	GR	0.014	**GG**	**0.929**	**GB**	0.017	96.0
	BR	0.062	**BG**	0.105	**BB**	**0.788**	95.5
9	**RR**	**0.844**	**RG**	0.066	**RB**	0.070	98.0
	GR	0.012	**GG**	**0.904**	**GB**	0.006	92.2
	BR	0.070	**BG**	0.133	**BB**	**0.795**	99.9
10	**RR**	**0.821**	**RG**	0.089	**RB**	0.061	97.0
	GR	0.012	**GG**	**0.847**	**GB**	0.013	87.3
	BR	0.063	**BG**	0.112	**BB**	**0.794**	96.8
11	**RR**	**0.816**	**RG**	0.075	**RB**	0.089	98.0
	GR	0.009	**GG**	**0.922**	**GB**	0.001	93.2
	BR	0.063	**BG**	0.148	**BB**	**0.760**	97.0
12	**RR**	**0.856**	**RG**	0.080	**RB**	0.044	98.0
	GR	0.016	**GG**	**0.898**	**GB**	0.032	94.6
	BR	0.055	**BG**	0.084	**BB**	**0.750**	88.9
13	**RR**	**0.872**	**RG**	0.037	**RB**	0.033	94.3
	GR	0.018	**GG**	**0.925**	**GB**	0.031	97.4
	BR	0.052	**BG**	0.095	**BB**	**0.747**	89.4

Table 5.3: Coefficients and usage efficiency
[RGBW Color and W Luminance] (Continued)

Pixel	Coefficients						Usage %
14	**RR**	**0.805**	**RG**	0.087	**RB**	0.091	98.2
	GR	0.009	**GG**	**0.915**	**GB**	0.000	92.5
	BR	0.073	**BG**	0.146	**BB**	**0.745**	96.4
15	**RR**	**0.819**	**RG**	0.073	**RB**	0.088	98.0
	GR	0.009	**GG**	**0.904**	**GB**	0.000	91.4
	BR	0.076	**BG**	0.141	**BB**	**0.756**	97.3

Table 5.3: Coefficients and usage efficiency

[RGBW Color and W Luminance] (Continued)

	Coefficients		Usage %
Min	**R**		93.9
	G		87.3
	B		88.9
Max	**R**		99.0
	G		98.8
	B		99.9
Avg	**R**		97.5
	G		94.6
	B		94.9

Table 5.4: Usage efficiency summary [RGBW Color and W Luminance]

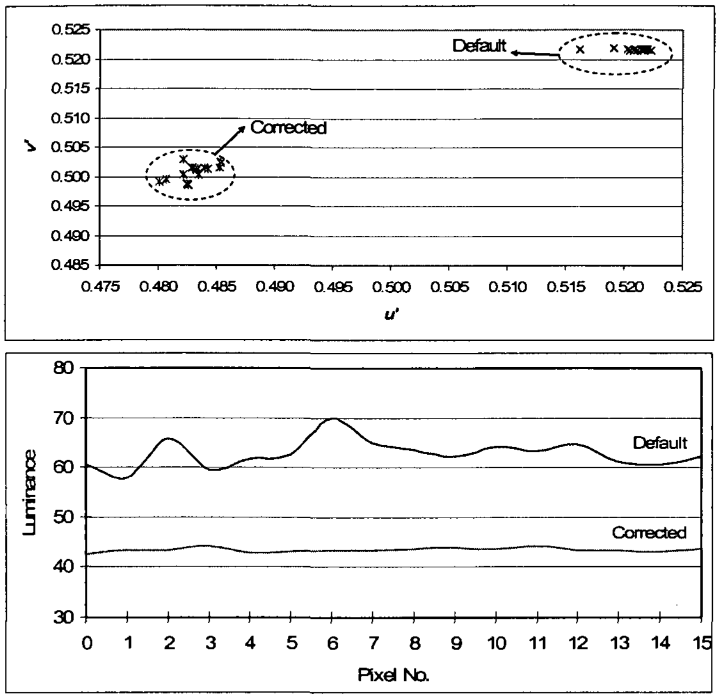


Figure 5.1: Red Corrected and Default Color & Luminance Parameters Chart [RGBW Color and W luminance methodology]

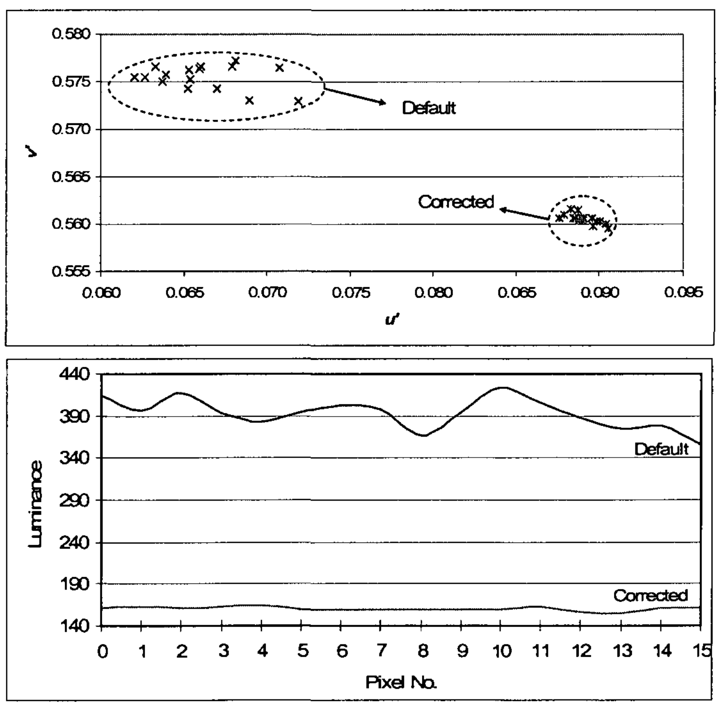


Figure 5.2: Green Corrected and Default Color & Luminance Parameters Chart [RGBW Color and W luminance methodology]

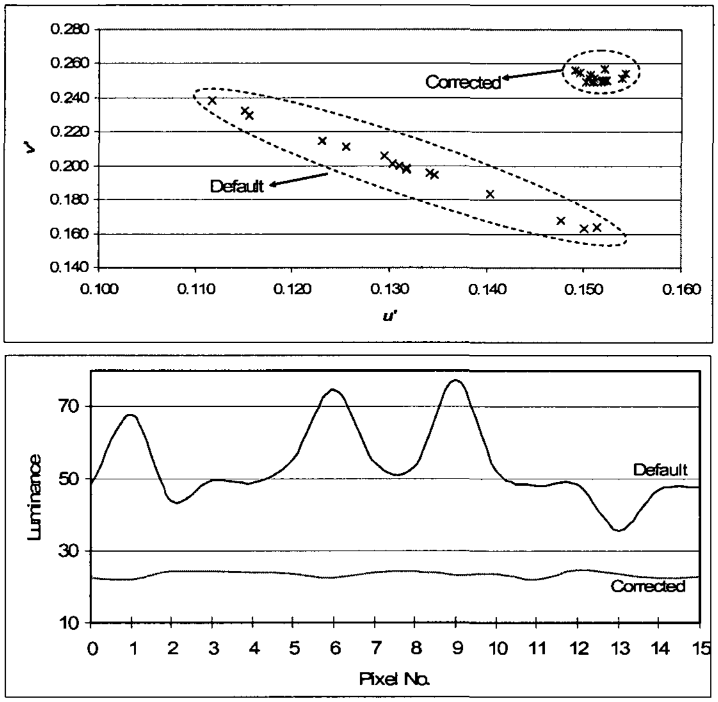


Figure 5.3: Blue Corrected and Default Color & Luminance Parameters Chart [RGBW Color and W luminance methodology]

