ADAPTIVE LIGHTING

By

Jered Greenspan
Madhav Khanna
Sichao Wang

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TA: Ryan May

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Abstract
We demonstrate an adaptive lighting system in which feedback from a color sensor is used to drive an RGB LED array to achieve the correlated color temperature (CCT) and brightness set by the user. Users of the system will benefit from the reduced energy consumption and the controllability. The settling time to reach the user setpoint is about ten seconds, but faster performance can be obtained with better tuning.

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1. Introduction

Lighting accounts for a substantial portion of energy consumption in homes and offices worldwide. More importantly, a lot of artificial lighting in use is not necessary, as there might be lighting in use well beyond the required intensity for a given activity, or lights are on when people are not present.

Our project involves an adaptive lighting system that responds to the environment in setting desired correlated color temperature (CCT) and intensity of light for a work surface. A sensor unit can be set on a table or other area to be illuminated. The sensor wirelessly transmits to a microcontroller on the light which controls an RGB LED lamp, and the desired setpoint is achieved within a few seconds. This system helps reduce overall lighting consumption and maintains a lighting environment that is both constant in a changing environment, and provides controllability that users can enjoy. As external lighting conditions become brighter, the LEDs dim. Thus our system also functions as a “daylight harvesting” device.

2 Design

Our system consists of three major units: (1) a Lighting Unit that contains the LED array and LED driver, (2) a Sensor Unit that transmits sensor readings and user settings, and (3) a Lighting Controller which process user setpoint and sensor values in driving the light to the setpoint. The LED lighting enclosure is mounted together with the PIR occupancy sensor and the main microcontroller inside a lamp enclosure. The sensor unit is placed under the lamp on a table.

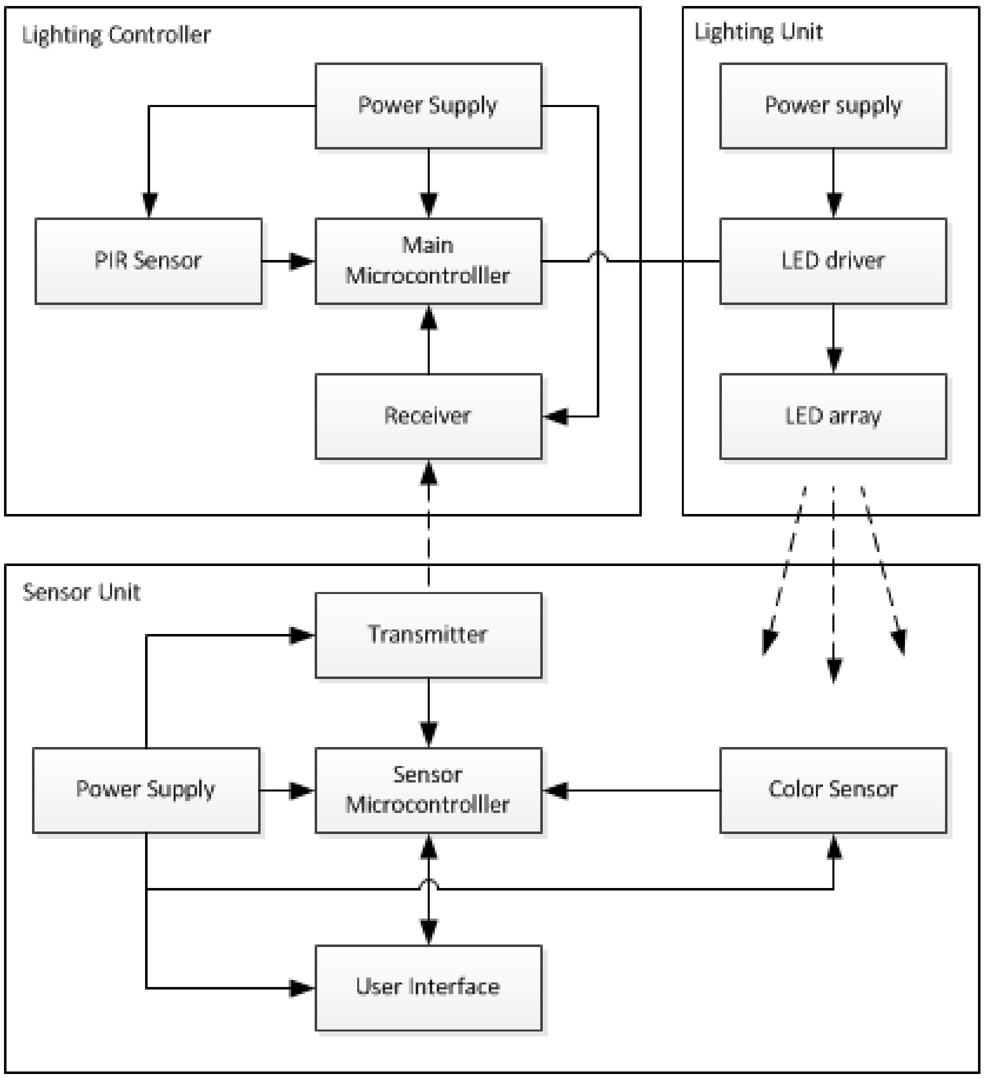

Figure 1: System Block Diagram

2.1 Lighting Unit

Our lighting unit consists of an RGB LED array, LED driver circuit and custom power supply. Since LED current is very sensitive to changes in voltage, the LEDs need to be current-limited. We designed a driver circuit to power 9 3-W RGB LEDs. We planned to connect each of the color channels of the LEDs in a series "string" which is driven by the driver circuit as described below. So we designed are lighting unit to have 3 such driver circuits on one board. Each of the drivers were designed to the entire LED string for each color.

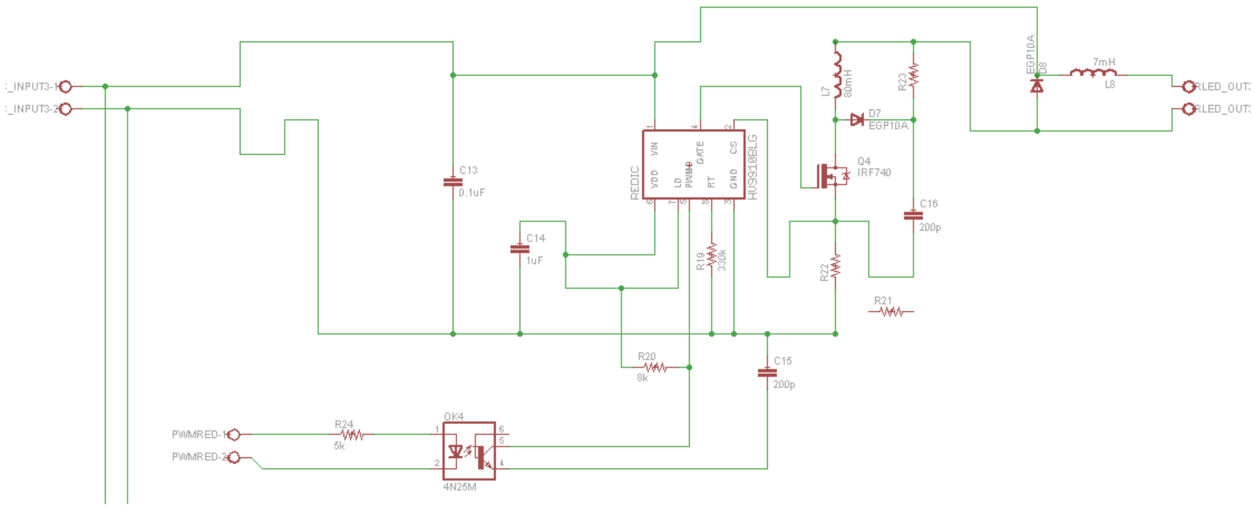

Figure 2: LED Driver Circuit

We used a HV9910 IC, which is an LED driver that can drive multiple high power LEDs. LED dimming is accomplished by setting a pulse width modulated signal to the PWM_D pin with a low frequency such as 500 Hz. For PWM operation, the PWM_D signal is connected to the VDD pin. When enabled, the rising edge of the internal clock turns on the gate driver of external power MOSFET, causing the inductor current to ramp up. When the voltage of the current sense pin (CS) of the IC exceeds a threshold the gate drive signal becomes low and the external MOSFET turns off. This causes the current to through the inductor to decay until the next rising edge of the clock. Thus the current is regulated.

