INTRODUCTION

This application note demonstrates color mixing using the PIC12F1572 processor. The PIC12F1572 processor features three 16-bit pulse-width modulators (PWMs), among other peripherals. The 16-bit PWMs allow precise control over each RGB LED, allowing smooth transitions even at low-brightness/luminosity levels.

Development efforts are supported by the following features of this demonstration board.

- ICSP™ programming connector
- EUSART bus tie-in points
- USB or battery powered
- Multiple test points

A color mixing software routine allows developers to specify colors in xyY format with the PIC® device performing color mixing calculations.

Microchip provides a demonstration board (www.microchip.com/RGBbadge) that applies the concepts described in this application note. The demonstration board comes configured for Mode 1: HSVW Slider operation.

![FIGURE 1: COLOR MIX DEMONSTRATION BOARD CONFIGURED AS HSVW SLIDER](image)

The demonstration board can be reconfigured for Mode 2: xy Chromaticity Chart Selector operation. See Section “Hardware Configurations” for additional information.

The depth of features designed into each demonstration mode requires that the board be reprogrammed to demonstrate these two unique modes.

The board can be powered either through a USB connection a 3V lithium coin cell (CR2032) or a AAAA battery.

For more information on the PIC12F1572: www.microchip.com/PIC12F1572

MODE 1: HSVW SLIDER

When first powered in HSVW Slider mode, the RGB badge board cycles through the hue, saturation, and value (HSV) color wheel, modified to include white (HSVW), as shown in Figure 5. After a period of time, the LEDs start blinking to conserve battery power. At any time the slider on the edge of the board can be used to select a color to display.

In this mode, the RA0/RA1 pins are configured to work with a “capacitive touch slider”. 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.

For more information, see Section “HSVW Slider.”
MODE 2: xy CHROMATICITY CHART SELECTOR

In this mode, the desired LED color is chosen from an on-screen chromaticity chart (See Figure 3). The RA0/RA1 pins are configured as a serial (EUSART) interface. xyY values are passed to the board by a USB serial connection. A PIC16F1455 serves to convert the USB messages to a EUSART (9600 baud) format. For more information, see Section “XY Chromaticity Chart”.

Raw xyY (scaled 0-255) are supplied via the EUSART, and the PIC12F1572 performs the color calculations using the ColorMix routine. If a color is specified, which does not fall into the color gamut of the LEDs, then the function will return the error message 'outside of gamut' and the color output will not be updated. If the color is within the color gamut, then the new color will be displayed.

FIGURE 2: COLORMIX DEMONSTRATION BOARD CONFIGURED AS XY CHROMATICITY CHART SECTOR
FIGURE 3: CHROMATICITY xy SELECTOR RUNNING ON PC
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.

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 and temperature these values will vary. For the purpose of this demonstration board, these variations are not a concern.

<table>
<thead>
<tr>
<th>LED color</th>
<th>x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>.6763</td>
<td>.3237</td>
</tr>
<tr>
<td>Green</td>
<td>.2088</td>
<td>.7408</td>
</tr>
<tr>
<td>Blue</td>
<td>.1405</td>
<td>.0391</td>
</tr>
</tbody>
</table>

This same information is shown in Figure 7 as a color gamut of a chromaticity chart.

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.

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

It is generally recognized that the human eye can detect flicker at approximately 200 Hz. Also, due to intermodulation with 60Hz/50Hz 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.
HSVW SLIDER

The primary mode of operation for the demonstration board is displaying colors of the spectrum via the mTouch™ interface. One common method of demonstrating colors is via the method shown below. This shows colors on the exterior of an HSV color wheel while keeping a smooth transition between colors.

FIGURE 4: HSV SLIDER

What has been created for the slider is a variation on this with a white transition inserted between pure red points, with eight distinct operating regions. For calculation of white point values, see Section “Calculation of the White Point”.

FIGURE 5: HSVW SLIDER
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. Individual LEDs of red, green, and blue colors have their duty cycle (brightness) controlled through PWM (pulse-width modulation). Each individual PWM has 16 bits of resolution, allowing for smooth color transitions operation even with very low duty cycle values.

The software is structured such that serial messages are received, and the data is used to call the “ColorMix” routine. The x, y and Y values are specified in the 0-255 range. This makes it very easy to display desired colors and brightness levels. The ColorMix routine is computationally intensive and takes about 7.7 ms (with 16 MHz oscillator clock) to compute the PWM values. If this routine was used to compute continuously changing colors, the update rate would slow to 130 Hz, and would degrade the smoothness of the changes.

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:

\[
X_{XYZ} = \frac{x}{y} Y_{XYZ} \\
Y_{XYZ} = Y_{XYZ} \\
Z_{XYZ} = \left(1-x-y\right)/y Y_{XYZ}
\]

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 YXYZ luminosity/brightness value is chosen, that will produce vibrant colors on the chart. A value of YXYZ = 0 could be chosen, but the chart would be devoid of color (and not useful). A chromaticity chart is shown below:

FIGURE 6: 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, Blue and Green 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

\[
\begin{align*}
X_{XYZ} &= X_R + X_G + X_B \\
Y_{XYZ} &= Y_R + Y_G + Y_B \\
Z_{XYZ} &= Z_R + Z_G + Z_B
\end{align*}
\]

Solving for luminosity values to produce a desired color: What we would like to do is find the duty cycle ratio required to produce our color mix value as selected on the PC.