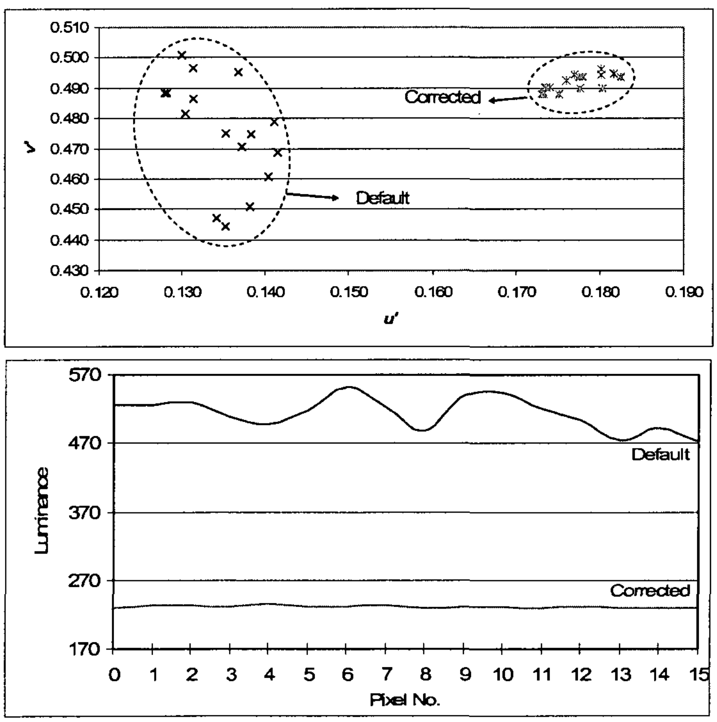


Figure 5.4: White Corrected and Default Color & Luminance Parameters Chart [RGBW Color and W luminance methodology]

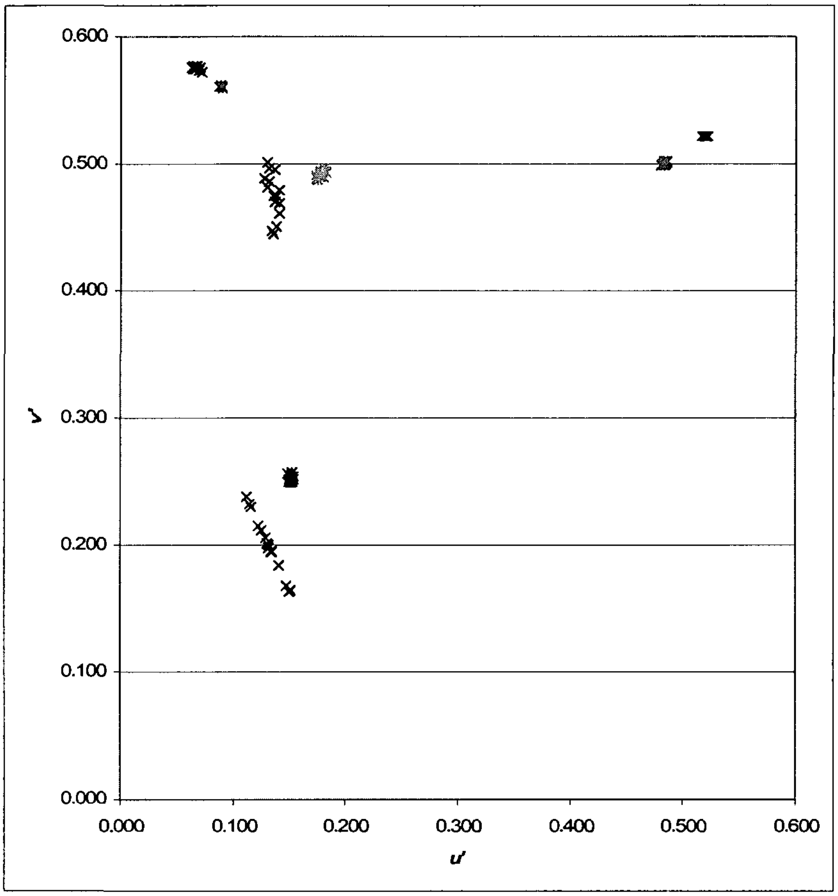


Figure 5.5: Red, Green, Blue and White Corrected and Default Color Coordinates Chart [RGBW Color and W luminance methodology]

Figure 5.1 shows the Red corrected and default color and luminance parameters chart. Figure 5.2 shows the Green corrected and default color and luminance parameters chart. Figure 5.3 shows the Blue corrected and default color and luminance parameters chart. Figure 5.4 shows the White corrected and default color and luminance parameters chart. Figure 5.5 shows zoomed out view for the Pixel corrected and default color coordinates chart.

5.3 RGB Color and Luminance Experiment

For this experiment we had the following target color coordinates and luminance;

Red target color coordinates : u' = 0.480, v' = 0.500 target luminance: 43.

Green target color coordinates : u' = 0.090, v' = 0.560 target luminance: 160.

Blue target color coordinates : u' = 0.150, v' = 0.250 target luminance: 16.

Table 5.5 shows the results for the default, calibrated, and corrected data. Table 5.6 shows a summary for the minimum, maximum, and average values for each color. Table 5.7 shows the coefficients for each pixel and the used percentage from each calibrated LED. Table 5.8 shows a summary for the maximum, minimum, and average usage efficiency for the proposed methodology.

Figure 5.6 shows the corrected and default Red color and luminance parameters chart. Figure 5.7 shows the corrected and default Green color and luminance parameters chart. Figure 5.8 shows the corrected and default Blue color and luminance parameters chart. Figure 5.9 shows the resulted corrected and default White color and luminance parameters chart. Figure 5.10 shows zoomed out view for the Pixel corrected and default color coordinates chart.

		Default			Calibrated		Corrected		
Pixel	Color	*u'*	*v'*	Y	Current %	Y	*u'*	*v'*	Y
0	R	0.516	0.522	60.6	21.0	48.9	0.482	0.501	42.5
	G	0.064	0.576	414.1	9.2	172.0	0.089	0.561	159.4
	B	0.130	0.206	48.5	14.2	20.5	0.150	0.253	16.1
	W	0.128	0.488	525.9			0.172	0.497	220.6
1	R	0.521	0.521	58.0	21.6	50.2	0.481	0.500	43.5
	G	0.066	0.577	395.8	10.2	162.0	0.090	0.560	159.8
	B	0.140	0.183	68.0	10.2	22.0	0.150	0.249	15.8
	W	0.134	0.447	526.6			0.174	0.497	224.4
2	R	0.521	0.522	65.8	18.6	48.0	0.481	0.499	43.5
	G	0.063	0.577	416.7	9.8	167.5	0.090	0.561	159.6
	B	0.150	0.163	44.1	16.5	21.6	0.152	0.250	16.0
	W	0.137	0.471	530.9			0.175	0.497	225.1
3	R	0.522	0.522	59.5	21.6	51.5	0.478	0.499	44.3
	G	0.062	0.576	393.2	12.4	176.6	0.089	0.560	158.9
	B	0.123	0.215	49.7	11.1	20.4	0.149	0.256	15.9
	W	0.128	0.489	508.2			0.173	0.499	222.8
4	R	0.521	0.522	61.6	20.8	49.2	0.477	0.499	42.9
	G	0.063	0.575	382.9	11.2	169.5	0.090	0.560	159.9
	B	0.126	0.211	48.8	11.4	20.1	0.149	0.249	15.2
	W	0.131	0.486	497.7			0.172	0.498	221.5
5	R	0.522	0.522	62.6	20.5	49.6	0.483	0.500	43.2
	G	0.068	0.577	394.9	10.6	171.5	0.089	0.560	158.7
	B	0.130	0.201	55.4	10.8	21.5	0.149	0.248	15.6
	W	0.135	0.475	517.7			0.173	0.497	222.4
6	R	0.522	0.522	69.8	18.9	50.2	0.481	0.499	43.4
	G	0.065	0.576	403.0	10.1	167.3	0.089	0.560	158.9
	B	0.134	0.196	74.7	6.7	20.1	0.148	0.250	15.9
	W	0.138	0.451	553.0			0.173	0.497	222.9

