
High Resolution RGB LED Color Mixing Application Note

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INTRODUCTION

This application note provides an example of RGB LED color mixing using the PIC12F1572 processor. The PIC12F1572 processor features three 16-bit pulse-width modulators (PWMs), along with other peripherals in a compact 8-pin package. 16-bit PWMs allow precise control over the intensity of each of the three colors in the CREE® RGB LED. This allows smooth transitions even at low-brightness/luminosity levels.

Microchip designed a RGB Badge Demonstration Board that applies the concepts described in this application note. The design files and software for this demonstration board can be obtained at www.microchip.com/RGBbadge.

The RGB Badge Demonstration Board utilizes several Microchip technologies. The three 16-bit PWMs on the PIC12F1572 are used to drive the RGB LEDs. The mTouch™ sensing solution is used to operate a capacitive touch slider. The on-board PIC16F1455 is operated as a USB-to-Serial converter to provide communications between a PC application and the RGB badge board. The USB software and mTouch™ Library are available as part of the Microchip Library for Applications (MLA). These Microchip technologies, along with custom application software, provide the RGB badge board functionality.

The RGB badge board can be powered by a battery, or from a USB connection. When powered by battery, a MCP1640 DC-DC converter provides 3.3 Vdc to operate the board. The board can be powered by either a 3V lithium coin cell (CR2032), or a 1.5V AAAA (E96) battery.

RGB BADGE OPERATION

The RGB badge board operates in two modes:

- Mode 1: HSVW Slider mode
- Mode 2: Chromaticity Chart Selector mode

The RGB badge board powers up in Mode 1, HSVW Slider mode. The board initially cycles through the Hue, Saturation, and Value plus White (HSVW) color wheel. After a period of time, the RGB LEDs change to a blinking operation to conserve battery power. If the mTouch slider on the edge of the board is touched while operating in Mode 1, the color selected on the slider is output on the RGB LED. The selected color is displayed for about five seconds before returning to the color wheel display.

For additional detail on Mode 1 operation, see [Section “Mode 1: HSVW Slider”](#).

In Mode 2 (Chromaticity Chart Selector mode), the RGB badge board displays the color selected in a PC application (See [Figure 6](#)). To operate the RGB badge board in Mode 2 (Chromaticity Chart Selector mode), the board must be connected to a PC. The RGB badge board connects to the computer via USB, and the ‘RGB badge Chromaticity Selector’ PC application is used to send color commands.

For additional detail on Mode 2 operation, see [Section “Mode 2: XY Chromaticity Chart”](#).

LED LIGHTING

The light produced by LEDs varies due to several factors. The brightness produced, measured in lumens, will vary for LEDs of different types, and between LEDs of the same type. For color LEDs, the specific color produced, measured in chromaticity, will vary between LEDs.

For the purposes of this application note, small samples of CREE® CLX6A-FKB RGB LEDs were measured to develop a brightness and chromaticity profile. These values were then used as typical values in the hardware design, and in the software's chromaticity calculations. This process is called Color Tuning.

COLOR TUNING

Using a chroma meter, resistor values were determined so that each color produced the same number of lumens. The LED series resistor values are:

- Red = 202 Ω
- Green = 325 Ω
- Blue = 61 Ω

Each LED was also measured (using a chroma meter) for color value, with the following results (see [Table 1](#)).

LED VARIATIONS

It should be noted that these values are provided for example only. The results will differ for other LEDs, and possibly even for LEDs in the same batch. Over time, the output from a LED may vary. For the purpose of this demonstration board, these variations are not addressed.

The information is also shown in [Figure 5](#) as a color gamut of a chromaticity chart.

TABLE 1: CIE 1931 xy VALUES FOR CREE® LED MEASURED WITH CHROMAMETER

LED color	x	y
Red	.6763	.3237
Green	.2088	.7408
Blue	.1405	.0391

TEMPERATURE COMPENSATION

Luminous intensity can have large variations due to temperature and varies according to the LED type. This application is not performing any temperature compensation. Temperature compensation was not part of the design goals of this demonstration board.

PWM BRIGHTNESS CONTROL AND FLICKER PERCEPTION

The PIC12F1572 contains three independent 16-bit pulse-width modulation (PWM) peripherals. A PWM peripheral varies the length of time a particular load is turned on. The ratio of the “on time” to the PWM period is called the “duty cycle” and corresponds to the percentage of power that is delivered to the load. Controlling power with a PWM is generally recognized as a precise and efficient method of regulating power output. A 16-bit PWM provides $2^{16} = 65,536$ levels of brightness control at its maximum period. With a clock of 16 MHz, the PWM period can be calculated by dividing the clock rate by the number of clocks in a PWM period.

$$\text{Clock rate/PWM period} = 16 \times 10^6 / 65,536 = 244.1 \text{ Hz}$$

It is generally recognized that the human eye can detect flicker at approximately 200 Hz. Also, due to intermodulation with 60 Hz/50 Hz lighting, it is recommended that all LED lighting applications switch above 200 Hz. The selected PWM period is well above the range where flicker would be perceived.