The PWM frequency is very small compared to the converter switching frequency, but it is still sufficiently large such that flickering in the LEDs cannot be seen.

2.1.1 Replacement LED Driver
The LED driver circuit failed due to a PCB error. To meet the deadline for the demonstration, we devised a replacement circuit to be described below.

2.1.2 Lighting Specifications
The luminous flux for the three color channels are 60, 55, and 20 lumens for the red, green, and blue LEDs respectively. Therefore the total luminous flux of the light is the number of fixtures times the sum of the flux of each of the LEDs. Therefore the maximum possible luminous flux that can be obtained with this light is 9(60+55+20)=1215 lumens. By comparison a typical 60 W incandescent outputs 840 lumens. So our system was designed to yield sufficient lighting for desktop use. In order to achieve color mixing to achieve white light we designed our system to include a diffuser.

2.2 Sensor Unit
We designed the sensor unit to consist of a color sensor, a microcontroller, a transmitter, and user interface elements.

2.2.1 Color sensor

To detect color we used a TAOS TCS3200, programmable color light to frequency IC. The output of the color sensor is a square wave with 50% duty cycle, whose frequency is directly proportional to received light intensity. The sensor has an 8x8 array of photodiodes with 16 photodiodes having red filters, 16 having green filter, 16 having blue filters, and 16 having no filter. The lens is 2.8 mm in diameter. Only one color channel of output can be selected at a time using two control pins. The output frequency of the sensor ranged from 2 Hz-150 kHz. If we wait for the microcontroller to capture 16 periods of the sensor output under dark conditions, the minimum wait time to receive each color channel is $T = \frac{16}{2Hz} = 8\ s$. So the total minimum wait time to read data from all three channels is 24s.

This IC was chosen over others for its simplicity of use. However, one drawback is the response of the blue and green sensors in the 700-1000 nm range, and the response of the red channel to blue light. The nonvisible spectrum—such as infrared from an incandescent external source—may contribute to the sensor reading for the color channels. Therefore, a filter was used to block the light above 650 nm.

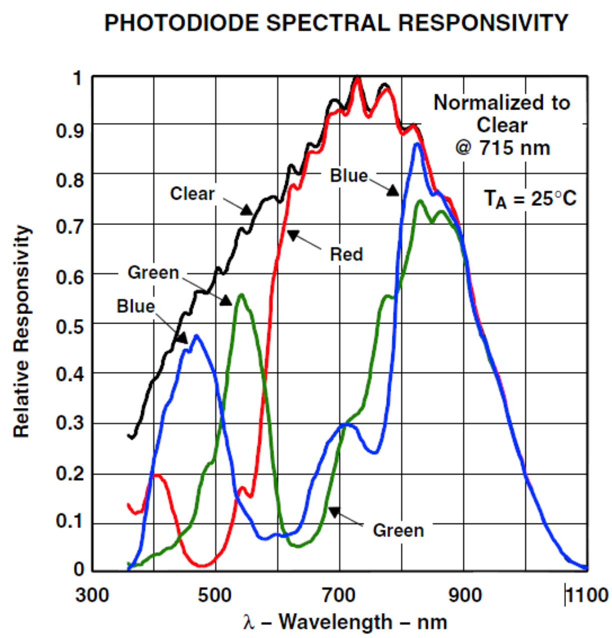

Figure 3: Spectral responsivity of color sensor taken from datasheet [3].

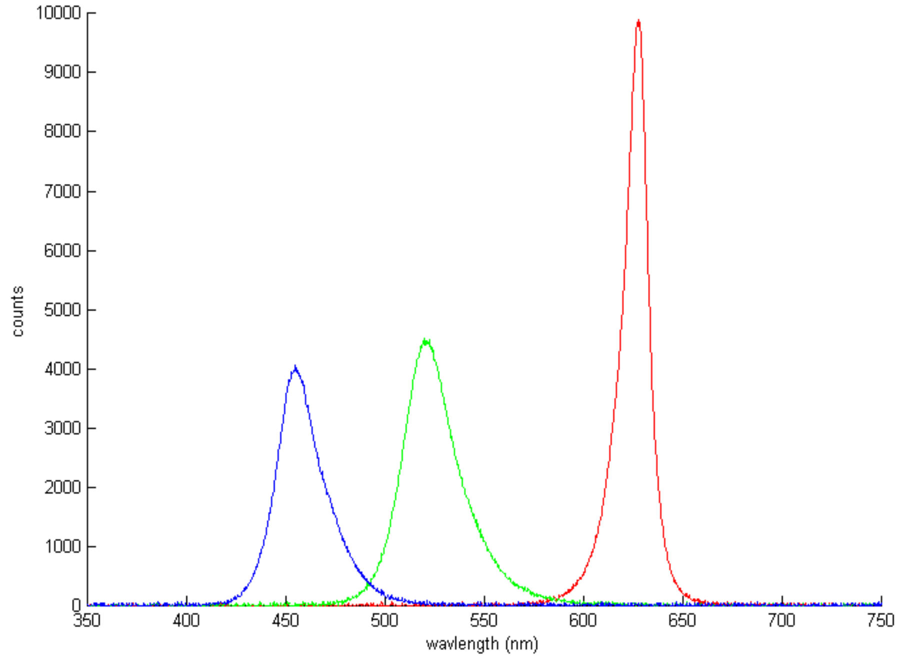

Figure 4: RGB LED Spectrum

Peak response	Sensor (nm)	LED (nm)
R	630	630
G	525	522
B	460	455

Table 1: Comparison between LED spectrum and sensor response

As shown in Table 1, the peaks of the LED spectrum very closely match the peak responses of the color sensor channels.

According to the datasheet [3], the sensor saturates at a saturation irradiance of 1266 µW/cm^2 for 640 nm incident light. We tested the irradiance under normal lighting conditions to see that this was indeed a reasonable figure for our system. The sensor IC is directly connected to the microcontroller and requires 5V supply, so it was suitable to use a 5V microcontroller.

2.2.2 Sensor microcontroller

A PIC16F887 was used to read data from the color sensor, process the user interface, send data to the transmitter.

The microcontroller sends control signals to the sensor for frequency scale and color channel selection. It uses a hardware timer to measure the time between 16 consecutive pulses, and divides to determine the frequency. This frequency is used as the sensor reading. This data is sent wirelessly to the main controller to perform the processing for lighting. The microcontroller receives an external clock from a 20 MHz oscillator chip.