Table 5.5: Default, Calibrated, and Corrected Color coordinates and Luminance [RGB Color and Luminance]

		Default			Calibrated		Corrected		
Pixel	Color	u'	v'	Y	Current %	Y	u'	v'	Y
7	R	0.521	0.521	64.9	19.1	50.7	0.480	0.499	43.5
	G	0.071	0.576	397.9	9.3	166.7	0.090	0.560	159.7
	B	0.132	0.198	54.7	10.1	20.3	0.150	0.252	16.1
	W	0.138	0.475	522.1			0.173	0.497	222.6
8	R	0.522	0.522	63.6	20.0	50.9	0.479	0.499	43.7
	G	0.072	0.573	367.4	11.1	170.6	0.089	0.560	159.1
	B	0.132	0.198	53.6	9.5	19.0	0.149	0.250	15.9
	W	0.142	0.469	489.1			0.173	0.497	223.0
9	R	0.520	0.522	62.3	20.0	51.0	0.478	0.499	44.0
	G	0.067	0.574	395.1	8.2	166.6	0.090	0.560	159.8
	B	0.135	0.195	77.4	6.1	19.7	0.149	0.251	16.2
	W	0.135	0.444	540.6			0.174	0.497	224.0
10	R	0.521	0.522	64.1	20.2	50.0	0.480	0.499	43.7
	G	0.064	0.575	424.2	8.2	173.8	0.089	0.561	159.0
	B	0.131	0.200	52.5	10.3	19.4	0.149	0.251	16.2
	W	0.130	0.482	544.7			0.173	0.497	222.7
11	R	0.521	0.521	63.2	19.4	49.4	0.477	0.499	44.1
	G	0.066	0.576	405.0	9.0	169.3	0.089	0.561	159.2
	B	0.115	0.232	48.2	11.1	20.8	0.150	0.256	16.7
	W	0.130	0.501	521.1			0.173	0.497	223.1
12	R	0.521	0.522	64.8	20.2	50.4	0.480	0.499	43.5
	G	0.065	0.574	387.1	9.2	168.0	0.089	0.560	159.1
	B	0.148	0.168	48.5	9.2	18.7	0.148	0.252	16.3
	W	0.140	0.461	505.1			0.173	0.497	223.3
13	R	0.519	0.522	61.1	20.5	49.6	0.478	0.498	43.4
	G	0.068	0.577	374.5	10.3	166.2	0.090	0.559	160.0
	B	0.151	0.164	35.7	17.2	22.1	0.149	0.256	16.5
	W	0.141	0.479	474.4			0.171	0.503	222.6

Table 5.5: Default, Calibrated, and Corrected Color coordinates and Luminance [RGB Color and Luminance] (Continued)

		Default			Calibrated		Corrected		
Pixel	Color	*u'*	*v'*	Y	Current %	Y	*u'*	*v'*	Y
14	R	0.521	0.522	60.5	20.0	51.6	0.483	0.500	43.1
	G	0.065	0.575	377.9	10.3	167.2	0.089	0.561	159.1
	B	0.116	0.230	47.1	9.9	19.3	0.152	0.248	15.8
	W	0.131	0.497	492.6			0.174	0.497	222.6
15	R	0.522	0.522	62.3	19.9	51.0	0.479	0.500	43.7
	G	0.069	0.573	355.9	10.9	170.0	0.090	0.560	159.9
	B	0.112	0.238	48.0	11.7	20.0	0.152	0.256	17.0
	W	0.137	0.495	471.9			0.173	0.497	221.6

Table 5.5: Default, Calibrated, and Corrected Color coordinates and Luminance [RGB Color and Luminance] (Continued)

		Default					Corrected		
	Color	*u'*	*v'*	Y			*u'*	*v'*	Y
Min	R	0.516	0.521	58.0			0.477	0.498	42.5
	G	0.062	0.573	355.9			0.089	0.559	158.7
	B	0.112	0.163	35.7			0.148	0.248	15.2
	W	0.128	0.444	471.9			0.171	0.497	220.6
Max	R	0.522	0.522	69.8			0.483	0.501	44.3
	G	0.072	0.577	424.2			0.090	0.561	160.0
	B	0.151	0.238	77.4			0.152	0.256	17.0
	W	0.142	0.501	553.0			0.175	0.503	225.1
Avg	R	0.521	0.522	62.8			0.480	0.499	43.5
	G	0.066	0.575	392.9			0.089	0.560	159.4
	B	0.132	0.200	53.4			0.150	0.252	16.1
	W	0.135	0.476	513.8			0.173	0.498	222.8

Table 5.6: Minimum, Maximum, and Average Color coordinates and Luminance [RGB Color and Luminance]

Pixel	Coefficients						Usage %
0	**RR**	**0.846**	**RG**	0.085	**RB**	0.015	94.5
	GR	0.009	**GG**	**0.838**	**GB**	0.005	85.2
	BR	0.079	**BG**	0.159	**BB**	**0.759**	99.7
1	**RR**	**0.818**	**RG**	0.076	**RB**	0.015	90.9
	GR	0.015	**GG**	**0.945**	**GB**	0.019	97.9
	BR	0.067	**BG**	0.138	**BB**	**0.625**	83.0
2	**RR**	**0.854**	**RG**	0.092	**RB**	0.015	96.1
	GR	0.017	**GG**	**0.915**	**GB**	0.045	97.7
	BR	0.051	**BG**	0.103	**BB**	**0.474**	62.8
3	**RR**	**0.806**	**RG**	0.117	**RB**	0.015	93.9
	GR	0.011	**GG**	**0.809**	**GB**	0.001	82.1
	BR	0.074	**BG**	0.139	**BB**	**0.767**	98.0
4	**RR**	**0.818**	**RG**	0.108	**RB**	0.015	94.1
	GR	0.013	**GG**	**0.949**	**GB**	0.003	96.5
	BR	0.073	**BG**	0.142	**BB**	**0.765**	98.0
5	**RR**	**0.833**	**RG**	0.079	**RB**	0.015	92.7
	GR	0.013	**GG**	**0.863**	**GB**	0.013	88.8
	BR	0.069	**BG**	0.135	**BB**	**0.667**	87.1
6	**RR**	**0.820**	**RG**	0.083	**RB**	0.015	91.8
	GR	0.012	**GG**	**0.816**	**GB**	0.011	83.9
	BR	0.077	**BG**	0.149	**BB**	**0.724**	95.0

Table 5.7: Coefficients and Usage efficiency [RGB Color and Luminance]