MODE 1: HSVW SLIDER

One common method of demonstrating colors is via the color wheel shown in [Figure 1](#). This shows colors on the exterior of a Hue, Saturation and Value (HSV) color wheel while keeping a smooth transition between colors. What has been created for the RGB badge demonstration is a variation of the HSV color wheel with a white transition inserted between pure red points. This is called the HSVW color wheel shown in [Figure 2](#). The HSVW color includes eight distinct operating regions. For calculation of white point values, see [Section "Calculation of the White Point"](#).

The primary mode of operation of the RGB Badge Demonstration Board is to select the colors of the spectrum to display via the mTouch slider interface.

In this mode, the RA0/RA1 pins are configured to work with a "capacitive touch slider", as shown in the simplified schematic in [Figure 3](#). This allows a finger press/slide to select different color values. This operation is limited to a one-dimensional color selection. Colors from a modified "HSVW color wheel" are presented in [Figure 2](#).

FIGURE 1: HSV SLIDER

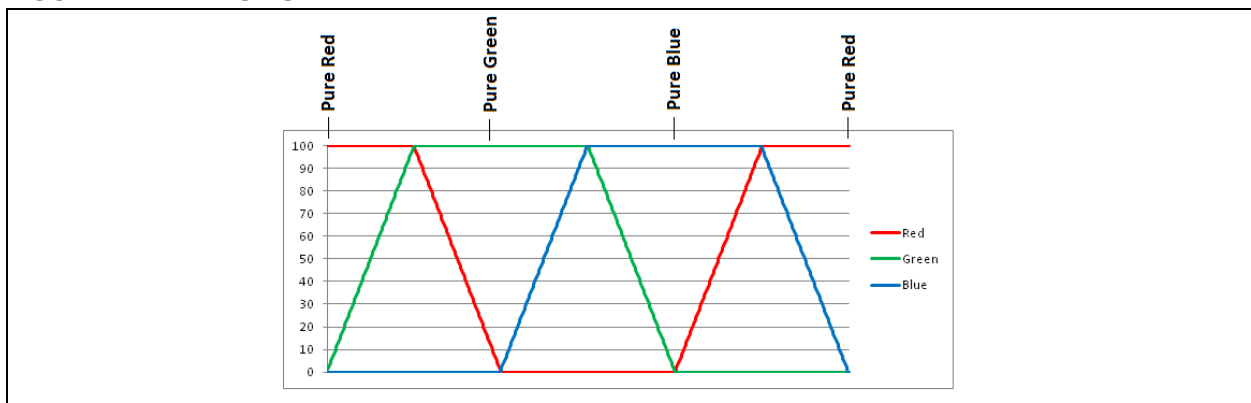


FIGURE 2: HSVW SLIDER

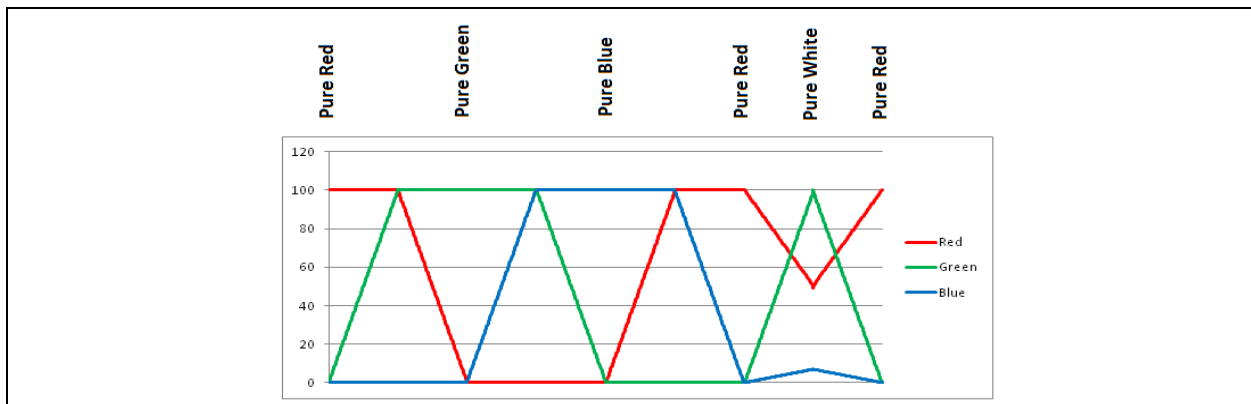
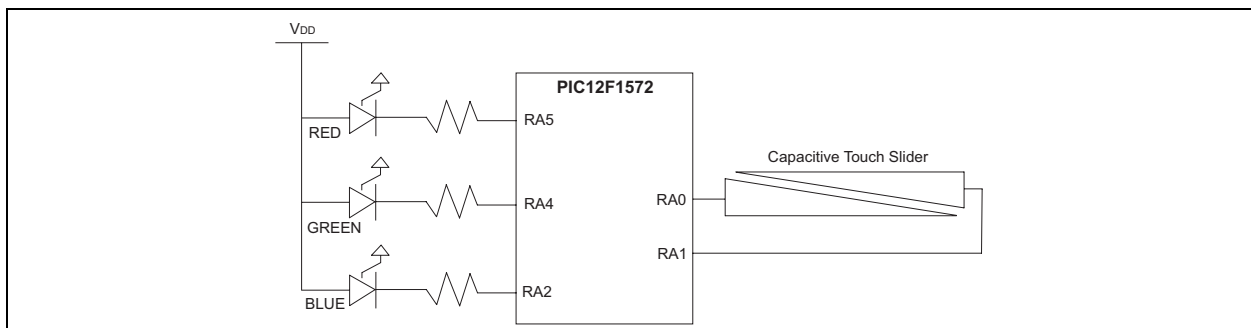