2.2.4 User interface

The user sets the setpoint for the control algorithm with a simple user interface located on the sensor unit. There are two knobs (potentiometers) to adjust the correlated color temperature from 2000K to 9000K (with 1000K step) and brightness with integer values from 0 to 100%. There is also a button to turn the light on and off. An LCD screen displays the value that the user has selected.
The LCD has a 16x2 character grid, and displays as follows:

C	C	T	:	9	0	0	0	K							
B	R	I	G	H	T	N	E	S	S		1	0	0	%	

Figure 5: LCD output for user interface

2.2.3 Transmitter

Our sensor unit uses a 315MHz ASK transmitter (part number CDT-88) to transmit the setpoint and sensor data. The module is supplied 5V and receives serial data from the UART output of the microcontroller using the RS232 protocol. We developed a simple 13-byte package to transmit the data. Since UART requires one byte at a time and our sensor readings are 2 bytes, we split the sensor data before transmitting. The package we send is summarized in the table below.

Byte	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Data	255	255	R[7:0]	R[15:8]	G[7:0]	G[15:8]	B[7:0]
Byte	**8**	**9**	**10**	**11**	**12**	**13**	
Data	B[15:8]	CCT (2-9)	0	Brightness (0-100)	0	On/Off	

Table 2: Summary of package

The transmission rate is entirely dependent on the output frequency of the sensor, since the microcontroller does not send a new package until the frequencies for each of the colors are captured.

2.3 Lighting Controller

The lighting controller processes the sensor and setpoint values and outputs PWM signals for the red, green, and blue LED arrays. It also reads the PIR sensor output in deciding to turn on or off the light down the system.

For our microcontroller, we chose a PIC24HJ128GP202, since the chip has a convenient 28-pin PDIP package, 4 PWM output, 16-bit PWM resolution, 16-bit multiplication, and up to 40 MIPS operation. The microcontroller has a V_{dd}=3.3V and is powered by an AC/DC converter. The microcontroller uses a 20 MHz external crystal. The main program flow for the microcontroller is shown in the diagram below.

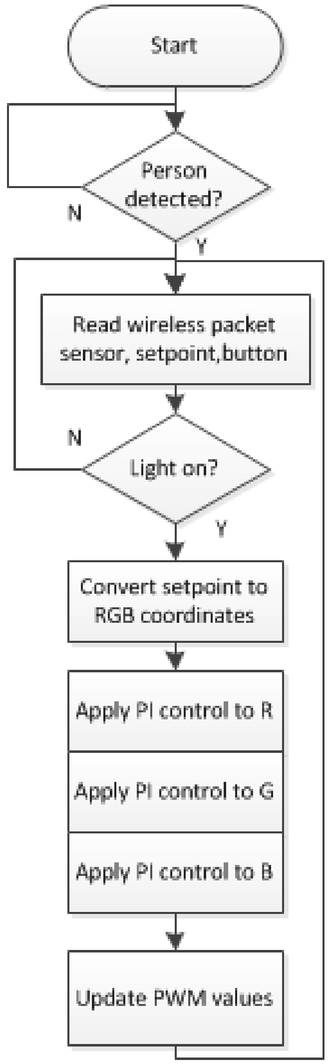

Figure 6: Program flow for main microcontroller

The microcontroller constantly needs to be reading new values from the wireless receiver, and performs each iteration of the control loop only after receiving a new packet.

2.3.1 Receiver

The receiver module is paired with the transmitter at 315 MHz. It connects to the PIC24, and is mounted in the lighting enclosure. The module receives 5V DC from an AC/DC converter.

2.3.2 PIR sensor

This passive-infrared sensor is used to detect the presence of a person in the area to be illuminated. It is mounted on the light and accurately detects the presence of a person nearby. The PIR sensor outputs a binary signal indicating whether a person is detected. If a person is not detected, then the microcontroller shuts off the light.

2.4 Control Algorithm

2.4.1 Calibration Procedure

We based our calibration procedure on the one described in [4] to map sensor data to chromaticity coordinates (X,Y,Z). This calibration needs to be done only once for the entire system.

A spectrometer and the appropriate software was used to derive the chromaticity values (in CIE XYZ coordinates) for 3 measurements: once for each of the LED colors at full brightness while the others are off.

R_{PWM}	G_{PWM}	B_{PWM}	Spectrometer Calculation	Sensor Reading
100	0	0	Xr, Yr, Zr	Rr, Gr, Br
0	100	0	Xg, Yg, Zg	Rg, Gg, Bg
0	0	100	Xb, Yb, Zb	Rb, Gb, Bb

Table 3: Calibration procedure and corresponding parameters

The matrix M is the linear mapping between the sensor values $(\mathrm{R_s}, \mathrm{G_s}, \mathrm{B_s})$ and the tristimulus measurement (X, Y, Z).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \mathrm{m}_{11} & \mathrm{m}_{12} & \mathrm{m}_{13} \\ \mathrm{m}_{21} & \mathrm{m}_{22} & \mathrm{m}_{23} \\ \mathrm{m}_{31} & \mathrm{m}_{32} & \mathrm{m}_{33} \end{bmatrix} \begin{bmatrix} R_s \\ G_s \\ B_s \end{bmatrix} \quad (2.4.1.1)$$

Given the matrices

$$C = \begin{bmatrix} \mathrm{X}_r & \mathrm{X}_g & \mathrm{X}_b \\ \mathrm{Y}_r & \mathrm{Y}_g & \mathrm{Y}_b \\ \mathrm{Z}_r & \mathrm{Z}_g & \mathrm{Z}_b \end{bmatrix} \quad (2.4.1.2)$$

$$T = \begin{bmatrix} \mathrm{R}_r & \mathrm{R}_g & \mathrm{R}_b \\ \mathrm{G}_r & \mathrm{G}_g & \mathrm{G}_b \\ B_r & B_g & \mathrm{B}_b \end{bmatrix} \quad (2.4.1.3)$$

The matrix M can thus be obtained by the relationship $M = CT^{-1}$.

2.4.2 Control Variables

The setpoints from the user are brightness and correlated color temperature (CCT). These need to be converted to R, G, B values for the control algorithm. To measure color, we used the CIE XYZ color space. To convert CCT to this space we use what is known as the Planckian locus using the method described in [5]. The method uses a cubic approximation to the locus, which is described by the equations below.

$$
\begin{aligned}
x_c &= -0.2661239\frac{10^9}{T^3} - 0.2343580\frac{10^6}{T^2} + 0.8776956\frac{10^3}{T} + 0.179910,\ 1667\text{K} \le T \le 4000\text{K} \\
x_c &= -3.0258469\frac{10^9}{T^3} + 2.1070379\frac{10^6}{T^2} + 0.2226347\frac{10^3}{T} + 0.240390,\ 4000\text{K} \le T \le 25000\text{K} \\
y_c &= -1.1063814x_c^3 - 1.34811020x_c^2 + 2.18555832x_c - 0.20219683,\ 1667\text{K} \le T \le 2222\text{K} \\
y_c &= -0.9549476x_c^3 - 1.37418593x_c^2 + 2.09137015x_c - 0.16748867,\ 2222\text{K} \le T \le 4000\text{K} \\
y_c &= 3.0817580x_c^3 - 5.87338670x_c^2 + 3.75112997x_c - 0.37001483,\ 4000\text{K} \le T \le 25000\text{K}
\end{aligned}
\tag{2.4.2.1}
$$

This gives the (x,y) coordinates, which are independent of brightness. In the XYZ color space, the Y coordinate represents brightness. We simply scale the brightness setpoint (0 to 100) to obtain Y, and use the following equations to get X and Z.