Pixel	Coefficients						Usage %
7	**RR**	**0.812**	**RG**	0.085	**RB**	0.015	91.2
	GR	0.013	**GG**	**0.915**	**GB**	0.006	93.5
	BR	0.078	**BG**	0.155	**BB**	**0.754**	98.6
8	**RR**	**0.806**	**RG**	0.080	**RB**	0.015	90.2
	GR	0.014	**GG**	**0.897**	**GB**	0.014	92.5
	BR	0.080	**BG**	0.155	**BB**	**0.751**	98.6
9	**RR**	**0.805**	**RG**	0.048	**RB**	0.015	86.8
	GR	0.015	**GG**	**0.945**	**GB**	0.015	97.5
	BR	0.077	**BG**	0.151	**BB**	**0.722**	95.0
10	**RR**	**0.821**	**RG**	0.052	**RB**	0.015	88.8
	GR	0.015	**GG**	**0.945**	**GB**	0.015	97.5
	BR	0.078	**BG**	0.130	**BB**	**0.732**	94.0
11	**RR**	**0.835**	**RG**	0.084	**RB**	0.015	93.4
	GR	0.013	**GG**	**0.914**	**GB**	0.007	93.5
	BR	0.077	**BG**	0.138	**BB**	**0.726**	94.1
12	**RR**	**0.815**	**RG**	0.117	**RB**	0.015	94.7
	GR	0.013	**GG**	**0.856**	**GB**	0.013	88.3
	BR	0.081	**BG**	0.137	**BB**	**0.760**	97.8
13	**RR**	**0.826**	**RG**	0.088	**RB**	0.015	92.9
	GR	0.010	**GG**	**0.913**	**GB**	0.001	92.4
	BR	0.083	**BG**	0.170	**BB**	**0.727**	98.0

Table 5.7: Coefficients and Usage efficiency [RGB Color and Luminance] (Continued)

Pixel	Coefficients						Usage %
14	**RR**	**0.799**	**RG**	0.101	**RB**	0.015	91.6
	GR	0.015	**GG**	**0.925**	**GB**	0.034	97.4
	BR	0.062	**BG**	0.104	**BB**	**0.603**	76.9
15	**RR**	**0.815**	**RG**	0.067	**RB**	0.015	89.7
	GR	0.011	**GG**	**0.905**	**GB**	0.012	92.8
	BR	0.076	**BG**	0.134	**BB**	**0.739**	94.9

Table 5.7: Coefficients and Usage efficiency
[RGB Color and Luminance] (Continued)

	Coefficients		Usage %
Min	**R**		86.8
	G		82.1
	B		62.8
Max	**R**		96.1
	G		97.9
	B		99.7
Avg	**R**		92.1
	G		92.3
	B		92.0

Table 5.8: Usage efficiency summary [RGB Color and Luminance]

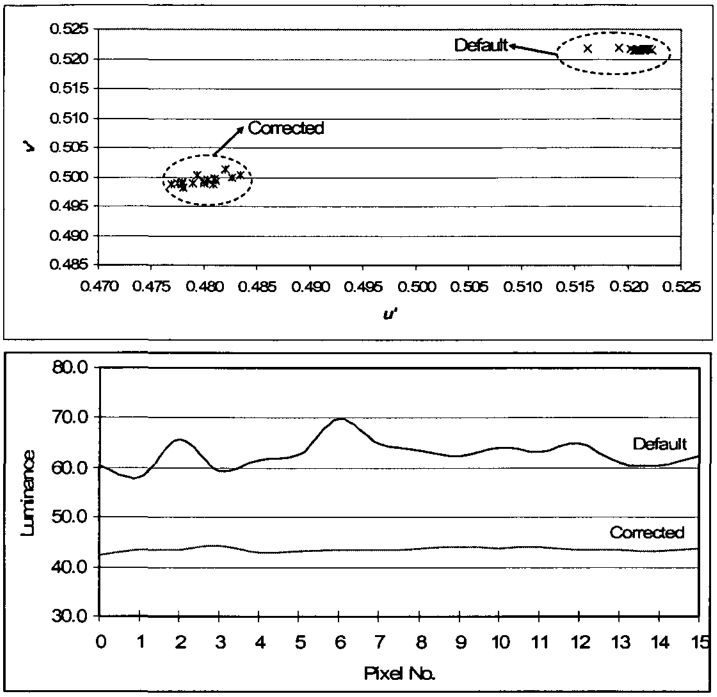


Figure 5.6: Red Corrected and Default Color & Luminance Parameters Chart [RGB Color and Luminance methodology]

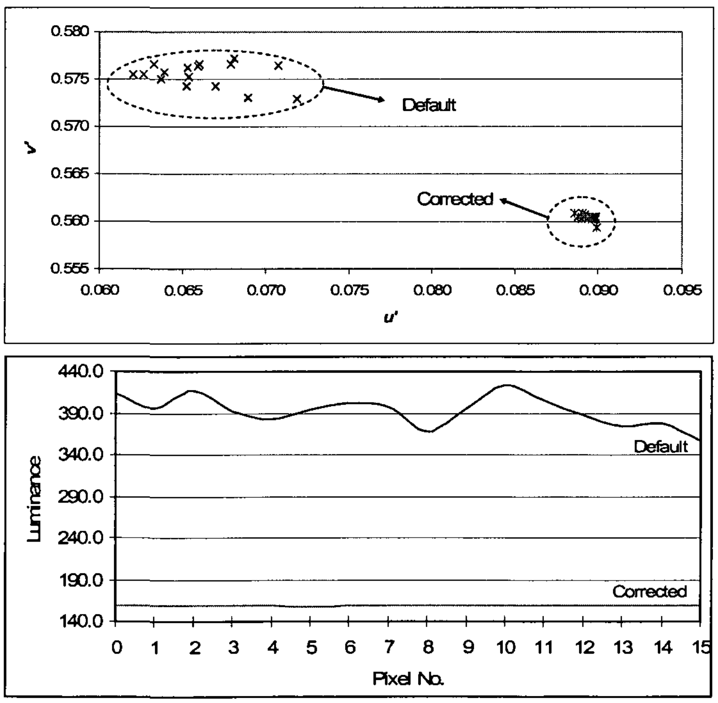


Figure 5.7: Green Corrected and Default Color & Luminance Parameters Chart [RGB Color and Luminance methodology]

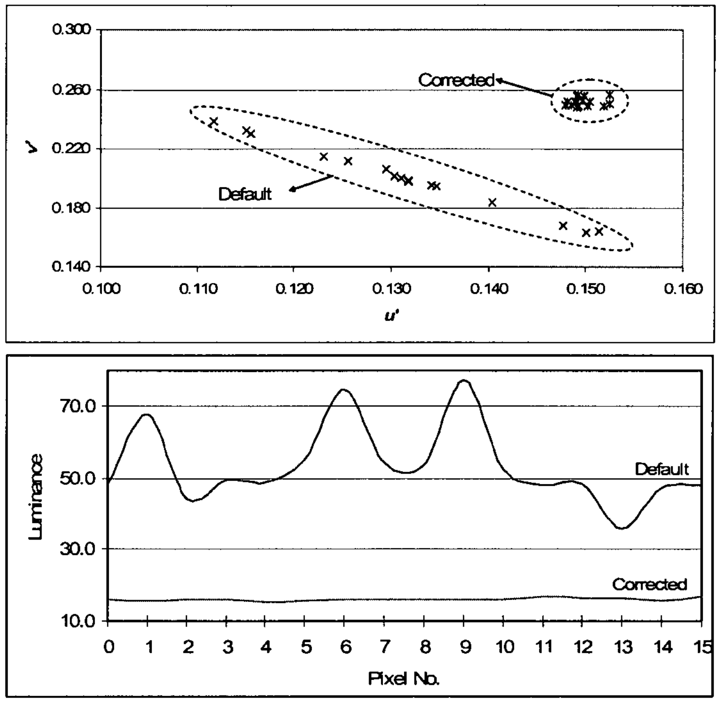


Figure 5.8: Blue Corrected and Default Color & Luminance Parameters Chart [RGB Color and Luminance methodology]

