AN1257

Closed Loop Chromaticity Control: Interfacing a Digital RGB Color Sensor to a PIC24 MCU

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OVERVIEW

This application note describes interfacing the TAOS TCS3414CS Digital Color Sensor with a PIC24F to establish a closed loop control system for maintaining a consistent chromaticity output for an RGB LED Back-Light Unit (BLU) illumination system for a graphics LCD panel. A chromaticity control system for LED illumination requires five main hardware components: a control processor, a constant current LED driver, RGB LEDs, a color mixing mechanism and a color sensor. Control system firmware and system calibration complete the application to achieve stable chromaticity output control.

The Explorer 16 Development Board, (DM240001) and a custom PICtail™ PCB design create a convenient development environment to explain the requirements for a closed loop control system, achieving a specific Correlated Color Temperature, (CCT). This closed loop color control backlight application can also be applied to general illumination systems.

Control Processor

The Explorer 16 Development Board includes the PIC24FJ128GA010 MCU, which allows easy migration to a low cost device such as the PIC24FJ16GA002. The MCU peripherals needed for this application are: three high-speed, high-resolution PWMs; 1k-2k bytes of RAM; and an I^2C™ bus. The application firmware was written in ANSI-C and uses floating point math to simplify the algorithms.

Constant Current LED Driver

An analog constant current driver, using an op-amp and an FET, was selected for simplicity and inexpensive cost. The circuit requires no real-time MCU resources to operate at constant current. Each of the three PWM outputs is used as an input to the op-amp circuits for dimming and color mix generation. The MCU A/D resources could be used to monitor current and voltage levels for additional design robustness.

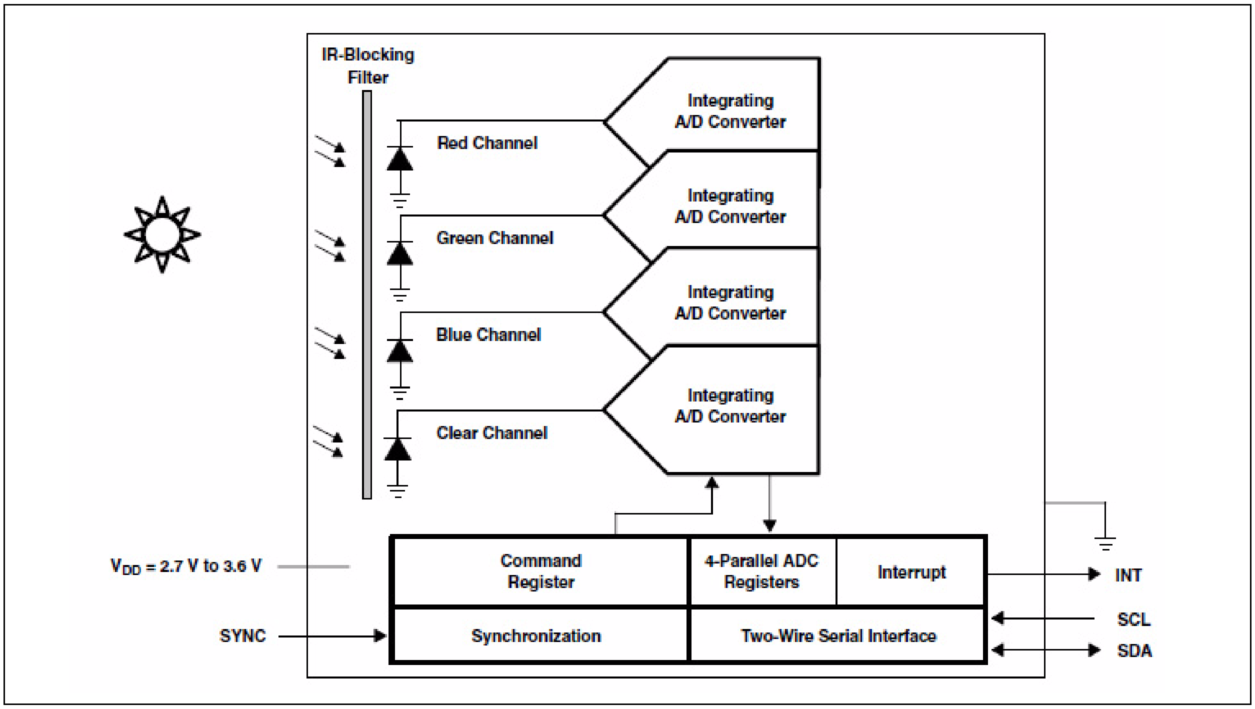
RGB LEDs and Color Mixing Mechanism

A graphics LCD display with integrated LED BLU is the device to be illuminated in this application. The assembled display contains 128 x 64 LCD, 4 parallel RGB LEDS, and an optical light pipe module that blends the RGB LED outputs into a uniform pattern across the LCD surface. In some applications, the color mixing mechanism may be as simple as the physical placement of the LEDs at a specific distance from the surface or object to be illuminated. (The graphics LCD and LCD driver are not used in this application.)

Color Sensor

The TCS3414CS digital color sensor uses the I^2C bus for communication to the setup and configuration registers. The sensor has four integrating ADC registers that enable simultaneous capture of light intensity over the visible spectrum. An IR blocking filter attenuates wavelengths above 680 nm, nearly eliminating IR spectrum contribution. Red, green, blue and clear filters enable the sensor to be calibrated to produce spectral responsivity very close to that of the human eye. Each of the four parallel integrating ADC channels provide a digital 16-bit output, reducing resource demand from the microcontroller, thus eliminating the requirement for high-priced processors.

FIGURE 1: TCS3414CS FUNCTIONAL BLOCK DIAGRAM



The TCS3414CS uses a light to frequency converter to measure the intensity of incident light. The wavelength of the light is filtered by red, green, blue and clear filters. An infrared filter eliminates contributions from wavelengths above 680 nm over the entire spectrum. These RGB filters provide a means to separate the primary wavelengths of the visible spectrum that the human eye perceives as color. The clear filter provides a measure of the intensity of light over the visible spectrum.

The sensor's internal control registers provide the functionality to capture light intensity over fixed integration time periods of a specific number of counts of a specific filter accumulator. Other registers allow amplification of the light, external synchronization of integration periods to optimize the sensor to specific environmental conditions.

The primary purpose of the sensor is to precisely measure the incident visible light and correlate the measured light to the color and amount of light perceived by the human eye.

This correlation is achieved by calibrating a fixed system of LEDs and a light sensor to a known color coordinate system.

Firmware

The firmware will control the system communication with the TCS3414CS sensor, user interface functions and timing as well as the system PI control loop. The system PI control loop requires many floating point operations to be executed in a short time in order for the system to converge on the color target output. (If faster response is required, this system can be adapted to use integer math.)

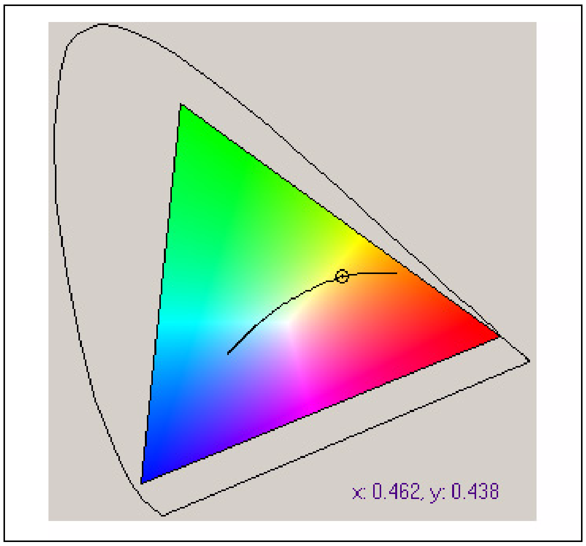
System Calibration

System calibration establishes a mathematical relationship between the unknown system component responses, LEDs and color sensor, and a CIE standard light measurement system using a chroma meter. This relationship enables the system to control and measure the LED output producing the expected output results with a high degree of accuracy over the life of the product.