FIGURE 3: COLOR MIX DEMONSTRATION BOARD CONFIGURED AS HSVW SLIDER



MODE 2: xy CHROMATICITY CHART

The Color Mixing Demo Board has been designed to demonstrate a range of colors that appear on the CIE 1931 xy Chromaticity Chart. These are converted to RGB (red, green, blue) values which are color-mixed to create the resultant color. The duty cycle of a PWM signal for each individual red, green, and blue LED are controlled to set their respective brightness levels. Each individual PWM has 16 bits of resolution, allowing for smooth color transitions operation even with very low-duty cycle values.

The setting of the color selected on the Chromaticity chart in the PC application is accomplished through a series of operations and interactions between the PC application and the RGB badge board. The PC application, 'RGB Badge Chromaticity Selector' calculates the red, green, and blue PWM duty cycles required to create the selected color. Equation 6 shows an example of these calculations. The calculated 16-bit duty cycle values are then transmitted to the RGB badge board over a USB link. The RGB badge software then uses the received PWM duty cycle values to display the selected color.

COLOR THEORY BACKGROUND

There are many different ways of expressing color values, including CMYK, RGB, CIE and HunterLab, among others. Graphic artists want to create accurate color matches to capture their artistic work and reinforce branding consistency. Accurate presentation of color on different equipment and media still remains a challenge. It has long been known that any given color of light can be described with three different variables (due to the three different types of cones in the human eye).

XYZ COLOR SPACE

One of the popular ways of representing color is with the CIE 1931 XYZ Color Space. In the CIE 1931 XYZ Color Space, Y is luminance (brightness), and the X and Z values formulate the chromaticity. Grey and white have the same chromaticity, but differ in luminance. This creates a three-dimensional (3D) color space which encompasses all colors that can be perceived by the human eye.

Creation of this space was done by allowing test subjects to mix colors – creating color matches and different colors of the same perceived brightness with a limited field of vision (2° arc inside the fovea). This is sometimes referred to as the "CIE 1931 2° Standard Observer".

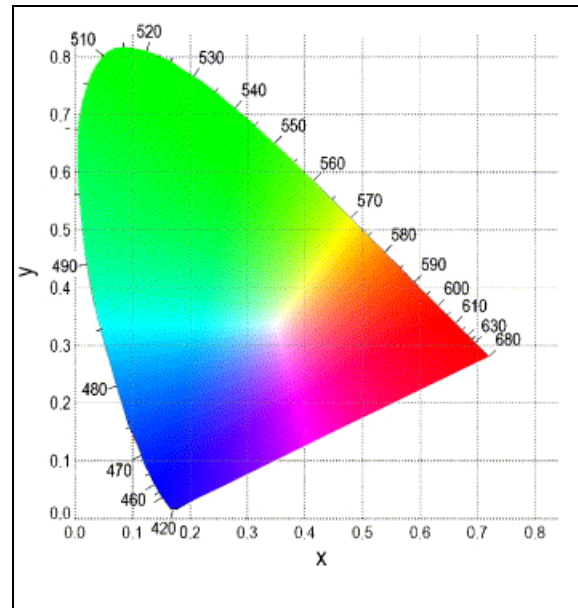
Looking at a 3D array of colors is impossible to do. Because it is desirable to present many different colors of the CIE 1931 XYZ color space on a single printed sheet, a 'plane' of the XYZ color space has been created, where:

EQUATION 1: MAPPING xy TWO-DIMENSIONAL SPACE TO THREE-DIMENSIONAL XYZ SPACE

$$\begin{aligned} X_{XYZ} &= x/y \ Y_{XYZ} \\ Y_{XYZ} &= Y_{XYZ} \\ Z_{XYZ} &= (1-x-y)/y \ Y_{XYZ} \end{aligned}$$

So, with just lowercase 'x' and 'y' values, and a brightness, 'Y', that particular color can be mapped to a location in the 3D XYZ space. For the creation of a chromaticity chart, a constant Y_{XYZ} luminosity/brightness value is chosen, that will produce vibrant colors on the chart. A value of $Y_{XYZ} = 0$ could be chosen, but the chart would be devoid of color (and not useful). A chromaticity chart is shown in Figure 4:

FIGURE 4: CIE 1931 COLOR SPACE CHROMATICITY DIAGRAM



The most important property of the XYZ color space is that the RGB color space is a subset of the XYZ color space. Any color vector in XYZ color space is the sum of the red, green and blue components. X_{XYZ} and Z_{XYZ} define the "chromaticity" while Y_{XYZ} defines the brightness.