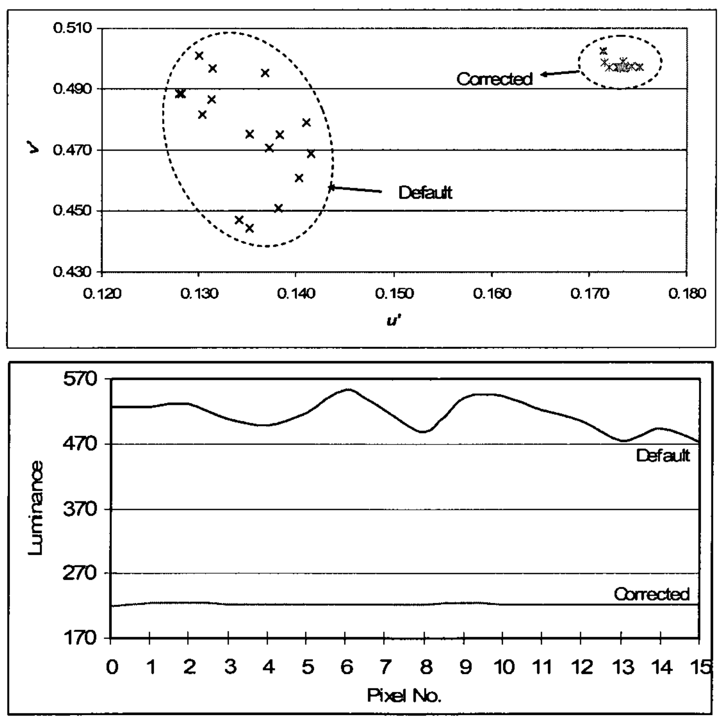


Figure 5.9: White Corrected and Default Color & Luminance Parameters Chart [RGB Color and Luminance methodology]

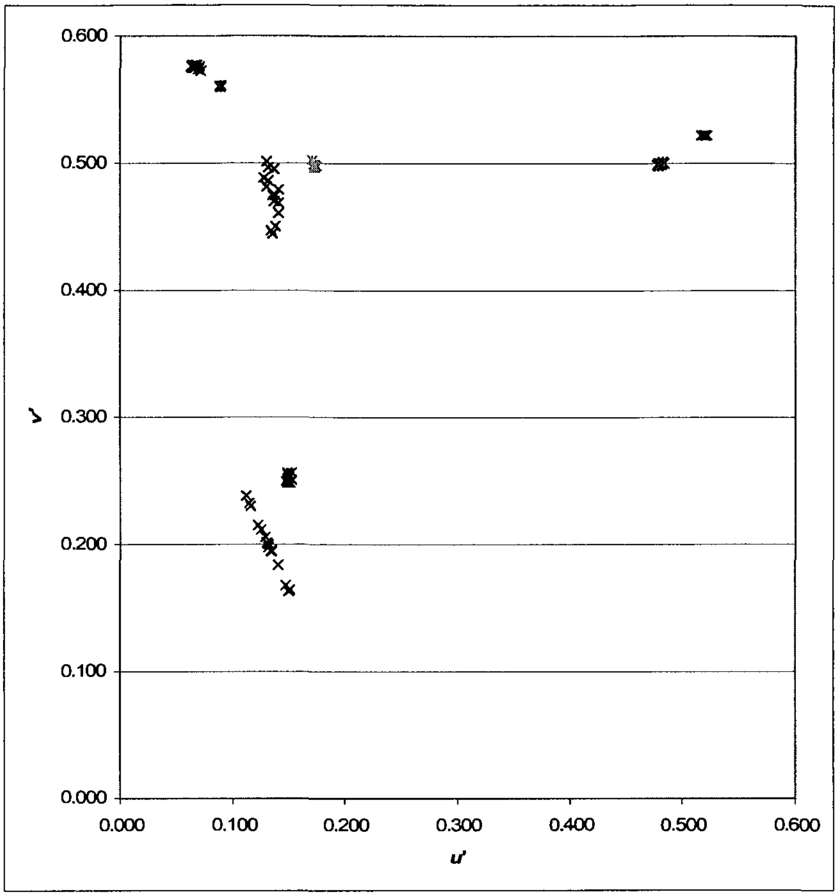


Figure 5.10: Red, Green, Blue and White Corrected and Default Color Coordinates Chart [RGB Color and Luminance methodology]

5.4 RGB Luminance Experiment

For this experiment we had the following target luminance;

Red target luminance	: 45 nits
Green target luminance	: 160 nits
Blue target luminance	: 20 nits

Table 5.9 shows the results for the default and calibrated data. Table 5.10 shows a summary for the minimum, maximum, and average values for each color. Since this methodology doesn't correct the colors, the coefficients will be as the following for all the pixels:

$K_{RR} = 1 \quad K_{RG} = 0 \quad K_{RB} = 0$

$K_{GR} = 0 \quad K_{GG} = 1 \quad K_{GB} = 0$

$K_{BR} = 0 \quad K_{BG} = 0 \quad K_{BB} = 1$

Figure 5.11 shows the calibrated and default Red color and luminance parameters chart. Figure 5.12 shows the calibrated and default Green color and luminance parameters chart. Figure 5.13 shows the calibrated and default Blue color and luminance parameters chart. Figure 5.14 shows the resulted calibrated and default White color and luminance parameters chart. Figure 5.15 shows zoomed out view for the Pixel calibrated and default color coordinates chart.

		Default			Calibrated		
Pixel	**Color**	*u'*	*v'*	**Y**	*u'*	*v'*	**Y**
0	**R**	0.516	0.522	60.6	0.519	0.522	44.1
	G	0.064	0.576	414.1	0.077	0.580	157.6
	B	0.130	0.206	48.5	0.121	0.220	20.8
	W	0.128	0.488	525.9	0.170	0.497	223.2
1	**R**	0.521	0.521	58.0	0.522	0.522	46.1
	G	0.066	0.577	395.8	0.076	0.580	162.1
	B	0.140	0.183	68.0	0.126	0.209	21.0
	W	0.134	0.447	526.6	0.172	0.488	230.9
2	**R**	0.521	0.522	65.8	0.522	0.522	43.9
	G	0.063	0.577	416.7	0.075	0.580	157.2
	B	0.150	0.163	44.1	0.145	0.170	19.7
	W	0.137	0.471	530.9	0.179	0.466	224.0
3	**R**	0.522	0.522	59.5	0.522	0.522	44.5
	G	0.062	0.576	393.2	0.072	0.579	158.4
	B	0.123	0.215	49.7	0.115	0.230	19.7
	W	0.128	0.489	508.2	0.173	0.495	223.3
4	**R**	0.521	0.522	61.6	0.522	0.522	44.9
	G	0.063	0.575	382.9	0.071	0.579	159.2
	B	0.126	0.211	48.8	0.117	0.224	19.1
	W	0.131	0.486	497.7	0.168	0.500	225.5
5	**R**	0.522	0.522	62.6	0.522	0.522	45.0
	G	0.068	0.577	394.9	0.076	0.579	159.6
	B	0.130	0.201	55.4	0.124	0.211	20.6
	W	0.135	0.475	517.7	0.173	0.489	226.5
6	**R**	0.522	0.522	69.8	0.522	0.522	45.6
	G	0.065	0.576	403.0	0.078	0.580	158.6
	B	0.134	0.196	74.7	0.123	0.214	19.5
	W	0.138	0.451	553.0	0.181	0.489	224.1

Table 5.9: Default and Calibrated Color Coordinates and Luminance [RGB Luminance]