OPERATIONAL THEORY

To understand the system operation, we will first look at it from a high level. Our goal is to produce a specific color or chromaticity value at a certain brightness or luminance. We want to maintain that selected color and brightness over the life of the product without color shift or loss in brightness. The CIE 1931 chart in Figure 2 provides an x-y coordinate map to the specific color output we want to produce, independent of the luminance level. This becomes the system set point.

FIGURE 2: CIE 1931 CHROMATICITY CHART WITH SYSTEM GAMUT



> **Note:** The maximum brightness will be determined during calibration and then dimming will become a percentage of the maximum. The maximum luminance will not be uniform across the entire gamut, since points near the center of the chart will use all three color emitters, but points near the edges use one or two emitters. The light output from the LEDs will gradually decrease over time as a function of operating temperature. LED lifetime is measured by the L70 curve (the number of hours over time at which the LED can only produce 70% of the original light output). For these reasons, we will select the maximum brightness during calibration at 80% of the maximum possible luminance with all LEDs driven at 100% duty cycle. This will permit achieving the color/luminance set point near the center of the chart for a long time, essentially extending the L70 of the system.

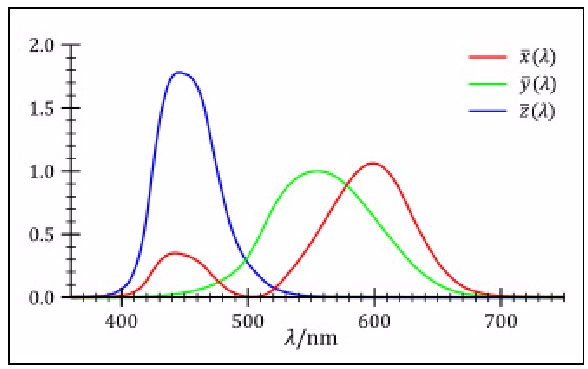
In this application, if the x-y color set point selected cannot be achieved at the given luminance value, the control system is designed to reduce the luminance value until the x-y color set point can be maintained.

Sensor Spectral Response

The set point, calibration matrix and sensor feedback are used by the feedback control system to determine the amount of error between the set point and compensated sensor feedback. The error is calculated for the red, green and blue channels and the PWM outputs are adjusted accordingly.

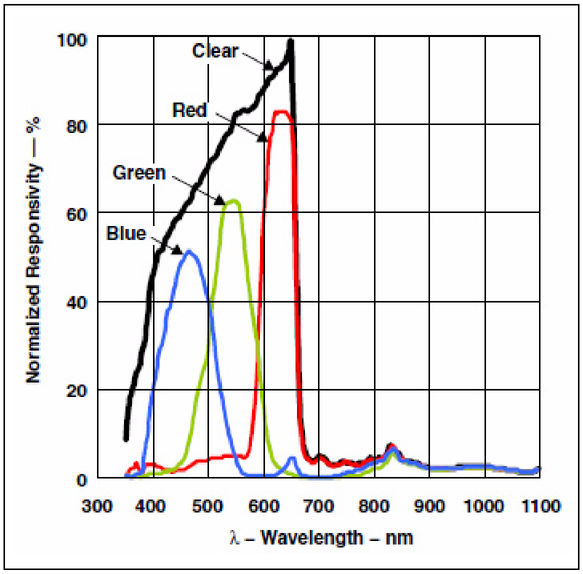
Figure 3 shows the CIE Standard Observer spectral response of the human eye. The human eye response to color is typically illustrated as a response to short, medium and long wavelengths, or, blue, green and red, respectively. The eye's response to these wavelengths is averaged by the brain and perceived as a mixed color. In order for an electro-optical system to match color to the human eye, the sensor must match these spectral response curves or a linear combination of these curves.

FIGURE 3: CIE STANDARD OBSERVER



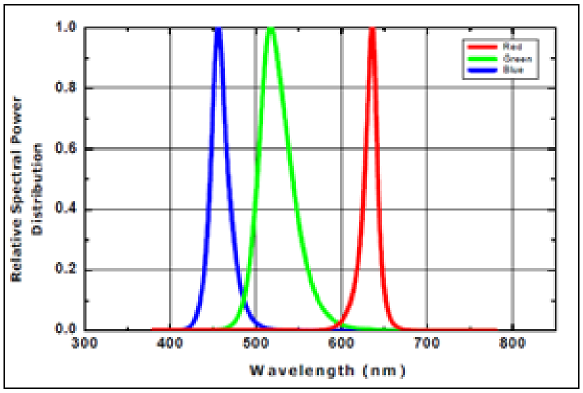
The TCS3414CS RGB sensor contains filters that reproduce this spectral response, enabling it to closely match the response of the human eye. Additionally, the sensor utilizes an infrared (IR) filter that blocks IR energy that would otherwise saturate the sensor. Figure 4 shows the spectral response of the sensor due to these filters.

FIGURE 4: TCS3414CS CS IR AND RGB FILTER SPECTRAL RESPONSE



Another component of the system spectral response is the energy emitted by the RGB LEDs. The wavelength emitted by an LED emitter is generally in a narrow band as shown in Figure 5 for red, green and blue emitters. The RGB LEDs emit 3 distinct wavelengths, which fall within the spectral response of the sensor's filters.