EQUATION 2: THE RGB COLOR SPACE RESIDES IN THE XYZ SPACE

$$X_{XYZ} = X_R + X_G + X_B$$

$$Y_{XYZ} = Y_R + Y_G + Y_B$$

$$Z_{XYZ} = Z_R + Z_G + Z_B$$

The duty cycle ratios required to produce desired color need to be calculated. The calculations involve solving for the luminosity values of the red, green, and blue LEDs, and multiplying those values by the selected color space values.

NOTATION

Unfortunately, because of the chosen variable names, it is easy in notation to confuse a lowercase 'x' with an uppercase 'X' in a smaller type size. Due to this, the notation shown in [Equation 3](#) is used:

- X_{XYZ} – X color component in 3D XYZ color space
- $X_{\{R\ G\ B\}}$ – RGB components of X_{XYZ} in 3D XYZ color space
- Y_{XYZ} – Y color component in 3D XYZ color space
- $Y_{\{R\ G\ B\}}$ – RGB components of Y_{XYZ} in 3D XYZ color space
- Z_{XYZ} – Z color component in 3D XYZ color space
- $Z_{\{R\ G\ B\}}$ – RGB components of Z_{XYZ} in 3D XYZ color space
- x – x-axis value of color mix on 2-dimensional chromaticity chart
- $x_{\{R\ G\ B\}}$ – x-coordinate of respective red, green, blue color source LED on 2-dimensional chromaticity chart.
- y – y-axis value of color mix on 2-dimensional chromaticity chart
- $y_{\{R\ G\ B\}}$ – y-coordinate of respective red, green, blue color source LED on 2-dimensional chromaticity chart.

Combining [Equation 1](#) and [Equation 2](#), we get:

EQUATION 3: WRITING IN MATRIX FORM

$$X_{XYZ} = \frac{x_R}{y_R} \cdot Y_R + \frac{x_G}{y_G} \cdot Y_G + \frac{x_B}{y_B} \cdot Y_B$$

$$Y_{XYZ} = Y_R + Y_G + Y_B$$

$$Z_{XYZ} = \frac{1 - x_R - y_R}{y_R} \cdot Y_R + \frac{1 - x_G - y_G}{y_G} \cdot Y_G + \frac{1 - x_B - y_B}{y_B} \cdot Y_B$$

writing in matrix form,

$$\begin{bmatrix} X_{XYZ} \\ Y_{XYZ} \\ Z_{XYZ} \end{bmatrix} = \begin{bmatrix} \frac{x_R}{y_R} & \frac{x_G}{y_G} & \frac{x_B}{y_B} \\ 1 & 1 & 1 \\ \frac{1 - x_R - y_R}{y_R} & \frac{1 - x_G - y_G}{y_G} & \frac{1 - x_B - y_B}{y_B} \end{bmatrix} \begin{bmatrix} Y_R \\ Y_G \\ Y_B \end{bmatrix}$$

Note: The middle row is all ones because we are using balanced (same luminous flux) light sources. If we were not using balanced light sources, these values would be changed to match the intensity of each specific RGB color.

EQUATION 4: SUBSTITUTION OF EQUATION SET 1 TO SOLVE FOR LUMINOSITY VALUES

inverting the matrix to solve for luminosity values:

$$\begin{bmatrix} Y_R \\ Y_G \\ Y_B \end{bmatrix} = \begin{bmatrix} \frac{x_R}{y_R} & \frac{x_G}{y_G} & \frac{x_B}{y_B} \\ 1 & 1 & 1 \\ \frac{1-x_R-y_R}{y_R} & \frac{1-x_G-y_G}{y_G} & \frac{1-x_B-y_B}{y_B} \end{bmatrix}^{-1} \begin{bmatrix} X_{XYZ} \\ Y_{XYZ} \\ Z_{XYZ} \end{bmatrix}$$

and substituting equation set 1 for $X_{XYZ}, Y_{XYZ}, Z_{XYZ}$:

$$\underbrace{\begin{bmatrix} Y_R \\ Y_G \\ Y_B \end{bmatrix}}_{\text{PWM Intensity}} = \underbrace{\begin{bmatrix} \frac{x_R}{y_R} & \frac{x_G}{y_G} & \frac{x_B}{y_B} \\ 1 & 1 & 1 \\ \frac{1-x_R-y_R}{y_R} & \frac{1-x_G-y_G}{y_G} & \frac{1-x_B-y_B}{y_B} \end{bmatrix}^{-1}}_{\text{x, y coordinates specific to LED}} \underbrace{\begin{bmatrix} \frac{x}{y} \\ 1 \\ \frac{1-x-y}{y} \end{bmatrix}}_{\text{color mix}}$$

“COLORMIX” ROUTINE

In order to allow easy color mixing, a “ColorMix” routine has been developed for the ‘RGB Badge Chromaticity Selector’ PC application, where x, y, Y values are specified. The PC application does the matrix inversion and multiplication/scaling to calculate the duty cycle values required to produce the desired color.

PROPERTIES OF THE CHROMATICITY DIAGRAM

It is a property of the chromaticity diagram that if you have two colors on the chromaticity diagram, and connect them in a straight line, by mixing the colors in different amounts, you can create any color along the line. This explains why blue LEDs commonly use a yellow phosphor to allow the creation of white light.