		Default			Calibrated		
Pixel	**Color**	***u'***	***v'***	**Y**	***u'***	***v'***	**Y**
7	**R**	0.521	0.521	64.9	0.523	0.521	45.9
	G	0.071	0.576	397.9	0.074	0.579	163.3
	B	0.132	0.198	54.7	0.119	0.222	19.8
	W	0.138	0.475	522.1	0.169	0.500	230.9
8	**R**	0.522	0.522	63.6	0.523	0.521	45.5
	G	0.072	0.573	367.4	0.075	0.579	163.1
	B	0.132	0.198	53.6	0.124	0.213	19.7
	W	0.142	0.469	489.1	0.170	0.500	229.3
9	**R**	0.520	0.522	62.3	0.523	0.522	45.5
	G	0.067	0.574	395.1	0.082	0.578	159.5
	B	0.135	0.195	77.4	0.124	0.211	19.2
	W	0.135	0.444	540.6	0.185	0.488	225.1
10	**R**	0.521	0.522	64.1	0.523	0.522	45.8
	G	0.064	0.575	424.2	0.079	0.577	162.3
	B	0.131	0.200	52.5	0.124	0.210	19.6
	W	0.130	0.482	544.7	0.174	0.495	230.5
11	**R**	0.521	0.521	63.2	0.521	0.522	45.2
	G	0.066	0.576	405.0	0.075	0.578	161.3
	B	0.115	0.232	48.2	0.119	0.221	20.3
	W	0.130	0.501	521.1	0.167	0.497	230.7
12	**R**	0.521	0.522	64.8	0.522	0.522	46.2
	G	0.065	0.574	387.1	0.069	0.578	162.2
	B	0.148	0.168	48.5	0.123	0.212	19.2
	W	0.140	0.461	505.1	0.164	0.502	229.0
13	**R**	0.519	0.522	61.1	0.522	0.522	45.4
	G	0.068	0.577	374.5	0.075	0.579	162.7
	B	0.151	0.164	35.7	0.106	0.250	19.1
	W	0.141	0.479	474.4	0.168	0.513	228.1

Table 5.9: Default and Calibrated Color Coordinates and Luminance [RGB Luminance] (Continued)

		Default			Calibrated		
Pixel	**Color**	***u'***	***v'***	**Y**	***u'***	***v'***	**Y**
14	**R**	0.521	0.522	60.5	0.522	0.522	46.1
	G	0.065	0.575	377.9	0.070	0.577	162.6
	B	0.116	0.230	47.1	0.138	0.184	19.5
	W	0.131	0.497	492.6	0.171	0.483	231.9
15	**R**	0.522	0.522	62.3	0.519	0.522	45.7
	G	0.069	0.573	355.9	0.079	0.577	160.6
	B	0.112	0.238	48.0	0.125	0.212	19.8
	W	0.137	0.495	471.9	0.178	0.492	228.3

Table 5.9: Default and Calibrated Color Coordinates and Luminance [RGB Luminance] (Continued)

		Default			Calibrated		
	Color	***u'***	***v'***	**Y**	***u'***	***v'***	**Y**
Min	**R**	0.516	0.521	58.0	0.519	0.521	43.9
	G	0.062	0.573	355.9	0.069	0.577	157.2
	B	0.112	0.163	35.7	0.106	0.170	19.1
	W	0.128	0.444	471.9	0.164	0.466	223.2
Max	**R**	0.522	0.522	69.8	0.523	0.522	46.2
	G	0.072	0.577	424.2	0.082	0.580	163.3
	B	0.151	0.238	77.4	0.145	0.250	21.0
	W	0.142	0.501	553.0	0.185	0.513	231.9
Avg	**R**	0.521	0.522	62.8	0.522	0.522	45.3
	G	0.066	0.575	392.9	0.075	0.579	160.6
	B	0.132	0.200	53.4	0.123	0.213	19.8
	W	0.135	0.476	513.8	0.173	0.493	227.6

Table 5.10: Minimum, Maximum, and Average Color Coordinates and Luminance [RGB Luminance]

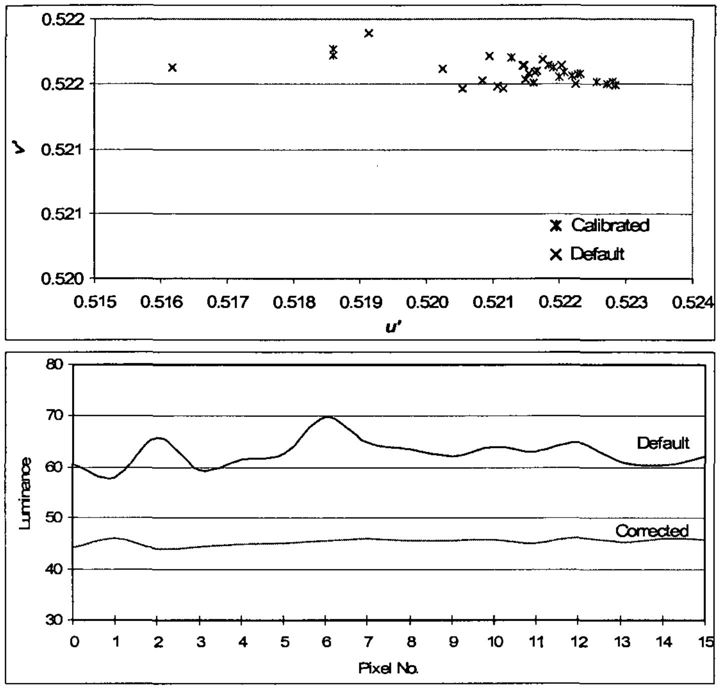


Figure 5.11: Red Calibrated and Default Color & Luminance Parameters Chart [RGB Luminance methodology]

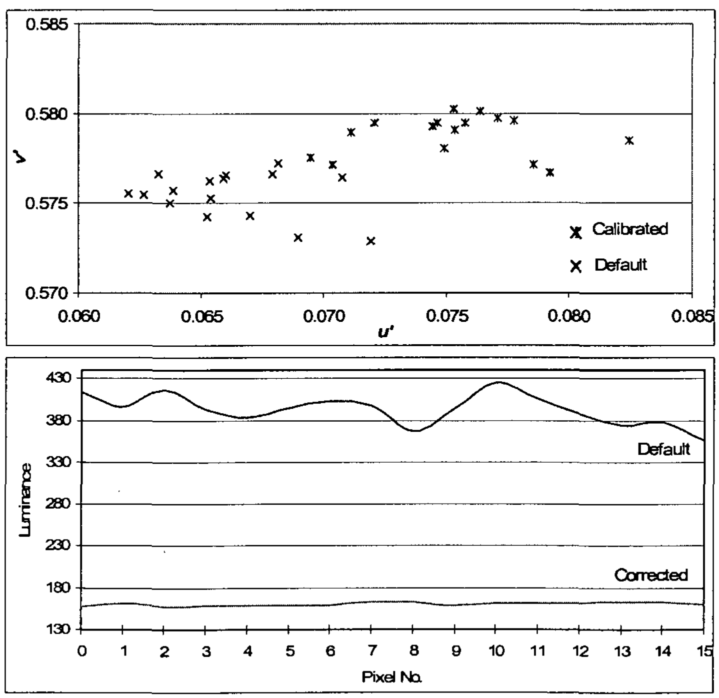


Figure 5.12: Green Calibrated and Default Color & Luminance Parameters Chart [RGB Luminance methodology]