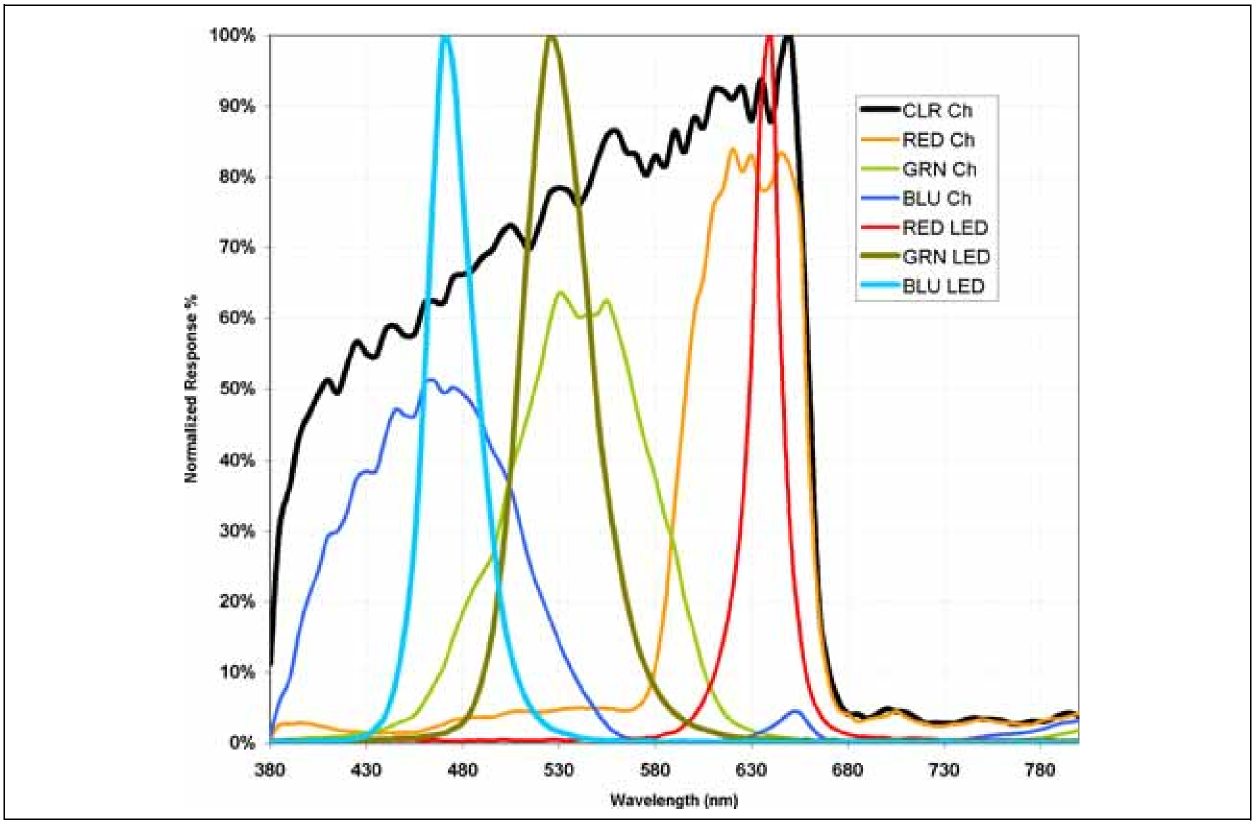
FIGURE 5: SEOUL SEMICONDUCTOR F50360 RGB LED SPECTRAL RESPONSE



This overlap is characterized on the sensitivity chart (refer to Figure 6) for the TCS3414CS.

In order to establish stability in the composite output of the three LED channels, we will make changes to a single channel and measure the effect of that change, then take new sensor readings and calculate the change to the next LED channel and repeat.

FIGURE 6: TCS3414CS AND RGB LED SPECTRAL RESPONSE



Color Coordinate System

In order to reduce the number of coordinate system conversions, we will use the XYZ coordinate system. This XYZ system integrates the RGB color information along with the intensity information into three values that will be indirectly applied to the PWM registers. The calibration matrix will establish a correlation between the RGB sensor data, RGB PWM outputs, RGB LEDs and XYZ coordinate system.

The x-y set point and luminance value will be mathematically converted into the XYZ coordinate system set point, when an output color is selected. The feedback control system will execute all operations based on the XYZ system, eliminating the need for any real-time conversions. XYZ to x-y luminance conversions will only be made periodically for display on the Explorer 16 Demo Board LCD for the user.

Note:	Working with other coordinate systems in our embedded PID control loop would require additional and more complex conversions. RGB data is typically displayed as three 8-bit color values or as x-y coordinates on the CIE 1931 chromaticity chart. While these systems may seem more meaningful to the user, converting from XYZ to either of these systems is complex and puts a much higher demand on the MCU resources and processor time.

CALIBRATION

In order to achieve accurate calibration, the system must use constant current LED drivers. If the LEDs are driven at variable current levels to achieve color mix and dimming, a different calibration process is required and is beyond the scope of this application note.

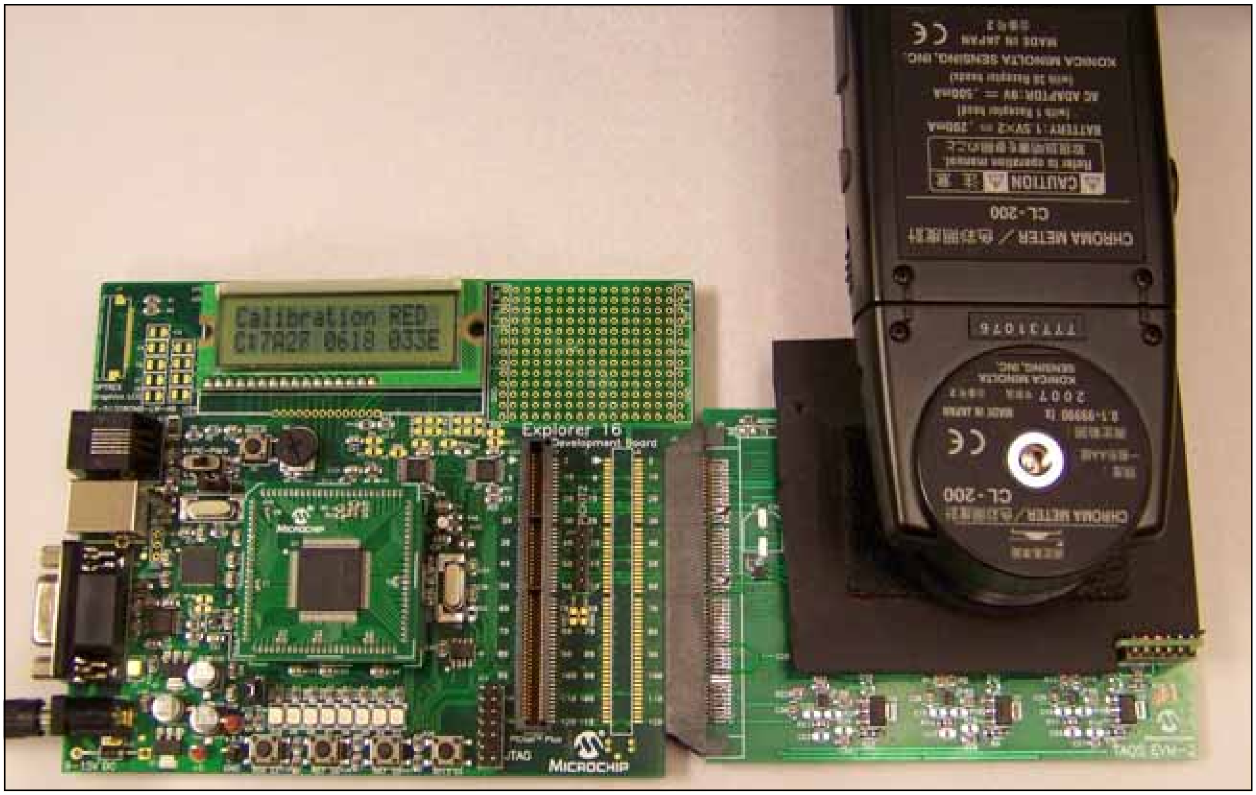
Note:	Successful calibration is completely dependant on the color sensor configuration and the physical arrangement of the sensor, LEDs and optical color mixing mechanism. In order to collect meaningful data from the sensor for calibration, the sensor must be configured the same as it will in our application. For this section of the application note, we will ignore the sensor configuration. The sensor configuration will be discussed in **"TCS3414CS Configuration"**.

Calibration Procedure – Setup

A Konica Minolta CL-200 chroma meter is used to collect chromaticity data from the RGB LED BLU system. This data is then used to create a calibration coefficient matrix to correlate the system output to the human eye response, producing the expected light output. A test setup, Figure 7, holds the RGB LED BLU in a fixed position and the chroma meter at a fixed position and distance from the BLU surface. The test setup is placed in a darkened chamber to eliminate ambient light contributions, providing data that is purely a response of the system.

The chroma meter is set up in XYZ mode and displays values for X, Y and Z.

FIGURE 7: SYSTEM CALIBRATION SETUP



Calibration Procedure – Data Collection

With the BLU and chroma meter in position, the red PWM is set to 100% duty cycle, while the green and blue PWMs are set to 0% duty cycle. This produces the maximum output from the red LED, with no output from the others. The RGB values from the TCS3414CS and the XYZ values from the chroma meter are recorded in the Calibration Data Entry section of the Calibration Worksheet, shown in Figure 9.

Note:	When recording the sensor values due to a single LED, you will see that the sensor measures a higher value for the clear filter and lower values for the other filters with respect to the corresponding filter. This is due to the spectral overlap of the TCS3414CS filters as previously seen in Figure 4.