$$X = \frac{x}{y}Y \tag{2.4.2.2}$$

$$Z = \frac{1-x-y}{y}Y \tag{2.4.2.3}$$

Using the matrix M above we convert to RGB by using the following calculation.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} \mathrm{m}_{11} & \mathrm{m}_{12} & \mathrm{m}_{13} \\ \mathrm{m}_{21} & \mathrm{m}_{22} & \mathrm{m}_{23} \\ \mathrm{m}_{31} & \mathrm{m}_{32} & \mathrm{m}_{33} \end{bmatrix}^{-1} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{2.4.2.4}$$

Note that even though this matrix mapping was obtained for the sensor, the R,G,B of sensor and PWM only differ by constant, so we can use the same matrix. Since our system uses only 9 setpoints for CCT, we can set constants in the above equations and rewrite as

$$X = aY,\ Z = bY \tag{2.4.2.5}$$

We pre-compute the values of *a* and *b* for each of our CCT setpoints, and compute the rest in real-time. The scaling of brightness to obtain Y and the scaling of the inverse of M were determined empirically such that the R, G, B setpoints were on the same order of magnitude as the sensor R, G, B.

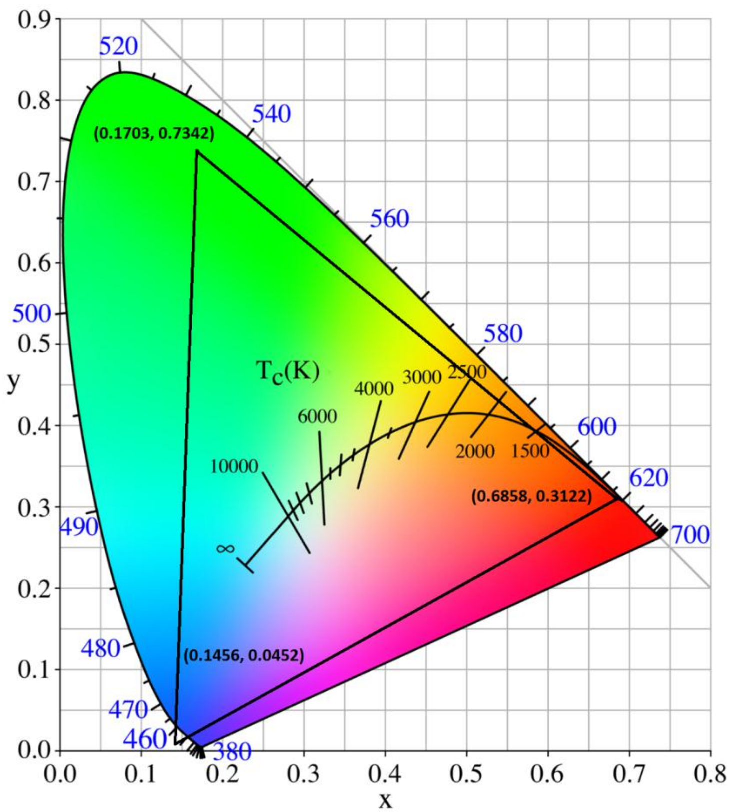

Figure 7: Three points taken for calibration on CIE chromaticity diagram, shown with Planckian locus. The triangle formed by these 3 points represents the color gamut that can be achieved by mixing.

Figure 7 shows the actual xy values obtained using the above procedure. A spectrometer was used to obtain the XYZ and xy values.

2.4.3 PI Controller

On the main microcontroller, we implemented a PI controller with R,G,B values as the manipulated variables and PWM duty cycles as the process variables.

For each of the three color channels, the microcontroller computes

$$Error_i = Target_i - Sensor_i \quad (2.4.3.1)$$

$$\Delta PWM_i = k_{P,i} Error_i + k_{I,i} ErrorSum \quad (2.4.3.2)$$

Each PWM channel is incremented by ΔPWM_i. Since the PWM duty cycle cannot be set less than 0% or greater than 100%, we clip the output if it exceeds this maximum or minimum.

3. Design Verification

3.1 Lighting Unit Testing

Each of the color of the LEDs needed to be in separate series string so that the current across each string could be controlled by their respective drivers. They need to be in series since even a very small difference in the voltage could result is very large variations in current. We maintained a current of 212mA across the zener diode initially for testing purposes.

3.1.1 LED driver testing and replacement circuit

Each individual driver consisted of a Clare HV9910 IC designed to drive high powered LEDs. We based the driver design around the recommended application circuit as specified by the datasheet and application note for the chip [1]. We implemented a standard current controlled buck converted topology using a rectified input voltage.

We initially were using a 47µF rated at 63V for the bridge rectification circuit. The output ripple with this capacitor was too high. Therefore we adjusted the capacitor value to 1000 µF rated at 200V.

The current across the LED was approximately 212mA but there was a lot of ripple. Another problem we faced was with the MOSFET we had used, and the current sensing pin. The circuit would remain in the off state, and this would cause the gate to always be off. We realized that this was being caused by the ringing of the MOSFET, which caused artificially high current reading across the current sense resistor. This also caused major current spikes in the current across the LEDs. We resolved this issue by using a smaller MOSFET and a lossless snubber circuit on the current sense pin. We used a fast rectifier in the snubber circuit (MUR 160).

Testing Values	Values
V_{IN}	160VDC
Current Sense Pin	1.8V
Ground pin	0V
Gate pin	V_{DD}-0.3 = 7.2V
V_{DD} pin	7.5V
LD pin	7.5V
PWM-D pin	6.3V (ON) ; 0V (OFF)
R_T pin	2.97V
V_{GS}(Across MOSFET)	3V
V_{DS} (Across MOSFET)	V_{IN}

Table 4: Testing values of LED driver circuit

We also faced problems with the PWM dimming of the circuit. The PWM should disable the gate of the MOSFET if the PWM is low. The circuit did not behave properly when the function generator was used to control the PWM pin. It was found that the ground of the PWM and the control chip had difference ground references. This was fixed using an opto-coupler (4N25) to isolate the PWM signal and to pull down the PWM when the opto-coupler’s output was high.

We completed the initial testing and generated simulations using Zener diodes as loads. Once we were confident with the results we used the actual LEDs to confirm results.

During the PCB implementation stage we faced many problems. After the drivers were placed on the PCB board and initial testing showed that the circuit was nonfunctional, we revisited the circuit and it was found that the capacitor of the snubber circuit was mistakenly connected to the current sense pin. We determined that once this fast current sensing pin detected a capacitance it started to oscillate. This caused the internal circuitry of the controller chip to fail, rendering the initial driver circuit useless. Due to time constraints we could not reorder parts and remake the circuit. Therefore we decided to make a replacement circuit which would instead drive only 3 LEDs.

The replacement driver is shown in figure 10 of the Appendix C. The circuit consists of a power NFET (MPS2222) which is used as a variable resistor, and an NPN transistor (2N7000) which is used as an over-current sensing switch. We also use resistor R2 (2Ω) as a current sense resistor. The circuit consists of a feedback loop which regulates the LED current. We use a high resistance R1 (100kΩ) such that when the NPN transistor turns on it easily overpowers R1.

This circuit allowed us to drive 3 LEDs to demonstrate the entire project and to conduct testing on the entire system.