Further, when using RGB lighting components to create colors that appear on the chromaticity chart, it confines the achievable colors to a triangle, referred to as “Maxwell’s triangle”. The range of colors that can be produced is known as a “gamut”. The range of colors that can be depicted with the CREE® tri-color LED are indicated in the diagram below. Coordinates for this diagram are taken from Figure 5 and the coordinates for the above diagram are sourced from Table 1.

FIGURE 5: CIE 1931 COLOR SPACE WITH RGB LED COLOR GAMUT

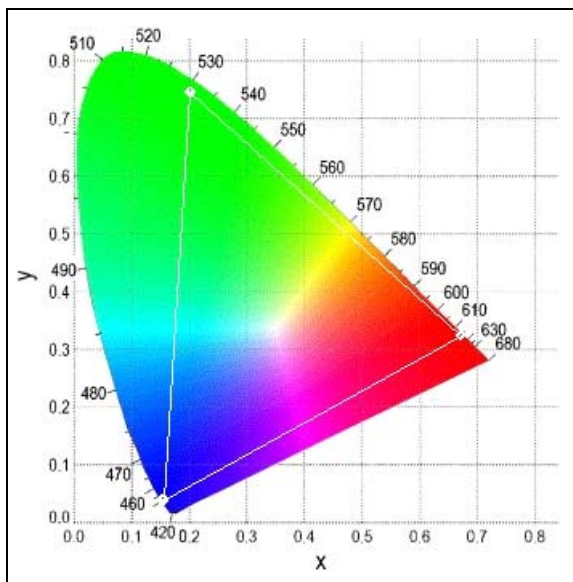


Figure 5 is not truly accurate because the colors that you can see are limited to the colors that your RGB monitor can produce (assuming you are reading this document on a monitor). You can only view colors that are within the gamut of your display.

It should also be noted from the chromaticity chart that the white spot in the center is confined to a small region of the chart. The ability to produce clean white light is generally regarded as a good indication that proper color mixing is being performed.

CALCULATION OF THE WHITE POINT

The white point value is calculated as follows:

For the white point, $x = 0.35$ and $y = 0.33$

The LEDs used here have the following properties:

$$x_R = 0.6763, y_R = 0.3237$$

$$x_G = 0.2088, y_G = 0.7408$$

$$x_B = 0.1405, y_B = 0.0391$$

EQUATION 5: FORMULA FOR CALCULATION OF WHITE POINT

$$\underbrace{\begin{bmatrix} Y_R \\ Y_G \\ Y_B \end{bmatrix}}_{\text{PWM Intensity}} = \underbrace{\begin{bmatrix} \frac{x_R}{y_R} & \frac{x_G}{y_G} & \frac{x_B}{y_B} \\ 1 & 1 & 1 \\ \frac{1-x_R-y_R}{y_R} & \frac{1-x_G-y_G}{y_G} & \frac{1-x_B-y_B}{y_B} \end{bmatrix}}_{\text{x, y coordinates specific to LED}}^{-1} \underbrace{\begin{bmatrix} \frac{x}{y} \\ 1 \\ \frac{1-x-y}{y} \end{bmatrix}}_{\text{color mix}}$$

EQUATION 6: CALCULATION OF WHITE POINT

$$\begin{bmatrix} Y_R \\ Y_G \\ Y_B \end{bmatrix} = \begin{bmatrix} 2.089 & 0.2819 & 0.3593 \\ 1 & 1 & 1 \\ 0 & 0.068 & 20.982 \end{bmatrix}^{-1} \begin{bmatrix} 1.061 \\ 1 \\ 0.9697 \end{bmatrix}$$

$$\begin{bmatrix} Y_R \\ Y_G \\ Y_B \end{bmatrix} = \begin{bmatrix} 0.55 & -0.1491 & -0.0871 \\ -0.5518 & 1.153 & 0.396 \\ 0.0178 & -0.0037 & 0.0475 \end{bmatrix} \begin{bmatrix} 1.061 \\ 1 \\ 0.9697 \end{bmatrix}$$

$$\begin{bmatrix} Y_R \\ Y_G \\ Y_B \end{bmatrix} = \begin{bmatrix} 0.3498 \\ 0.6060 \\ 0.0443 \end{bmatrix}$$

This shows the brightness values for the red, green, and blue light components (as% of duty cycle) to produce the desired color mix values for white. To scale these values for a 16-bit PWM, multiply by 0xFFFF.

$$Y_R * 0xFFFF = 0.3498 * 0xFFFF = 0x598C$$

$$Y_G * 0xFFFF = 0.6060 * 0xFFFF = 0x9B22$$

$$Y_B * 0xFFFF = 0.0443 * 0xFFFF = 0x0B57$$

RGB BADGE MODE CHANGES

When the RGB badge board is operating in Mode 2, the desired LED color is selected from a chromaticity chart in the RGB Badge Chromaticity Selector PC application (See [Figure 6](#)). The red, green, and blue PWM duty cycle values are calculated by the PC application. The duty cycle values are passed to the RGB badge board by a USB serial connection.

In order to operate in Mode 2, the configuration of the RA0 and RA1 pins PIC12F1572 Color Mix chip are changed from mTouch Slider operation to EUSART communication operation.