This process is repeated with the red, green and blue PWMs at 0% and 100% with 0% duty cycle, and then PWMs at 0% and 0% with 100% duty cycle. The data recorded will be used to correlate the RGB LEDs and color sensor system to the CIE Standard Observer reference. The recorded data also establishes the system color gamut. The color gamut is the triangle formed inside the CIE chart by the maximum red, green and blue obtainable points, and quantifies the potential colors that can be produced by the system.

The demo system firmware is setup with a calibration mode that will display the red, green and blue sensor values for LED output settings of 100% for each LED, as well as all three LEDs at 100% and 0%. The 0% setting allows the user to see any noise detected by the sensor in a dark environment or the ambient contributions.

FIGURE 8: CALIBRATION VALUE ON EXPLORER 16 DISPLAY

Calibration Matrix – The Math

$C = M * T$, where C (chroma meter XYZ value), M (Calibration Matrix) and T (TCS3414CS RGB sensor data) are 3 x 1, 3 x 3 and 3 x 1 matrices, respectively.

The 3 x 3 matrix "M" is a transfer function that is derived by calibrating the system as described above. Solving for "M":

$$M = C * T–1$$

Example data is provided in the Calibration Worksheet, Figure 9, and used in the following example to help illustrate the calibration mathematics required.

FIGURE 9: CALIBRATION DATA ENTRY

GENERAL INFORMATION

Data Entry Cells	X= (x/y)*Y	M=	T^{-1}*X
Calculated / Transferred Data	Z= ((1/y)-(x/y)-1)*Y	X=	T*M
	Y= given	M=transfer RGB->XYZ matrix	
	x= X/(X+Y+Z)	X=XYZ meter data	
	y= Y/(X+Y+Z)	T=RGB sensor data	

CALIBRATION DATA ENTRY

TCS3414 Sensor Count (Hexidecimal)

T Matrix (Hex)	RED 100%	GREEN 100%	BLUE 100%	RGB 0%	RGB 100%
R	82BE	14C8	11A4	E	A540
G	656	7EB6	2F62	F	AC5E
B	38D	3A92	A590	A	DD5B

CL 200 XYZ Data (Decimal)

X Matrix	RED 100%	GREEN 100%	BLUE 100%	RGB 0%	RGB 100%	Ymax	80% Ymax
X	91.9	25.3	40.8	0.0	140.6		
Y	41.1	89.7	19.4	0.0	135.3	135.3	108.24
Z	0.0	11.7	231.1	0.0	223.7		

VERIFICATION - If the Calibration Matrix is accurate, we should be able to take any sensor data and apply the Matrix and calculate the same XYZ values that we collect from the Chroma meter.

		Sensor Data Hex	Sensor Data Decimal		Calculated XYZ Matrix	Calculated XYZ Algebraic
Enter Data >>	R	82BE	33470	X	91.9	91.9
Enter Data >>	G	656	1622	Y	41.1	41.1
Enter Data >>	B	38D	909	Z	0.0	0.0

	xyY
x	0.6910
y	0.3090
Y	41.1

CALCULATED CALIBRATION INFORMATION

TCS3414 Sensor Count (Decimal)

T Matrix (Decimal)	RED 100%	GREEN 100%	BLUE 100%	RGB 0%	RGB 100%
R	33470	5320	4516	14	42304
G	1622	32438	12130	15	44126
B	909	14994	42384	10	56667

The potential RGB LED Gamut is defined by the XYZ coordinates with Each LED @ 100%

X	RED 100%	REEN 100	BLUE 100%
X	91.9	25.3	40.8
Y	41.1	89.7	19.4
Z	0.0	11.7	231.1

T^{-1} Inverse T Matrix

0.0000301	-0.0000040	-0.0000021
-0.0000015	0.0000357	-0.0000101
-0.0000001	-0.0000126	0.0000272

M Matrix Calibration Matrix (|X| * |T^{-1}|)

0.0027265	0.0000255	0.0006648
0.0011049	0.0027969	-0.0004605
-0.0000472	-0.0024827	0.0061681

Gamut	Red (x,y)	Green (x,y)	Blue (x,y)
x	**0.6910**	**0.1997**	**0.1401**
y	**0.3090**	**0.7080**	**0.0666**

FINAL CALIBRATION DATA

Cal Matrix	0.0027265	0.0000255	0.0006648
Cal Matrix	0.0011049	0.0027969	-0.0004605
Cal Matrix	-0.0000472	-0.0024827	0.0061681
Gamut Rxy	0.6910	0.3090	
Gamut Gxy	0.1997	0.7080	
GamutBxy	0.1401	0.0666	
Ymax (luminance)	108.24		

The data collected forms two 3 x 3 matrices.

The data collected from the chroma meter is:

$$\mathbf{C} = \begin{bmatrix} Xr & Xg & Xb \\ Yr & Yg & Yb \\ Zr & Zg & Zb \end{bmatrix} = \begin{bmatrix} 1914 & 301 & 406 \\ 921 & 1086 & 281 \\ 0 & 157 & 2242 \end{bmatrix}$$

And the data collected from the sensor is (converted from hexadecimal to decimal):

$$\mathbf{T} = \begin{bmatrix} Rr & Rg & Rb \\ Gr & Gg & Gb \\ Br & Bg & Bb \end{bmatrix} = \begin{bmatrix} 6210 & 465 & 524 \\ 308 & 2838 & 1270 \\ 180 & 1404 & 5449 \end{bmatrix}$$

The equation for the calibration matrix is:

$$M = C \bullet T^{-1}$$

where T^{-1} is the inverse matrix of T

An Excel spreadsheet (CalibrationWorksheet.xls) is provided with this application note to calculate the calibration matrix as well as the inverse of Tcs. As a convenience, the spreadsheet also calculate the x-y coordinates for the gamut of this system.

Using the spreadsheet, T^{-1} is:

$$Tcs^{-1} = \begin{bmatrix} 0.000162 & -0.000021 & -0.000011 \\ -0.000017 & 0.000401 & -0.000092 \\ -0.000001 & -0.000103 & 0.000207 \end{bmatrix}$$

and M is:

$$M = \begin{bmatrix} 0.004516 & 0.000279 & 0.001500 \\ 0.001788 & 0.006323 & -0.000838 \\ -0.000103 & -0.0052222 & 0.012514 \end{bmatrix} = \begin{bmatrix} m11 & m12 & m13 \\ m21 & m22 & m23 \\ m31 & m32 & m33 \end{bmatrix}$$

Now X, Y and Z can be calculated from calibration matrix M and the sensor data Tcs using the equation:

$$C = M \bullet T$$

or

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} m11 & m12 & m13 \\ m21 & m22 & m23 \\ m31 & m32 & m33 \end{bmatrix} \bullet \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

This matrix math function can be represented in algebraic form, which is easier to program and calculate in firmware.

$$X = (R \bullet m11) + (G \bullet m12) + (B \bullet m13)$$
$$Y = (R \bullet m21) + (G \bullet m22) + (B \bullet m23)$$
$$Z = (R \bullet m31) + (G \bullet m32) + (B \bullet m33)$$

We can verify that our equations are correct by plugging in the Tcs values collected for the calibration. The output of the X, Y and Z equations should match the data collected by the chroma meter.

Closed Loop Control System

In our closed loop system, the PWM duty cycles will be adjusted based on compensated feedback from the sensor using the calibration matrix. Adjustments to each PWM will be made until the feedback error is within a predetermined error margin.

Free Run Mode – PWM Sync

By using the sync input pin on the TCS3414CS, the measurement integration period is controlled in even multiples of the PWM period. This eliminates “ripple” in the sensor counts, and permits a very stable control system.