3.2 Sensor Unit Testing

3.2.1 Color Sensor Testing

Initially, we observed the frequency output for various lighting conditions. The color sensor has 4 frequency scaling modes and we recorded the dark and saturation frequencies for each of the channels with the sensor covered up and with a 60 W incandescent bulb close to the sensor. We chose the full scale output to achieve a maximum resolution. We also verified that the sensor did not saturate with the LEDs at full brightness when place a distance of 2 ft. from the sensor.

3.2.2 Microcontroller Testing

We connected the microcontroller to the breadboard with appropriate voltage and programmer connections with an LED connected to an output pin. We programmed the microcontroller and verified that the LED was blinking.

After we connected the microcontroller to the color sensor and programmed it to capture frequency, we compared the output of the microcontroller to the oscilloscope frequency measured directly at the sensor output.

3.2.3 User Interface Testing

First we set up the microcontroller to read analog input from the potentiometers. Next, we scaled the potentiometer readings to match the range form 2-9 (1000K) for CCT and 0-100 for the brightness setting, and observed that the LCD showed the correct range.

3.2.3 Transmitter Testing

We set up one PIC16 to send data, and the PIC24 connected to an LCD to read the incoming data from the receiver. We programmed the transmitting microcontroller to send a short message of three characters at a time repeatedly. We varied the baud rate and chose the highest rate for successful transmission. The distance between the transmitter and the receiver was fixed at 5ft. We moved the pair to a distance of 10 ft. and the transmission rate was unaffected.

3.3 Lighting Controller Testing

We set the microcontroller to read from a potentiometer and set the PWM output to have a duty cycle set by the potentiometer. We probed the PWM output on the oscilloscope and observed that it changed from 0% to 100% duty.

3.3.3 Calibration Procedure Verification

To verify the calibration procedure, we illuminated the sensor and the spectrometer with the same arbitrary light source using different PWM values for the LEDs. We performed the calculation to get XYZ from the spectrometer. Next we calculated the XYZ values from the sensor readings using the calibration matrix. The calculated tristimulus values differed from the ones obtained from the spectrometer directly significantly. We believe this error was because the orientation of the spectrometer opening caused significant variance in the spectrum output.

3.4 System Level Verification

For our control system to function properly, the sensor output must be linear with incident power, and LED output power must be linear with PWM duty cycle. To verify that the sensor responds linearly, we varied the duty cycle of the PWM signal to each color channel in a dark room. The results are shown in the figure below.

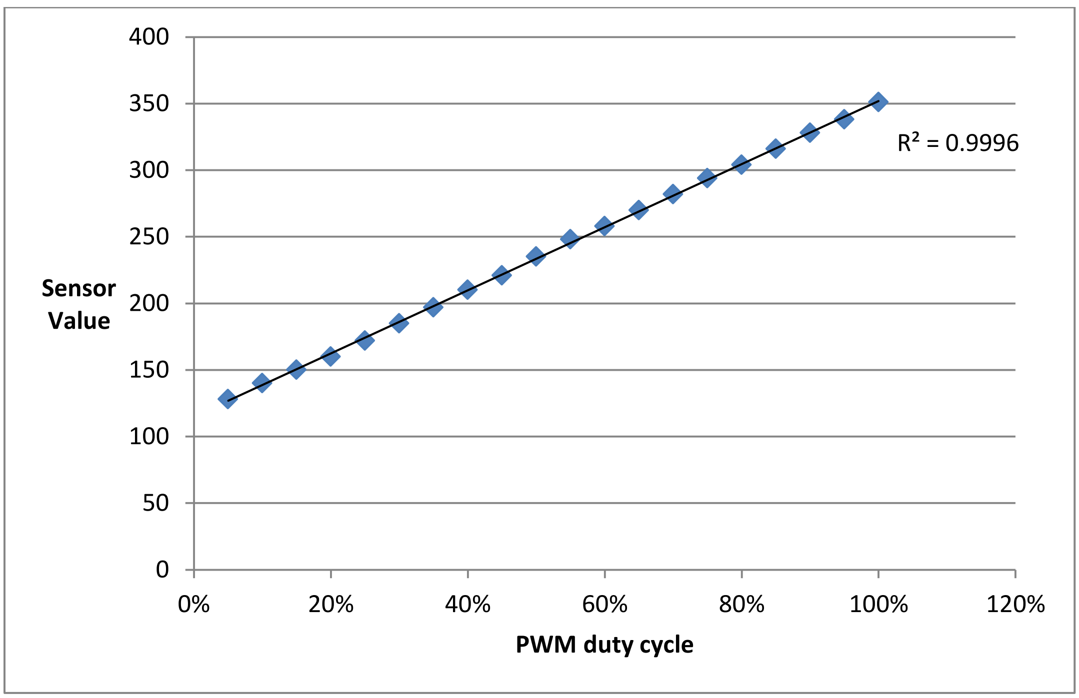

Figure 8: Green sensor readings vs. PWM duty cycle verifying linearity.

Nonlinearities under low lighting conditions led to instability when the setpoint brightness was set too low (less than 20%).

After system integration, we confirmed rate of transmission met specification by counting packets. We counted 300 packages/min, or about 5 packages/s.

Once the system was fully integrated, only the PI controller needed testing. Our original specification stated that the system should reach the setpoint within 10 seconds of being adjusted to a new value.

For most setpoints this specification was met, after some tuning of the Kp and Ki factors. Dark setpoints (R, G, B less than 100) resulted in longer settling time and occasional instability.

4. Costs

4.1 Parts

Part	Quantity	Model	Retail Cost ($)	Actual Cost ($)
Color Light to Frequency Converter	1	TAOS TCS3200	2.44	2.44
RF transmitter	1	CDT-88	4.00	0.00
RF receiver	1	CDR03A	5.00	0.00
PIR sensor	1	sku023606	2.71	0.00
LED driver IC	3	MXHV9910	2.25	2.25
RGB LEDs	9	Vollong H01RGB00302	44.55	44.55
LCD (16x2)	1	Hitachi HD44780	15.95	15.95
PIC microcontroller	1	Microchip PIC16F877A	2.80	0.00
PIC microcontroller	1	Microchip PIC24HJ128GP202	6.48	6.48
Diode	10	Various	2.00	0.00
Voltage Regulator	2	LM7805 LP2950CZ-3.3	1.60	0.00
Power Mosfet	3	Fairchild IRF740B	2.49	0.00
AC/DC adapter	2	N/A	12.00	6.00
Pushbutton	1	N/A	0.25	0.00
potentiometer	3	N/A	1.50	1.00
Resistors	20	N/A	2.00	0.00
Capacitors	10	N/A	4.00	4.00
750 uH inductor	3	N/A	2.00	2.00
Enclosure for LED light	1	N/A	5.00	0.00
Total			**119.02**	**84.67**

4.2 Labor

Name	Rate	Hours	Total	Total x 2.5
Jered Greenspan	$35/hr.	200	$7000	$17,500
Madhav Khanna	$35/hr.	100	$3500	$8,750
Sichao Wang	$35/hr.	170	$5950	$14,785
Total		450	$16,450	$41,035

5. Conclusion

5.1 Accomplishments and Uncertainties

We achieved an adaptive lighting system that responses to the user setpoints in a varying environment. We were able to verify most of our performance requirements. The microcontroller reads the frequency output of the sensor accurately, verified by comparison with oscilloscope. The wireless data transmission works as desired with sufficient speed. The calibration matrix is acceptable for converting CCT to (R,G,B), but accuracy could be improved. Our PI controller works but requires tuning for shorter settling time and to avoid possible oscillations. The lighting unit that was designed could not be realized due to errors on the PCB which destroyed our LED drivers. The replacement worked as a temporary lighting source to test our system, but was not bright enough for daily use. Due to time limitation, we have not fully evaluated the contributions to the sensor outputs from wavelengths other than LEDs. Thus, whether the calibration matrix is valid under various conditions has not been fully verified. Overall, these issues did not prevent a working adaptive lighting system.