[Figure 7](#) shows a simplified schematic for the RGB badge board when operating in Mode 2.

The configuration change is implemented in the software. The USB software was modified to prevent the PIC16F1455 from enabling its EUSART during initialization. This prevents the EUSART from interfering with the Mode 1 Slider operation on the

Color Mix chip (see [Figure 3](#)). When the PIC16F1455 receives data from the PC application on its USB port, it signals the Color Mix chip to exit Mode 1, and enter Mode 2. When the PIC16F1455 detects that the Color Mix chip has changed modes, it enables its EUSART and forwards the data from the PC application to the Color Mix chip.

The PIC16F1455 on the RGB badge board passes the data to the Color Mix chip using its EUSART running at 9600 baud.

When the Color Mix chip is operating Mode 2, it sends a 'keep alive' byte to the PC about once every second. This is used to show that the USB and serial connection from the PC to the Color Mix chip is operating. The PC application then echoes the byte back to the Color Mix chip. This handshake keeps the Color Mix chip in Mode 2. When the PC application is closed, or the USB connection is broken, the Color Mix chip detects the loss of communication, and reverts to Mode 1 operation.

FIGURE 6: RGB BADGE CHROMATICITY SELECTOR RUNNING ON PC

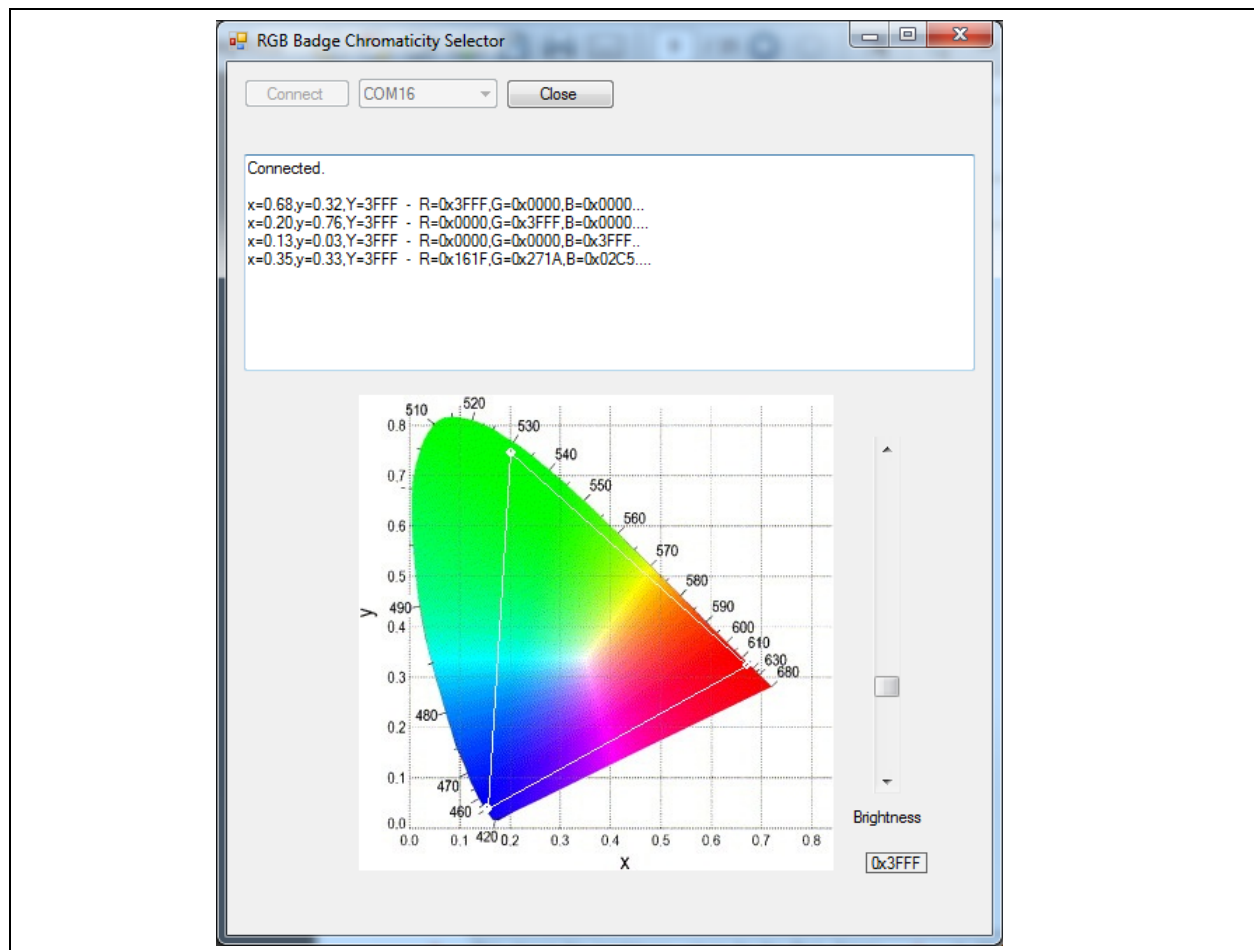
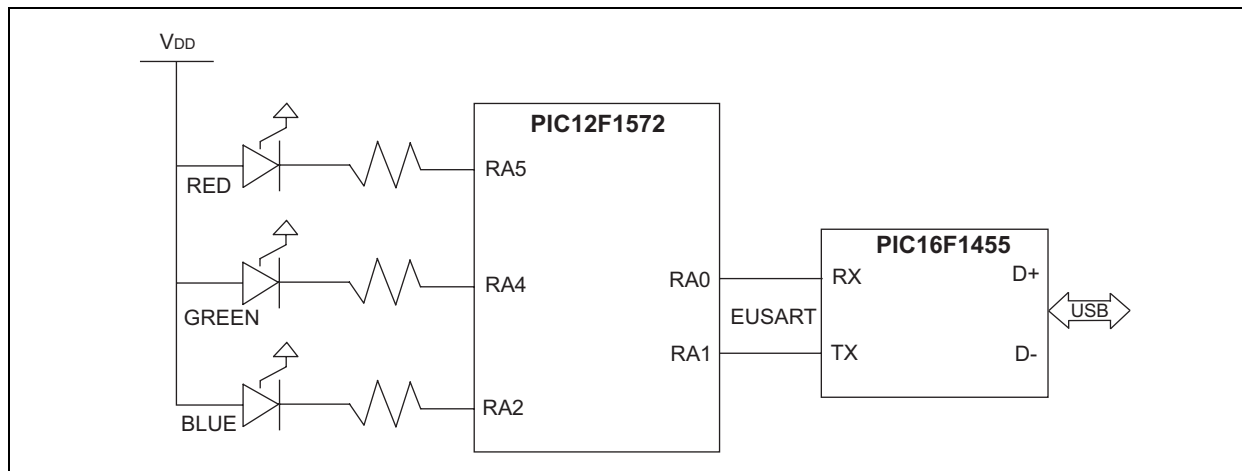