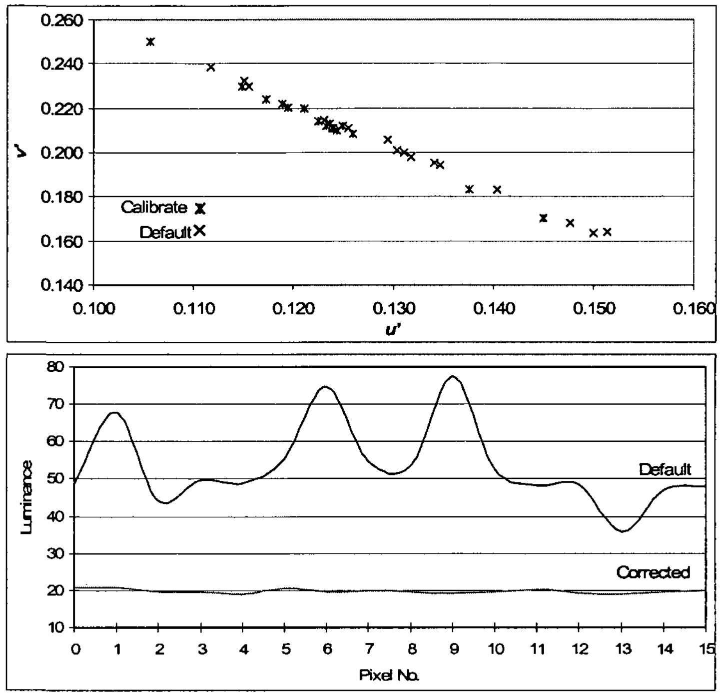


Figure 5.13: Blue Calibrated and Default Color & Luminance Parameters Chart [RGB Luminance methodology]

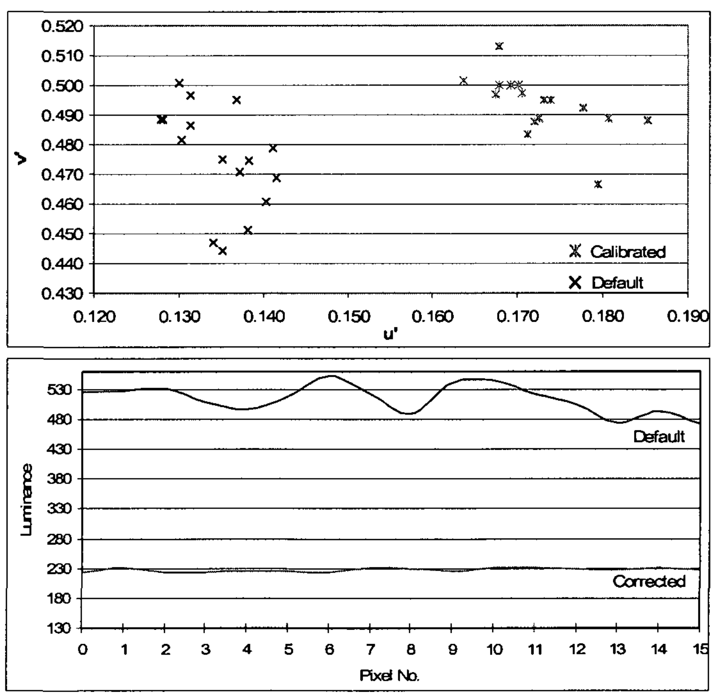


Figure 5.14: White Calibrated and Default Color & Luminance Parameters Chart [RGB Luminance methodology]

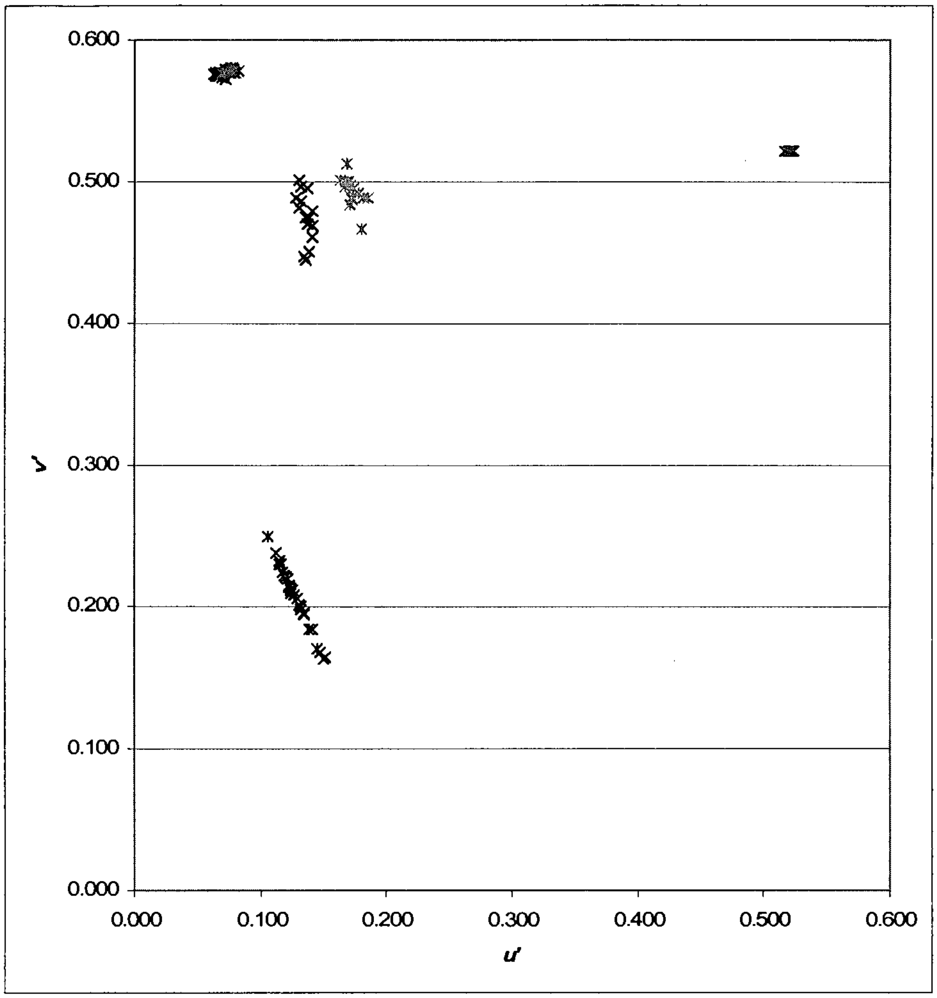


Figure 5.15: Red, Green, Blue and White Calibrated and Default Color Coordinates Chart [RGB Luminance methodology]

5.5 Discussion

In this section we will summarize the experiments results and discuss the image quality and resolution out of each methodology.

		RGBW Color & W Lum.				RGB Color and Lum.				RGB Luminance			
		u'	v'	Y	Usage %	u'	v'	Y	Usage %	u'	v'	Y	Usage %
R	Min	0.48	0.499	43	93.9	0.477	0.498	42.5	86.8	0.519	0.521	43.9	100
	Max	0.485	0.503	48.8	99	0.483	0.501	44.3	96.1	0.523	0.522	46.2	100
	Avg	0.484	0.501	45.4	97.5	0.48	0.499	43.5	92.1	0.522	0.522	45.3	100
G	Min	0.088	0.559	154.8	87.3	0.089	0.559	158.7	82.1	0.069	0.577	157.2	100
	Max	0.091	0.562	164.7	98.8	0.09	0.561	160	97.9	0.082	0.58	163.3	100
	Avg	0.089	0.561	160.5	94.6	0.089	0.56	159.4	92.3	0.075	0.579	160.6	100
B	Min	0.149	0.249	22.1	88.9	0.148	0.248	15.2	62.8	0.106	0.17	19.1	100
	Max	0.154	0.257	24.7	99.9	0.152	0.256	17	99.7	0.145	0.25	21	100
	Avg	0.151	0.252	23.4	94.9	0.15	0.252	16.1	92	0.123	0.213	19.8	100
W	Min	0.173	0.488	228.9		0.171	0.497	220.6		0.164	0.466	223.2	
	Max	0.182	0.496	234.9		0.175	0.503	225.1		0.185	0.513	231.9	
	Avg	0.177	0.492	231.5		0.173	0.498	222.8		0.173	0.493	227.6	

Table 5.11: Experiments results summary

Table 5.11 shows results summary for the three methodologies experiments. The results shows that the maximum deviation over the average and the minimum deviation under the average for the chromaticity coordinates, for the *RGBW Color and W Luminance* methodology and *RGB Color and Luminance* methodology, are within ± 0.005 $\Delta u'v'$. Also for the white luminance for the three methodologies, the maximum deviation over the average and the minimum deviation under the average are within ± 3%.