5.2 Ethical considerations

Safety of device was considered and evaluated before implementation and before the demonstration. Precautions were taken while building and soldering for safety consideration. In addition, the IEEE Code of Ethics [6] mandates that its members commit themselves "to be honest and realistic in stating claims or estimates based on available data." We are careful to not overstate our performance claims, especially since we did not meet all of the requirements stated in the design review.

5.3 Future work

Future improvements might include:

- More sensors could be used to better evaluate the environment. For instance, the average value of multiple color sensors may be utilized to evaluate the ambient light.
- Time-of-day settings. For example the user sets the light to change to warmer colors at night. Such a system might improve the sleep pattern or mood of the user.
- The system is extendable for LEDs with more colors to refine the output light, i.e. amber and cyan. With multiple solutions for target values, the system might use a search algorithm to find a solution based on minimum power or best color rendering index [8].
- Users are able to achieve arbitrary color in (x,y) space—not just points lying near the Planckian locus.
- More analysis is required to determine if the sensor board could be battery powered.

References

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Appendix A: Requirement and Verification Table

Table 5: System Requirements and Verification

Requirement	Verification	Results
The sensor module outputs a digital intensity measure that is linear with respect to the intensity of the source, with a nonlinear error that is less than 10%.	We will vary the irradiance of each color channel of the LED by slowly sweeping the duty cycle of the PWM from 0% to 100%. We will then observe the sensor output using the microcontroller for the corresponding color and record the output. After analyzing the results, we should observe a linear trend and the corresponding nonlinear error.	Linearity was observed with a linear regression (R^2=0.9996)
The sensor does not saturate under normal lighting conditions.	We will place the sensor in the ECE 445 lab, in various parts of the room and check that it does not saturate.	Verified
PIR module should accurately detect motion. The voltage input to the PIR sensor is at least 4.5V for proper operation The maximum distance to be sensed is adjustable between 3 to 7 meters. The delay time between sensing can be 5 to 200 seconds.	When the PIR sensor is connected to the supply, the measured voltage always exceeds 4.5V. We will test that the sensitivity potentiometer on the PIR module behaves as specified in the data sheet, and accurately detects when a person moves by at a walking pace with a distance of less than 3m from the sensor when set to the lowest sensitivity, and at 7m when set to the highest sensitivity. We will verify that the delay time for motion sensing can be adjusted between 5 to 200 s as stated in the data sheet by timing how long before the data output goes low after we stop moving.	Verified
There is a proper communication link between the main microntroller and the sensor unit. The main microcontroller receives the correct setpoints from the sensor microcontroller. Able to transmit data as far as 10 ft.	After a communication link is established, we will send setpoint data, and see if it can be received and read properly. Then we send sensor data and see if this is received as well. Finally, we send a calibration command and see if it can be received as well. Place the microcontrollers at the appropriate distance and verify no packets are dropped	Verified
LED driver circuitry functions properly The LED input voltage V_{in} should range from 45-55 V before connecting to the LED driver (open circuit voltage) for proper operation.	Testing procedure: A DMM will be used to measure the open voltage of the output of the transformer and rectification stage, without a load connected.	All tests were completed and verified with the initial breadboard

The driver should also be able to provide 350mA for the green and blue LEDs and 400 mA for the Red LED. LED power must be linear with respect to PWM duty cycle.	After the entire circuit is connect and PWM is set to maximum duty cycle an ammeter will be used to measure the current through the LEDs and this should correspond to 350 mA and 400 mA We will use the DMM to measure both the voltage and the RMS current to verify that the power is linear.	testing. After the PCB board failed to verify, the same test were performed and verified on the replacement circuit.
The voltage input to the lighting microcontroller should be between 2.97-3.63 V for working operation.	After connect the power supply to the board test the voltage at the output of the regulator and verify that it is within this range. Also verify that the same voltage appears across each of the microcontroller power pins.	Verified
The tristimulus values measured by the microcontroller matches that obtained from the spectrometer calculation with an error of less than 2%.	After initial calibration, we will measure the tristimulus values as they appear on the LCD with various settings on the LEDs. We will record these measurements with those from the spectrometer, and determine the percentage error.	Does not meet requirement, error due to limitation of measuring equipment

Appendix B: Power Calculations

Table 6: Power Calculations

	Vsupply (V)	Isupply (A)	Power (W)
Color sensor	5	1.40E-03	7.00E-03
LCD driver	4.5	2.50E-02	1.13E-01
LCD backlight	5	3.00E-03	1.50E-02
Transmitter	5	3.00E-03	1.50E-02
Microcontroller	5	2.00E-05	1.00E-04
Sensor Total Power			**1.50E-01**
Microcontroller	3.3	6.20E-02	2.05E-01
PIR sensor	5	6.00E-05	3.00E-04
Receiver	5	3.00E-03	1.50E-02
Light Controller Power			**2.20E-01**

The total power without the LEDs is approximately 0.330 W. The power of the LED system totals to 27.1 W.