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 following notation is being 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 sets 1 and 2, we get:

EQUATION 3:

\[
\begin{align*}
X_{XYZ} &= x_R \cdot \frac{Y_R}{y_R} + x_G \cdot \frac{Y_G}{y_G} + x_B \cdot \frac{Y_B}{y_B} \\
Y_{XYZ} &= Y_R + Y_G + Y_B \\
Z_{XYZ} &= \frac{1-x_R-y_R}{y_R} \cdot Y_R + \frac{1-x_G-y_G}{y_G} \cdot Y_G + \frac{1-x_B-y_B}{y_B} \cdot Y_B
\end{align*}
\]

Writing in matrix form,

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

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 \(X_{XYZ}, Y_{XYZ}, Z_{XYZ}\):

\[
\begin{bmatrix}
Y_R \\
Y_G \\
Y_B
\end{bmatrix} = \begin{bmatrix}
\frac{x_R}{y_R} & \frac{x_G}{y_G} & \frac{x_B}{y_B} \\
1 & 1 & 1 \\
\frac{1-x_R-y_R}{y_R} & \frac{1-x_G-y_G}{y_G} & \frac{1-x_B-y_B}{y_B}
\end{bmatrix}^{-1} \begin{bmatrix}
\frac{x}{y} \\
1 \\
1 - \frac{x - y}{y}
\end{bmatrix}
\]

PIC DEVICE “COLOMIX” ROUTINE

In order to allow easy color mixing, a “ColorMix” routine has been developed in ‘C’, where \(x, y, Y\) values are specified. The PIC device does the matrix inversion and multiplication/scaling to produce the desired color. All calculations are done as integers. Scaling is done throughout, so that values will not overflow the ‘long’ (32-bit) variable type.

If the color calculation reveals a color choice which is outside of the color gamut, the message “outside of gamut” will be sent out the serial port (via ‘printf’) and displayed on the PC monitor window. Developers are free to make use of the “printf” function to send status updates and assist with debug.
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 7: CIE 1931 color space chromaticity diagram with indicated color gamut of CREE® tri-color LED. Coordinates for above diagram are sourced from Table 1: CIE 1931 x y values for CREE® LED as measured with chromameter.

FIGURE 7: CIE 1931 COLOR SPACE CHROMATICITY DIAGRAM

Figure 7 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, $x = 0.33$ and $y = 0.33$

The LEDs used here have the following properties:

$\begin{align*}
   x_R &= 0.6763, \quad y_R = 0.3237 \\
   x_G &= 0.2088, \quad y_G = 0.7408 \\
   x_B &= 0.1405, \quad y_B = 0.0391
\end{align*}$
EQUATION 5: CALCULATION OF WHITE POINT

\[
\begin{bmatrix}
Y_R \\
Y_G \\
Y_B
\end{bmatrix}
= \begin{bmatrix}
x_R/y_R & x_G/y_G & x_B/y_B \\
1 & 1 & 1 \\
1 - x_R - y_R/y_R & 1 - x_G - y_G/y_G & 1 - x_B - y_B/y_B
\end{bmatrix}
\begin{bmatrix}
x \\
y
\end{bmatrix}
\]

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 65,535.

EQUATION 6: CALCULATION OF WHITE POINT

\[
\begin{bmatrix}
Y_R \\
Y_G \\
Y_B
\end{bmatrix}
= \begin{bmatrix}
2.089 & 0.281 & 3.59 \\
1 & 1 & 1 \\
0 & 0.068 & 2.098
\end{bmatrix}
\begin{bmatrix}
1 \\
1 \\
1.003
\end{bmatrix}
\]

\[
\begin{bmatrix}
Y_R \\
Y_G \\
Y_B
\end{bmatrix}
= \begin{bmatrix}
0.5999 & -0.149 & -0.087 \\
-0.5517 & 1.1528 & 0.039 \\
0.0017 & -0.0037 & 0.0475
\end{bmatrix}
\begin{bmatrix}
1 \\
1 \\
1.003
\end{bmatrix}
\]

\[
\begin{bmatrix}
Y_R \\
Y_G \\
Y_B
\end{bmatrix}
= \begin{bmatrix}
0.313 \\
0.64 \\
0.045
\end{bmatrix}
\]
FEATURES TO AID IN DEVELOPMENT

• Programming connectors can be populated in P1 and P2.
• ‘C’ function “ColorMix” creates colors based on xyY color values. The PIC device performs color calculations.
• Power can be supplied through USB port or battery.
• Serial port connection which supports ‘printf’ for output status messages.

The intent of this application note is to increase understanding of color mixing theory, and that it may also provide a starting point for developing colorful/bright applications with the PIC12F1572.

HARDWARE CONFIGURATIONS

The RGB Badge demonstration board is configured and programmed from the factory for operation in Mode 1: HSVW Slider.

To operate the board in Mode 1 HSVW Slider, the PIC12F1572 must be programmed with the RGBSlider software, and the PIC16F1455 must be erased.

To operate the board in Mode 2: xyY Chromaticity Selector, the PIC12F1572 must be programmed with the RGBChroma software, and the PIC16F1455 must be programmed with the RGBChromaUSB software.

To reprogram the PIC12F1572 with the RGBSlider or RGBChroma software, install a programming header on the board at P1.

Note: The HSVW slider function will not function while a programming tool is connected to P1. The ICSP pins are shared with the slider.

To reprogram the PIC16F1455 with the RGBChromaUSB software, or to erase the PIC16F1455, install a programming header on the board at P2.

When operating in Mode 2: xy Chromaticity Selector, the USB to RS-232 conversion is performed through the use of the PIC16F1455.
APPENDIX B:

FIGURE B-1: BILL OF MATERIALS MICROCHIP RGBbadge BOARD

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