HARDWARE

The hardware for this system is captured in two schematics. The first is for the Explorer 16 Development Board and can be found in the Explorer 16 Development Board User’s Guide (DS51589). The second, for the PICtail™ PCB designed for this application, can be found in **Appendix A: “PICtail™ PCB Schematic”**. Since the Explorer 16 Development Board is a standard demo, we will not discuss that schematic, but we will discuss the interface signals that are used by the RGB LED BLU PICtail™ board. The PICtail board for this application consists of four main sections: the analog constant current drivers, the RGB LED BLU, the TCS3414CS interface and the Explorer 16 Development Board PICtail Plus interface. The block diagram in Figure 12 illustrates the hardware system.

SYSTEM COMPONENT PHYSICAL ARRANGEMENT

In order to achieve a reliable and stable control system, optimizing the physical placement of the sensor is critical. The LED colors are mixed by the integrated color mixing light guide, which provides a uniform color across the BLU surface. The sensor should be positioned to collect an amount of color mixed light that is significantly higher than the ambient light. In this application, the sensor interface board is positioned at the edge of the BLU light guide 90 degrees to the BLU surface. Figure 10 shows the Sensor Interface PCB and Figure 11 Illustrates the Sensor Interface PCB placement with respect to the RGB LED BLU light guide.

FIGURE 10: RGB SENSOR PCB

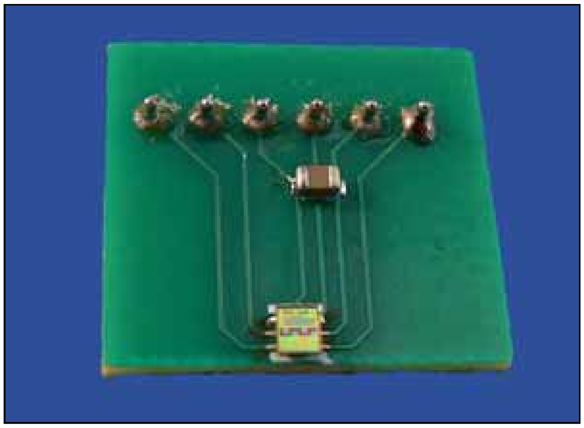


FIGURE 11: RGB SENSOR PLACEMENT

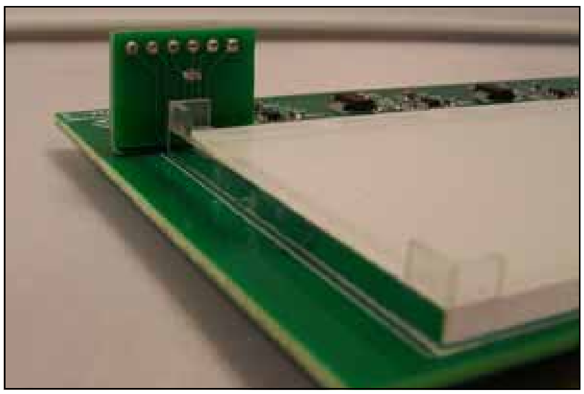
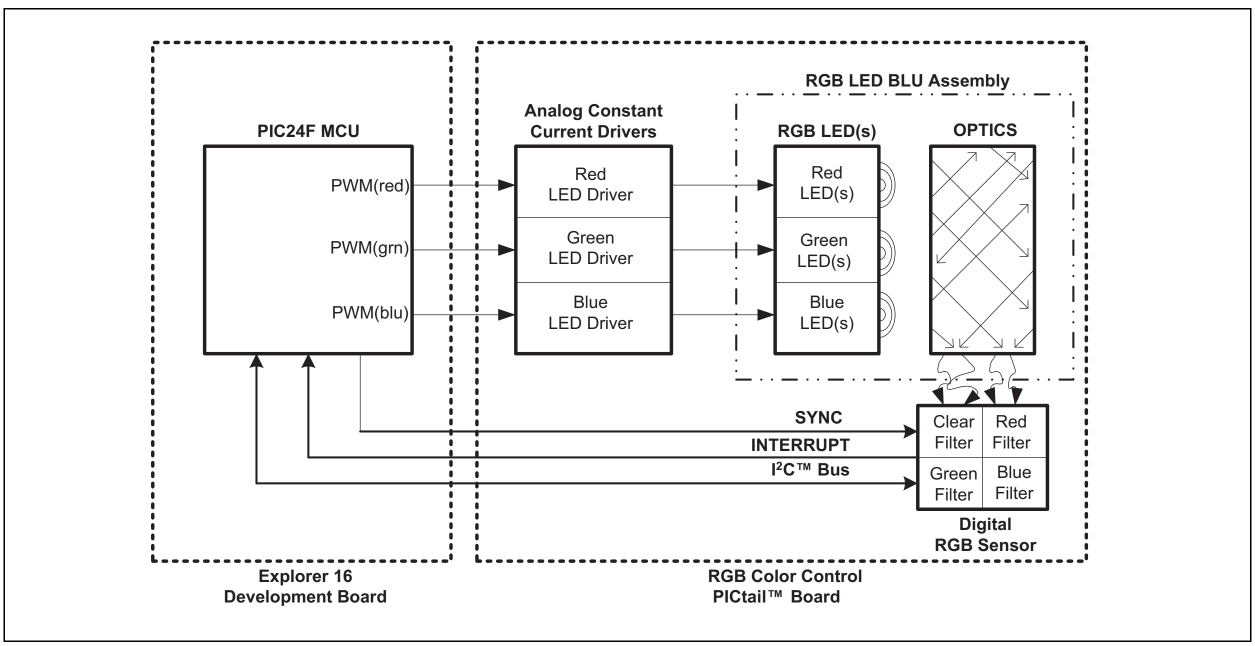


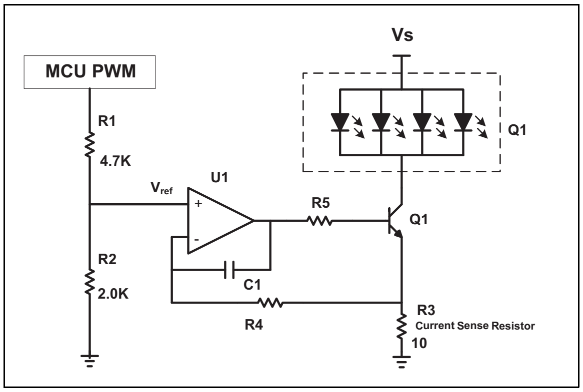
FIGURE 12: HARDWARE SYSTEM BLOCK DIAGRAM



Analog Constant Current Driver

The analog constant current driver is designed to take advantage of the power supply sources available on the Explorer 16 Demo Board platform. The op-amp circuit is configured as an error amplifier that controls the LED current by monitoring the voltage across an LED current sense resistor and a voltage divider powered by the MCU. The op-amp adjusts the base current of a BJT to make the voltage on the current sense resistor match the reference voltage provided by the voltage divider.

FIGURE 13: ANALOG CONSTANT CURRENT DRIVER



Current is controlled by adjusting VREFOUT and the value of R3 to produce the current output desired by using Equation 1.

EQUATION 1:

$$Iout = \frac{VREFOUT}{R3}$$

The op-amp will try to keep VREFOUT = VREFSP. Therefore, we need to determine a value for VREFOUT and VREFSP. The input to voltage divider formed by R1 and R2 is one of the PWM outputs of the PIC24F MCU. The DC voltage output of the PWM is nominally = VDD (3.3V).