FIGURE 7: COLORMIX BOARD CONFIGURED AS XY CHROMATICITY CHART SELECTOR

BUILDING THE SOFTWARE

The RGB badge board includes three separate pieces of software:

- RGB badge (PIC12F1572)
- Device – CDC - Serial emulator (PIC16F1455)
- RGB Badge Chromaticity Selector (PC)

The requirements for the 'RGB badge' and 'USB Device – CDC - Serial Emulator' are:

- XC8 v1.32 or later, running in PRO mode
- MPLAB® X Configuration: LPC_USB_Development_Board PIC16F1455

The requirements for the 'RGB Badge Chromaticity Selector' are:

- Visual C++ 2008 Express Edition

The code used in this application note is based on the code from the Microchip Library of Applications (MLA) version 2013-06-15.

Refer to: www.microchip.com/MLA for more information.

The MLA projects used are:

- Microchip\mTouchCap\PIC12F 16F Library
- USB\Device – CDC - Serial Emulator

REPROGRAMMING THE BOARD

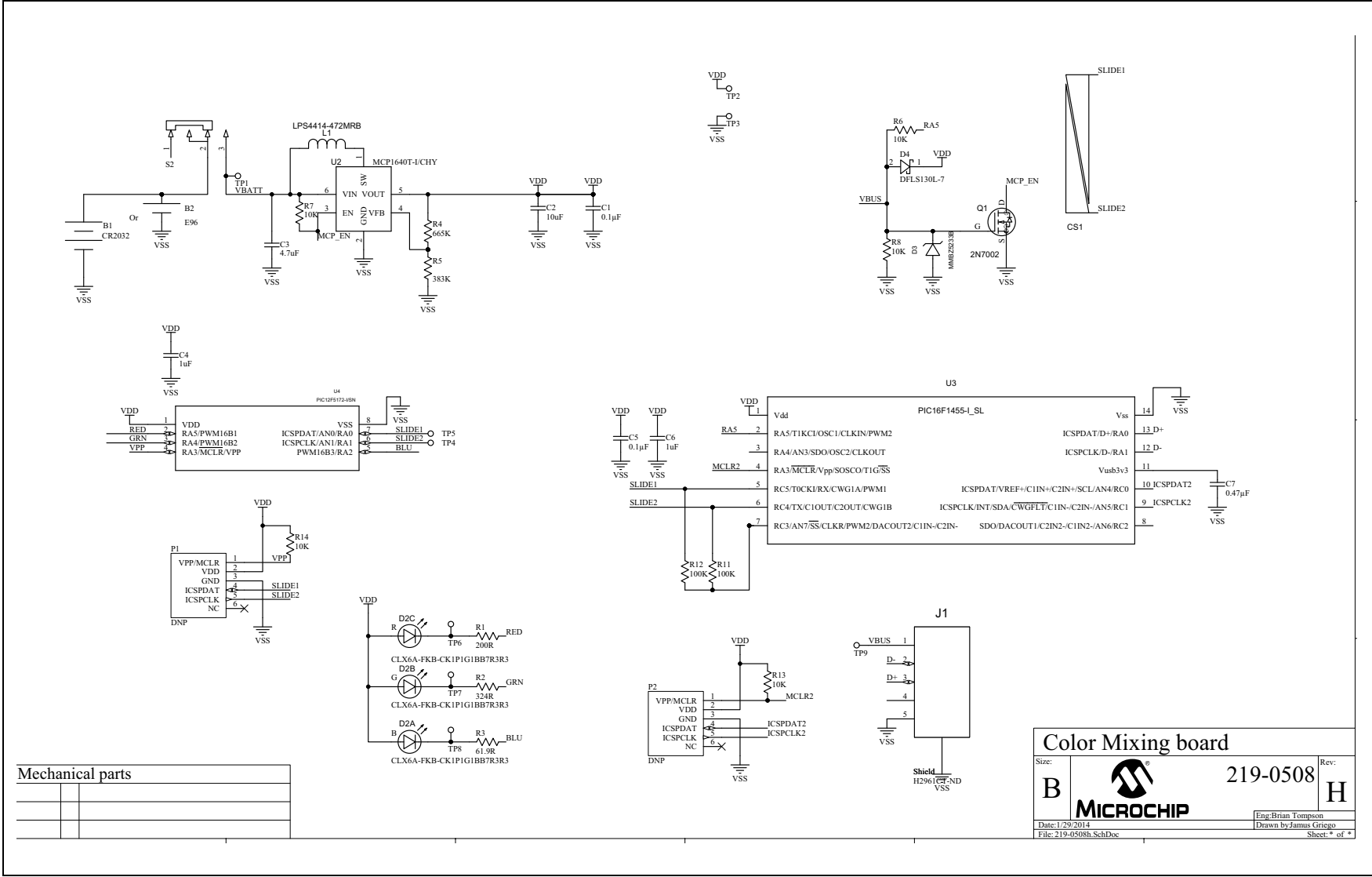
To reprogram the PIC® devices on the board, 6-pin headers can be temporarily inserted in the P1 or P2 headers location. The unpopulated P1 and P2 ICSP™ header locations have been laid out with offset pins. The offset pins hold the temporary header pins more securely than a standard straight header.