Appendix C: Schematics

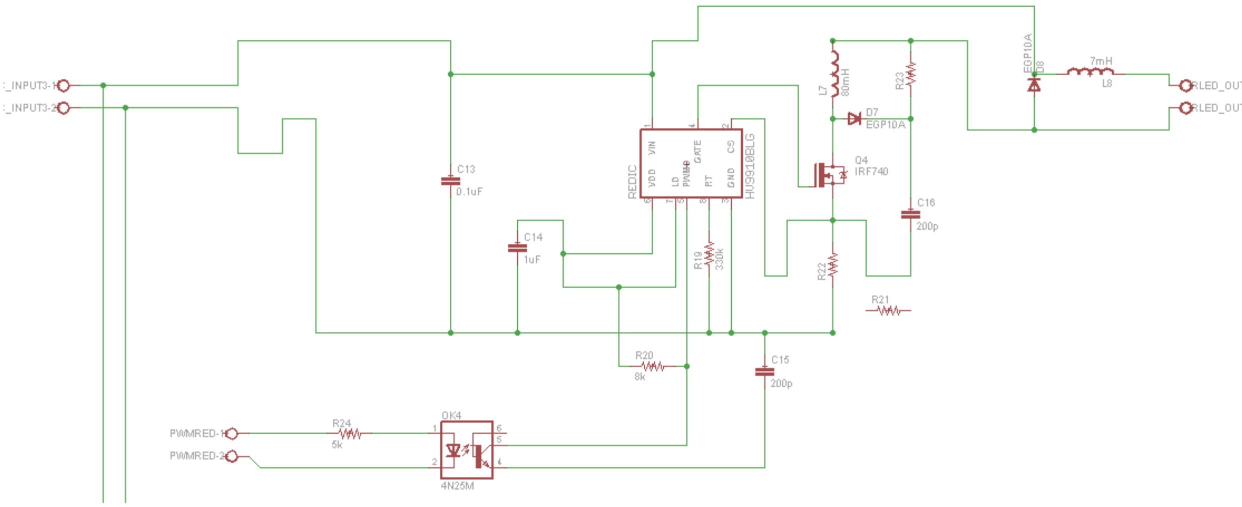

Figure 9: LED Driver Circuit

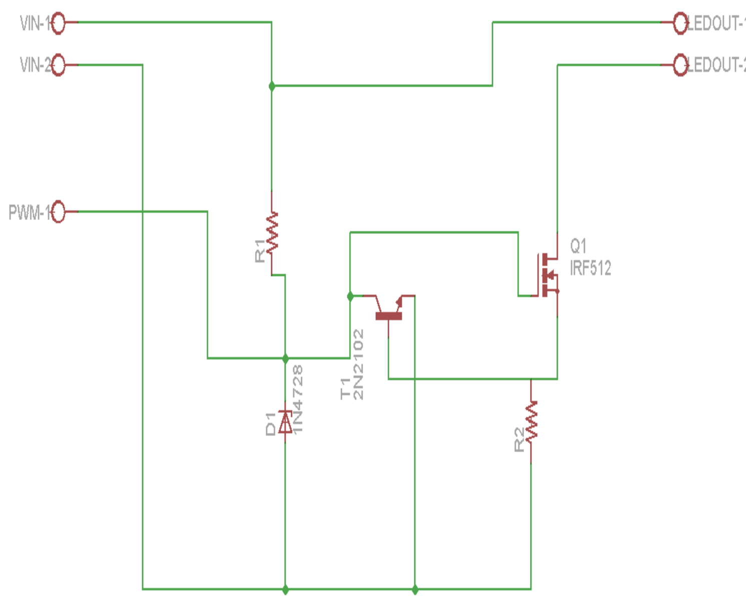

Figure 10: LED Driver Replacement

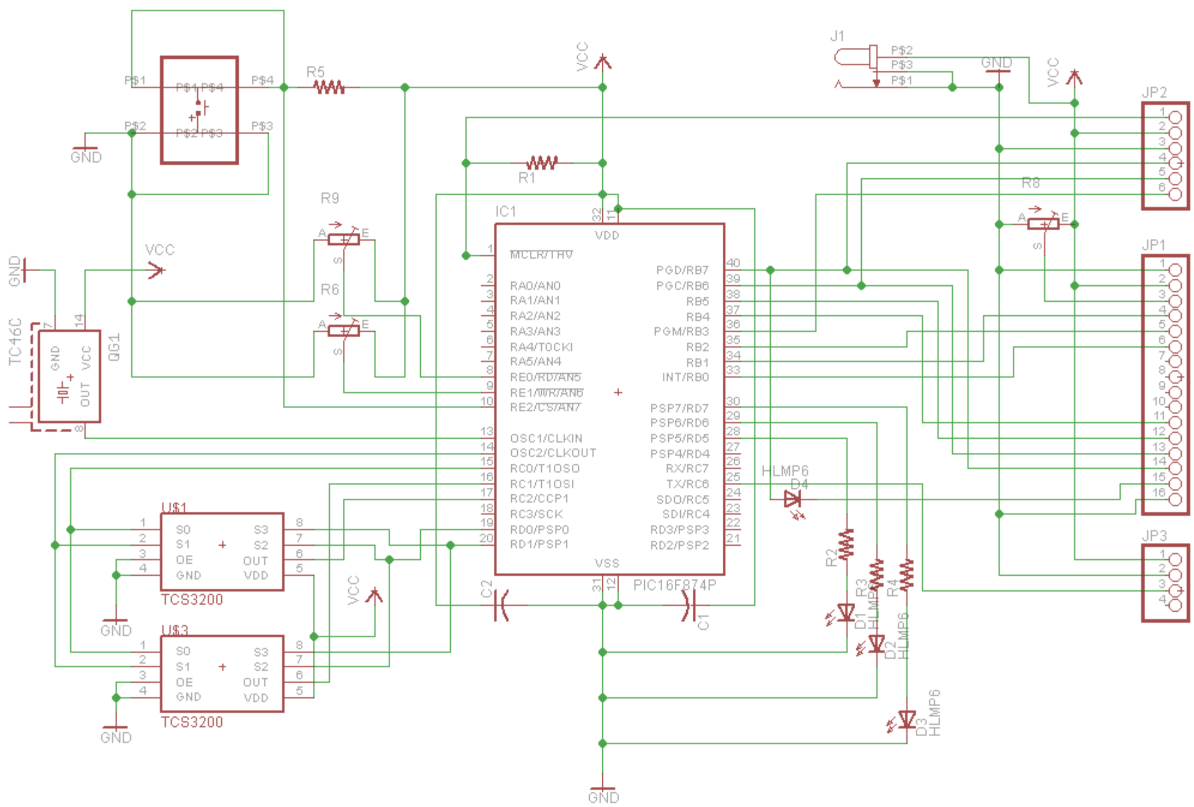

Figure 11: Sensor Unit

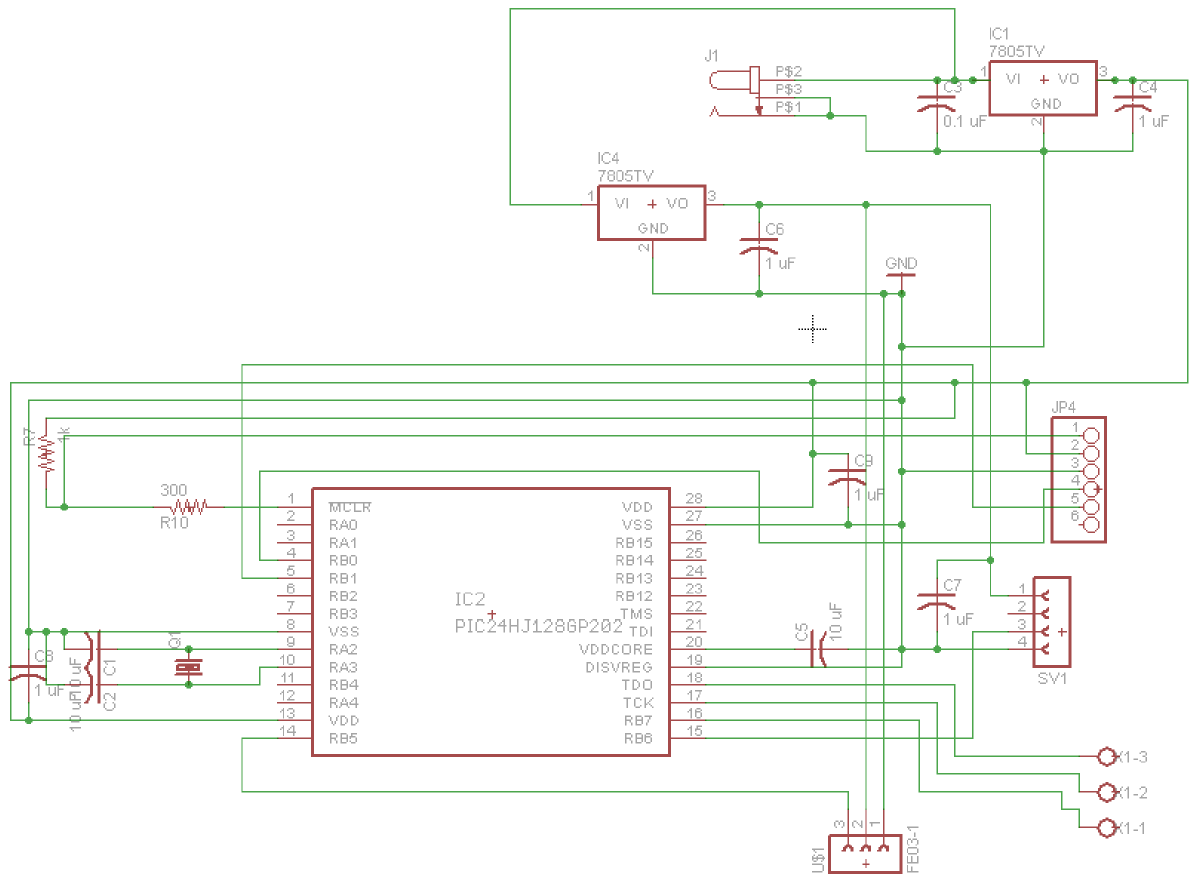