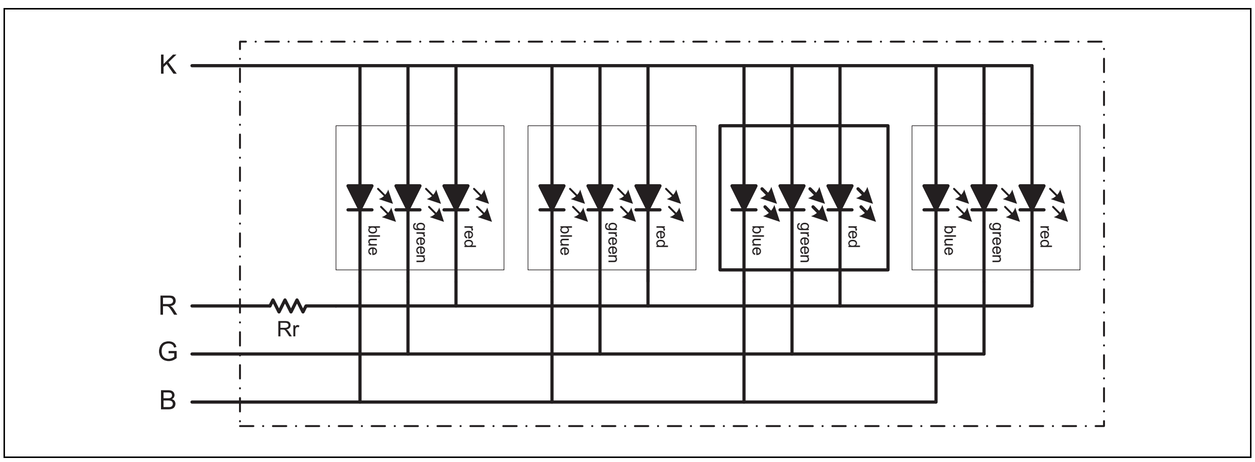
The MCP6021 op-amp was selected for its 10 MHz gain bandwidth product, which allows the output to drive from rail to rail within a couple of bit times of the PWM, allowing finer resolution control.

RGB LED BLU Module

The RGB LED BLU selected for this application is integrated in a Displaytech 128 x 64 Graphics LCD module, P/N S64128MFCBW-RGB. The LCD glass is easily removed from the BLU module to make the light from the BLU more visible in this application.

The BLU incorporates a small PCB with 12 LEDs: four red, four green and four blue. The forward current, If, of the LEDs is specified at 20 mA, and each color is configured in parallel, resulting in 80 mA per LED string. The forward voltage, Vf, of each LED string is specified at 3.2V.

FIGURE 14: RGB LED CONFIGURATION SCHEMATIC



Note:	Driving the LED strings at 80 mA results in thermal rise on the LED PCB that cannot be easily dissipated. This rise in thermal conditions causes the LED outputs to drift when an LED string was driven near 100% duty cycle. In order to eliminate the output drift in the LEDs, the driver circuit must be reduced to drive at 55 mA. This eliminates the thermal issue and allows a stable control system.

TCS3414CS Interface

The TCS3414CS communicates via an I^2C bus to setup the configuration registers at up to 400 kHz, (the TCS3404 uses SMBus up to 100 kHz). The sensor has many advanced features that can be used to increase accuracy, speed or be used for applications that require syncing the integrated capture to timing signals, such as video. In this application, we will concentrate on the basic use of the sensor for closed loop chromaticity control.

Operating the I^2C bus at 400 kHz allows us to minimize the time required for communication with the sensor. Reading the four 16-bit ADC registers uses 310 uS. The time required to transfer data over the I^2C bus is displayed in Figure 16.

Most of the MCU processing time is spent waiting in an Idle condition, but when data is ready, we want the MCU to collect and process the information as quickly as possible avoiding data collisions and race conditions.

FIGURE 15: TCS3414CS INTERFACE SCHEMATIC

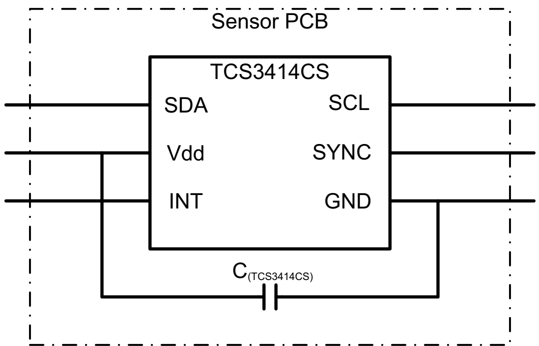


FIGURE 16: TCS3414CS I^2C™ READ OF ADC REGISTERS

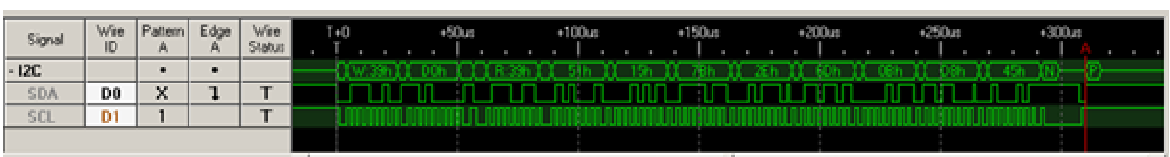
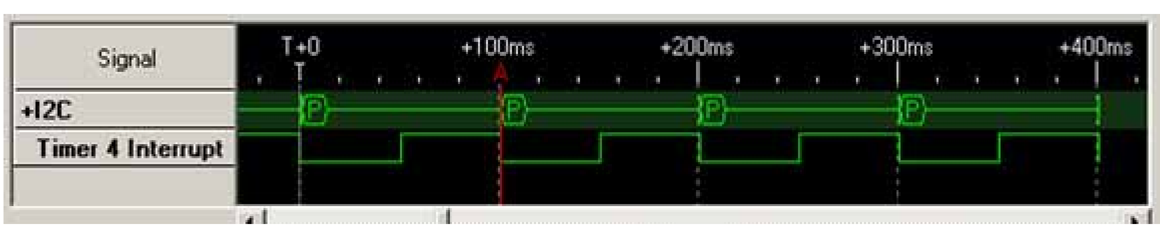


FIGURE 17: INTEGRATION TIMING USING TIMER4 INTERRUPT



PERIPHERAL AND SENSOR INITIALIZATION

Timer4 – System Clock

Timer4 is initialized to generate an interrupt every 50 mS. This interrupt will be used a the system time base.

Timer2 – PWM Clock

Timer2 is initialized to generate a 62.5 nS time base for the PWMs. This translates to a PWM period of 4.096 mS.

I2C1 Peripheral

The I2C1 peripheral is initialized to operate at a baud rate of 400 kHz. The I2C1 is used to communicate with the TCS3414CS and the calibration EEPROM. The calibration data could be stored on the MCU Flash memory in a solution where the LED's sensor and MCU are assembled as a single unit.

TCS3414CS Configuration

The Timing register is setup to operate in "sync in" mode, using the rising edge of the sync in signal to start and stop integration counters every 4 PWM periods. The Gain Register is setup for an analog gain of 64x and a digital prescale divide of 1. The Interrupt Control, Interrupt Source and Interrupt Threshold registers are not used and are left in the default Reset state.

The selected gain and sync count were determined during testing such that the ADC register value was maximized, but did not overflow when the system was operating at 100% brightness. This configuration requires an integration time of approximately 16.4 mS.

CONTROL SYSTEM FIRMWARE

The system control operation is described by the flowchart (refer to Figure 18). A small percentage of the system loop time is used to determine the output light color and calculate the necessary changes to adjust the PWMs for a more accurate color output. The majority of time is required by the sensor for the integration period capturing the LED output. Since the sensor integration period requires no CPU resources, it is convenient to use this time to handle other system functions such as communications, display updates, key scan, etc.