- Use the P1 connector position to reprogram the RGB badge software on the PIC12F1572 Color Mix chip.
- Use the P2 connector position to reprogram the USB-to-Serial converter software on the PIC16F1455 USB chip.

Note: The HSVW slider function will not function while a programming tool is connected to P1. The ICSP™ and the Slider sensor use the same pins on the PIC12F1572 Color Mix chip.

APPENDIX A: SCHEMATIC

FIGURE A-1: RGB LED WITH SLIDER SCHEMATICS



APPENDIX B: BILL OF MATERIALS

TABLE B-1: BILL OF MATERIALS MICROCHIP RGB BADGE BOARD

Quantity	Designator	Description	Part Number
1	B1	HOLDER COIN CELL 20MM SMD	BK-912
2	B2	BATCLIP_AAAA_SMT	50
1	C1, C5	Cap, Ceramic, 0.1 uF, 50V	C1608X7R1H104M
1	C2	Cap, Ceramic, 10 uF, 16V X5R	EMK212BJ106MG-T
1	C3	Cap, Ceramic, 4.7 uF, 10V, 20% X7R SMD	C2012X7R1A475M
2	C4, C6	Cap, Ceramic, 1 uF, 16V	C1608X5R1C105K
1	C7	Cap, Ceramic, 0.47 uF, 10V, 20% X5R	C1608X5R1A474M
1	D2	Light Emitting Diode	CLX6A-FKB-CK1P1G1BB7R3R3
1	D3	DIO-ZENER-BZX84-SOT23	MMBZ5233B
1	D4	DIODE SCHOTTKY 30V 1A POWERDI12	DFLS130L-7
1	J1	CONN RECEPT MINI USB2.0 5POS	UX60A-MB-5ST
1	L1	LPS4414-472MRB	
1	Q1	N-Channel Enhancement-Mode MOSFET (TMOS)	2N7002
1	R1	RES 200 OHM 1/10W 1% 0603	RMCF0603FT200R
1	R2	RES 324 OHM 1/10W 1% 0603	RMCF0603FT324R
1	R3	RES 61.9 OHM 1/10W 1% 0603	RMCF0603FT61R9
1	R4	Res, 665K 1/10W 1%	ERJ-3EKF6653V
1	R5	Res, 383K, 1/10W 1% 0603	RMCF0603FT383K
5	R6, R7, R8, R13, R14	Res, 10K, 1/10W 1%	RMCF0603FT10K0
2	R11, R12	Res, 100K, 1/10W 1%	RMCF0603FT100K
1	S2	Switch, Slide, SPDT, Rt Angle, SMT, Low Profile	MLL1200S
1	U2	MCP1640T-I/CHY	MCP1640T-I/CHY
1	U3	PIC16F1455-I_SL	PIC16F1455-I_SL
1	U4	PIC12F1572-I/SN	PIC12F1572-I/SN

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== ISO/TS 16949 ==

Microchip received ISO/TS-16949:2009 certification for its worldwide headquarters, design and wafer fabrication facilities in Chandler and Tempe, Arizona; Gresham, Oregon and design centers in California and India. The Company's quality system processes and procedures are for its PIC® MCUs and dsPIC® DSCs, KEELoQ® code hopping devices, Serial EEPROMs, microperipherals, nonvolatile memory and analog products. In addition, Microchip's quality system for the design and manufacture of development systems is ISO 9001:2000 certified.

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