		Default			
		u'	v'	Y	Usage %
R	Min	0.516	0.521	58.0	100
	Max	0.522	0.522	69.8	100
	Avg	0.521	0.522	62.8	100
G	Min	0.062	0.573	355.9	100
	Max	0.072	0.577	424.2	100
	Avg	0.066	0.575	392.9	100
B	Min	0.112	0.163	35.7	100
	Max	0.151	0.238	77.4	100
	Avg	0.132	0.200	53.4	100
W	Min	0.128	0.444	471.9	
	Max	0.142	0.501	553.0	
	Avg	0.135	0.476	513.8	

Table 5.12: Default results summary

Table 5.12 shows the default color coordinates and luminances for the LED colors before the correction and the calibration. The Red and Green LEDs do have small color coordinates deviations under and over the average; on the other hand, they have a large deviation in the luminances. The Blue and the resulted White have a large deviation in both color coordinates and luminances.

As for the image quality, the *RGBW Color and W Luminance* methodology and *RGB Color and Luminance* methodology experiments results show how all the deviations in the color and luminance were significantly reduced, which leads for a high image quality.

The *RGB Luminance* methodology reduced the deviation in the luminance significantly, which leads to a less color perception differences.

As for the image resolution, the *RGB Luminance* methodology keeps the maximum resolution that can be provided by the LED Screen. The *RGBW Color and W Luminance* methodology and *RGB Color and Luminance* methodology provide less resolution associate with a high image quality. The experimental results show how the *RGBW Color and W Luminance* methodology can provide a higher resolution than the *RGB Color and Luminance* methodology. On the other hand, the *RGB Color and Luminance* methodology provides a faster correction process than the *RGBW Color and W Luminance* methodology.

CHAPTER 6

Conclusion and Future Work

6.1 Conclusion

In this thesis, a novel technique for color and luminance correction and calibration for LED Video screens was presented. The proposed method used the CIE color system for measuring and calculating the color coordinates and Luminance. A new algorithm was developed to calculate the color mixture components, based on the CIE system, to calibrate and correct the LED pixels in the LED screens.

The proposed technique was an integrated hardware and software solution where it uses robotic spectrometer head and Windows based graphical user interface (GUI) application software. The software was developed using Visual Basic .net (VB.net). The proposed technique was implemented, tested, and integrated in collaboration with LSI SACO technologies.

The root cause of the color and luminance non-uniformity problem in the LED screens along with the available solutions in the market were presented and discussed. The Image quality and resolution along with the cost was the main target of the proposed correction system as these are the main keys for a cost-effective and high quality product. The system can run different methodologies, which are based on the developed algorithm, to calibrate and correct the LED screen. The user has the choice to select the proper methodology according to his need. The experiments show the results for three different methodologies along with the image quality and resolution efficiency out of each of them. One methodology was developed for LED lighting products correction and calibration, although the other methodologies still can be applied for LED lighting products as well.

6.2 Future Work

The proposed system in this thesis provides accurate correction coefficients with very small pixel-to-pixel color and luminance differences, ± 0.03% brightness and ± 0.005 $\Delta u'v'$, where it is needed to enhance the algorithm further more to reduce these differences. In addition, as a future work, from the practical point of view, the current system measures, calibrates and corrects one single pixel at the time, so it is valuable to add another spectrometer head to speed up the calibration process. Other things can be considered to enhance the system measurement and calibration speed, by having larger solid core fiber cable and extra optics (as lenses) to amplify the input light to the spectrometer to have more accurate light readings.

Finally, we believe this thesis project is an important milestone towards producing a cost-effective and high quality and resolution LED video screens. Therefore, it is important to develop the system further more to make it a commercial viable device.

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Appendix A

CIE 1931 color matching functions;

Measurements table of (5 nm intervals)

λ, nm	$\bar{x}(\lambda)$	$\bar{y}(\lambda)$	$\bar{z}(\lambda)$
380	0.001368	0.000039	0.006450
385	0.002236	0.000064	0.010550
390	0.004243	0.000120	0.020050
395	0.007650	0.000217	0.036210
400	0.014310	0.000396	0.067850
405	0.023190	0.000640	0.110200
410	0.043510	0.001210	0.207400
415	0.077630	0.002180	0.371300
420	0.134380	0.004000	0.645600
425	0.214770	0.007300	1.039050
430	0.283900	0.011600	1.385600
435	0.328500	0.016840	1.622960
440	0.348280	0.023000	1.747060
445	0.348060	0.029800	1.782600
450	0.336200	0.038000	1.772110
455	0.318700	0.048000	1.744100
460	0.290800	0.060000	1.669200
465	0.251100	0.073900	1.528100
470	0.195360	0.090980	1.287640
475	0.142100	0.112600	1.041900
480	0.095640	0.139020	0.812950
485	0.057950	0.169300	0.616200

490	0.032010	0.208020	0.465180
495	0.014700	0.258600	0.353300
500	0.004900	0.323000	0.272000
505	0.002400	0.407300	0.212300
510	0.009300	0.503000	0.158200
515	0.029100	0.608200	0.111700
520	0.063270	0.710000	0.078250
525	0.109600	0.793200	0.057250
530	0.165500	0.862000	0.042160
535	0.225750	0.914850	0.029840
540	0.290400	0.954000	0.020300
545	0.359700	0.980300	0.013400
550	0.433450	0.994950	0.008750
555	0.512050	1.000000	0.005750
560	0.594500	0.995000	0.003900
565	0.678400	0.978600	0.002750
570	0.762100	0.952000	0.002100
575	0.842500	0.915400	0.001800
580	0.916300	0.870000	0.001650
585	0.978600	0.816300	0.001400
590	1.026300	0.757000	0.001100
595	1.056700	0.694900	0.001000
600	1.062200	0.631000	0.000800
605	1.045600	0.566800	0.000600
610	1.002600	0.503000	0.000340
615	0.938400	0.441200	0.000240
620	0.854450	0.381000	0.000190
625	0.751400	0.321000	0.000100
630	0.642400	0.265000	0.000050
635	0.541900	0.217000	0.000030

640	0.447900	0.175000	0.000020
645	0.360800	0.138200	0.000010
650	0.283500	0.107000	0.000000
655	0.218700	0.081600	0.000000
660	0.164900	0.061000	0.000000
665	0.121200	0.044580	0.000000
670	0.087400	0.032000	0.000000
675	0.063600	0.023200	0.000000
680	0.046770	0.017000	0.000000
685	0.032900	0.011920	0.000000
690	0.022700	0.008210	0.000000
695	0.015840	0.005723	0.000000
700	0.011359	0.004102	0.000000
705	0.008111	0.002929	0.000000
710	0.005790	0.002091	0.000000
715	0.004109	0.001484	0.000000
720	0.002899	0.001047	0.000000
725	0.002049	0.000740	0.000000
730	0.001440	0.000520	0.000000
735	0.001000	0.000361	0.000000
740	0.000690	0.000249	0.000000
745	0.000476	0.000172	0.000000
750	0.000332	0.000120	0.000000
755	0.000235	0.000085	0.000000
760	0.000166	0.000060	0.000000
765	0.000117	0.000042	0.000000
770	0.000083	0.000030	0.000000
775	0.000059	0.000021	0.000000
780	0.000042	0.000015	0.000000