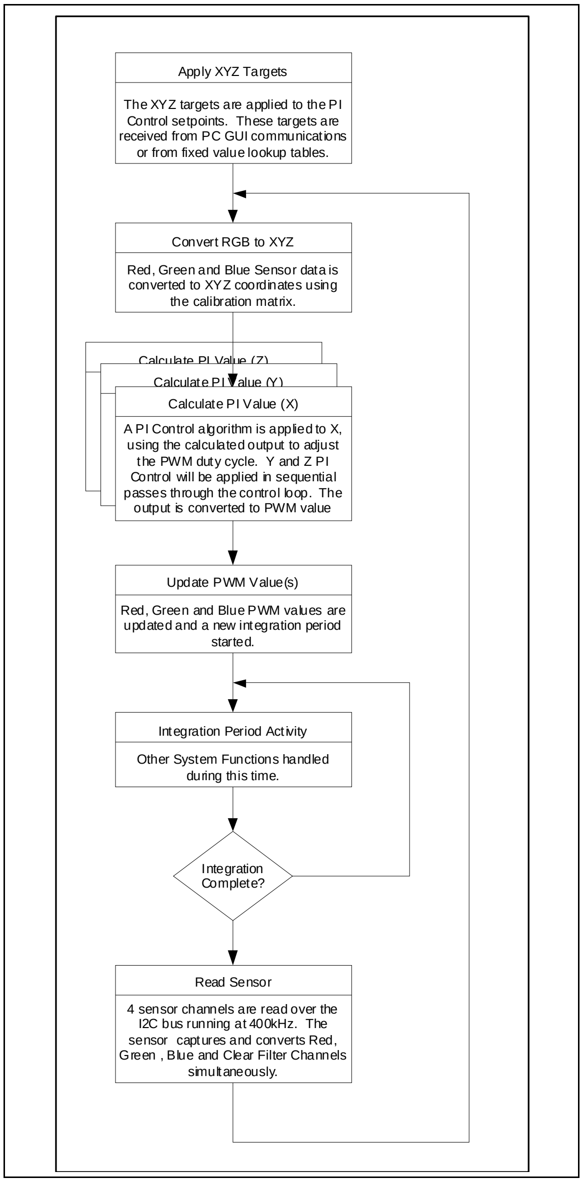
The sensor allows an external sync source to trigger integration periods based on the programmable number of sync pulse edges. Using the PWM output as the sync input allows the integration registers to measure exact intervals of light produced per PWM period. The number of periods captured can be set in the Timing register, from 1 to 256 pulses (in powers of 2).

The integration period needs to be balanced with light intensity to provide the best gamut resolution. A longer integration period permits more data to be collected increasing the system resolution. Averaging the data over multiple integration periods increases the noise immunity of the system. In a high brightness system, a long integration period may cause the 16-bit count registers to overflow, resulting in unusable data. In a low light environment, a short integration period may not provide enough counts to produce the color resolution required.

If the system requires high speed response a long integration period will not be acceptable. For example, if the integration time is 400 mS, the minimum cycle time for three LEDs to be adjusted will be about 1.2 seconds, (additional time is required to execute the control functions outside the integration period x 3).

Let's examine each functional block.

FIGURE 18: CONTROL SYSTEM FLOWCHART



Apply XYZ Targets

The CIE 1931 chromaticity chart provides color coordinates in the x-y plane independent of luminance. Because this coordinate system is independent of luminance, it provides a color reference that is easily understood (identifiable) by most people.

Inherently, the sensor measures the color as well as luminance. Since the XYZ coordinate values contain both color and luminance values, using the XYZ coordinate minimizes the number of real-time conversions necessary for the control system, and is the coordinate system of choice for this application.

These color set points may be communicated from an external controller (a PC GUI) or a lookup table of predetermined target values. It is more convenient to apply the color set point in terms of x-y coordinates and luminance.

The variables `XYZ_Xt`, `XYZ_Yt` and `XYZ_Zt` are used for the target values.

X, Y and Z are related to the x, y and Y values typically seen on the CIE 1931 Chromaticity Chart in the following equations:

$$X = (x/y) \bullet Y$$

$$Y = Y$$

$$Z = ((1-x-y)/y) \bullet Y$$

Given that x, y and Y are nominally in the range [0.0, 1.0], then X, Y and Z will be in the range [0.0, 1.0]. A value of y = 0 is not valid, since it will cause a divide by zero and would be outside the standard CIE 1931 Chromaticity Chart.

Convert RGB to XYZ

Once the sensor data is collected, a calibrated conversion is required to normalize the data in terms of XYZ coordinates, taking into account the spectral response of the sensor and the LED emitters. This conversion provides a quantified response to a known reference, the chroma meter.

CODE FUNCTION

```
void ConvertRGB2XYZ()   // Calculating Feedback
{
    PI_XYZ[0].Sensor  = (float)A2D[F_RED] * Mcal[0];
    PI_XYZ[0].Sensor += (float)A2D[F_GRN] * Mcal[3];
    PI_XYZ[0].Sensor += (float)A2D[F_BLU] * Mcal[6];

    PI_XYZ[1].Sensor  = (float)A2D[F_RED] * Mcal[1];
    PI_XYZ[1].Sensor += (float)A2D[F_GRN] * Mcal[4];
    PI_XYZ[1].Sensor += (float)A2D[F_BLU] * Mcal[7];

    PI_XYZ[2].Sensor  = (float)A2D[F_RED] * Mcal[2];
    PI_XYZ[2].Sensor += (float)A2D[F_GRN] * Mcal[5];
    PI_XYZ[2].Sensor += (float)A2D[F_BLU] * Mcal[8];
    a3d = A2D[F_RED];
}
```

CALCULATE PI VALUE

```
void CalcPI_XYZ(int axis)
{
    float PIout;
    int pass = 0;
// ******  For Debug / Tuning of PI Control
    PI_XYZ[0].Ki = (float)kix;
PI_XYZ[1].Ki = (float)kiy;
PI_XYZ[2].Ki = (float)kiz;
PI_XYZ[0].Kp = (float)kpx;
PI_XYZ[1].Kp = (float)kpy;
PI_XYZ[2].Kp = (float)kpz;
// ******  For Debug / Tuning of PI Control
    PI_XYZ[axis].Error = (PI_XYZ[axis].Target - PI_XYZ[axis].Sensor);
    if(PI_XYZ[axis].Saturate == 0x02)
    {
        while((PI_XYZ[axis].Error > 0) && (++pass < 10))
        {
            AdjustLuminance();
            PI_XYZ[axis].Error = (PI_XYZ[axis].Target - PI_XYZ[axis].Sensor);
        }
    }
    if((PI_XYZ[axis].Error > ErrorThreshold) || (PI_XYZ[axis].Error < -ErrorThreshold))
    {
        PI_XYZ[axis].Stable = 0;
        if(PI_XYZ[axis].Saturate == 0x00)
            PI_XYZ[axis].ErrorSum += PI_XYZ[axis].Error;
        PIout = PI_XYZ[axis].Kp * PI_XYZ[axis].Error + PI_XYZ[axis].Ki * PI_XYZ[axis].ErrorSum;
        PI_XYZ[axis].Saturate = 0x00;
        if( PIout <= MinLimit )
        {
            PI_XYZ[axis].Saturate = 0x01;
            PIout = MinLimit;
        }
        if( PIout >= MaxLimit)
        {
            PI_XYZ[axis].Saturate = 0x02;
            PIout = MaxLimit;
        }
        PI_XYZ[axis].Output = (int)((PIout*(float)PWM_FULL_SCALE) * 0.0001);
    }else
        PI_XYZ[axis].Stable = 1;
}
```


Update PWM

Updating the PWM is performed by two functions: `SetValuePWM()` and `UpdatePWM()`. The first function is used as a placeholder for the newly determined PWM values. The second functions copies the values into the PWM registers so that all PWMs are updated together on the start of the next PWM cycle. This method is used as a double buffering method, to maintain calculated PWM values while toggling through the demo system's operating modes.

EXAMPLE 1: UPDATE PWM

```
void SetValuePWM()
{
    PWMred = PI_XYZ[0].Output;// copy output value from PI structure
    PWMgrn = PI_XYZ[1].Output;
    PWMblu = PI_XYZ[2].Output;
}

void UpdatePWM()
{
    OC2RS = PWMred;// copy to the PWM channel for RED LED
    OC3RS = PWMgrn; // copy to the PWM channel for GREEN LED
    OC1RS = PWMblu; // copy to the PWM channel for BLUE LED
}
```

Integration Period

The sensor integration period is configured to integrate over four PWM cycles.

During this time period, the system processes other activities such as button presses, display updates, communications, etc. An interrupt will trigger the next PI control loop activity. This interrupt can be from a timer, a PWM cycle or from the sensor interrupt pin indicating the previous integration period is complete. In this application, the timer interrupt is used, updating the system every 100mS.

If a faster system response is required, the system can use the sensor interrupt pin. Some additional firmware will be required to clear the interrupt and restart the integration period.

Read Sensor

The sensor is read using the I^2C bus and reading the ADC channel registers. The data is configured low byte/high byte for each of the four channels (green, red, blue and clear). The ADC registers can be individually addressed or read sequentially, as in this application. The clear channel data is ignored, except during calibration.

TUNING THE PI LOOP COEFFICIENTS USING MPLAB® IDE DMCI

The general equation for PI control is:

$$Output = Kp \bullet Error + Ki \bullet \Sigma Error$$

where Kp and Ki are coefficients that need to be determined to provide a system response that reaches stability as quickly as possible. Each control loop is designed to have a unique set of coefficients but, in reality, using the same Kp and Ki for each control loop will work well.

For this application, we have three sets of coefficients, which are:

PI_XYZ[axis].Kp and PI_XYZ[axis].Kp

where “axis” is the X, Y or Z axis control loop

Kp and Ki need to be determined once for the system design and should be independent from the individual unit calibration.

Usually, tuning the PI control system would be accomplished by connecting an oscilloscope to the output channels and reprogramming the coefficients to see the response.

A new tool that is available in MPLAB IDE is the Data Monitor Control Interface, DMCI. This interface is supported using the MPLAB REAL ICE™ in-circuit emulator or the MPLAB ICD 3 debugger. A feature of the DMCI, Dynamic Data Control and Dynamic Data Input, allows the user to use some simple buttons and sliders on a PC GUI, assigning input variables from the firmware application to each gadget. This allows the user to change the variable values in the MCU in real time without reprogramming the device.

The other feature that makes the DMCI extremely useful for tuning the PI control loop, is the Dynamic Data View. This feature allows the user to declare up to 4 arrays of data to be displayed graphically in the PC GUI window as the MCU executes firmware, acting as an oscilloscope.

For more information about using the Data Monitor Control Interface, see the “*Real-Time Data Monitor User's Guide*” (DS70567) on the Microchip website, www.microchip.com.

REFERENCES AND LINKS

- http://www.brucelindbloom.com/

  This site contains useful calculators related color coordinate systems and standards. It also contains many useful equations related to color coordinate systems.

- http://www.taosinc.com/

  “*TCS3414CS Data Sheet*”, TAOS Inc.

- http://www.displaytech-us.com/

  “*64128M-RGB Series Data Sheet*”, DisplayTech Ltd.

- http://www.microchip.com/

  “*PIC24FJ128GA010 Family Data Sheet*” (DS39747), Microchip Technology Inc.

  “*Explorer 16 Development Board User’s Guide*” (DS51589), Microchip Technology Inc.

  “*Real-Time Data Monitor User’s Guide*” (DS70567)

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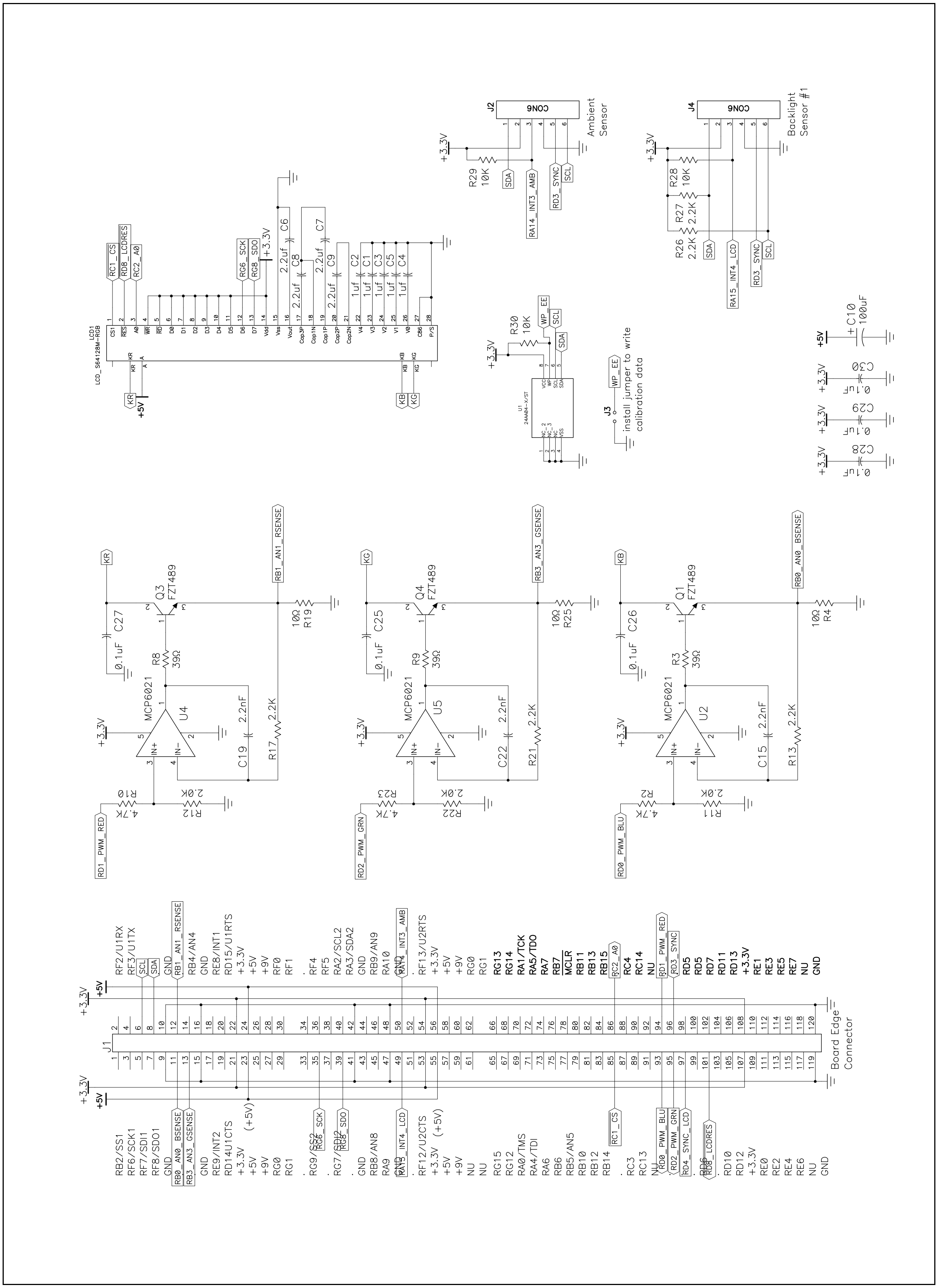
APPENDIX A: PICtail™ PCB SCHEMATIC



REVISION HISTORY

Rev A Document (7/2009)

Original version of this document.

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