Figure 12: Lighting Controller

Appendix D: Oscilloscope Traces

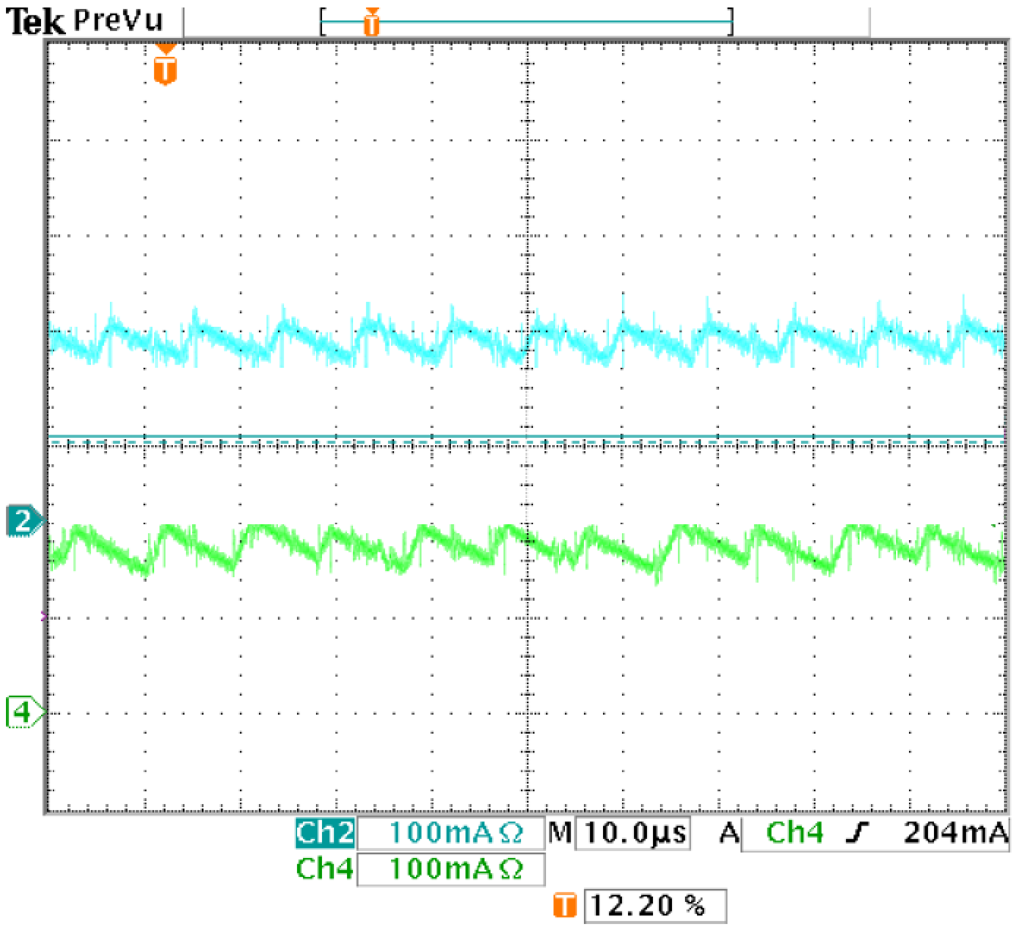

Figure 13: Current across LED's after introduction of snubber circuit.

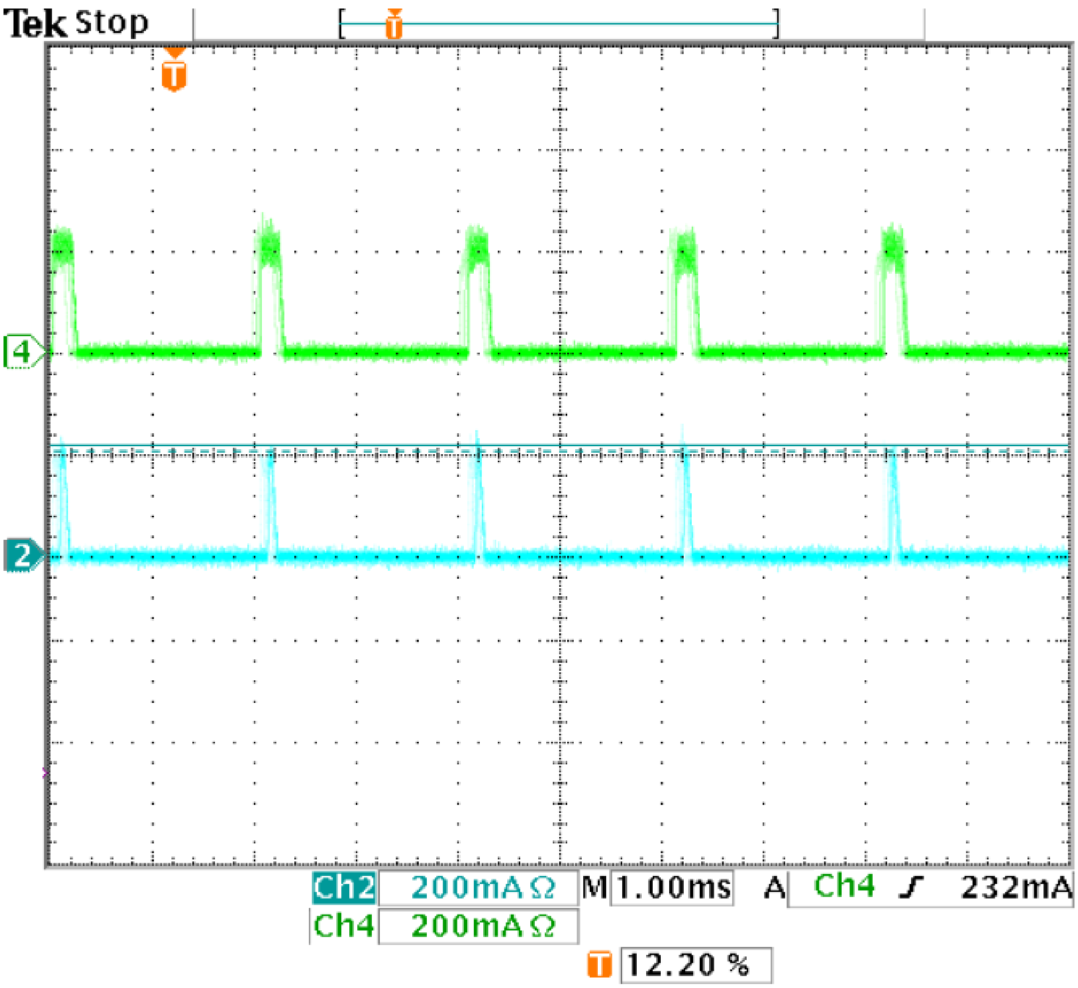

Figure 14: Current output with a PWM signal at 13%

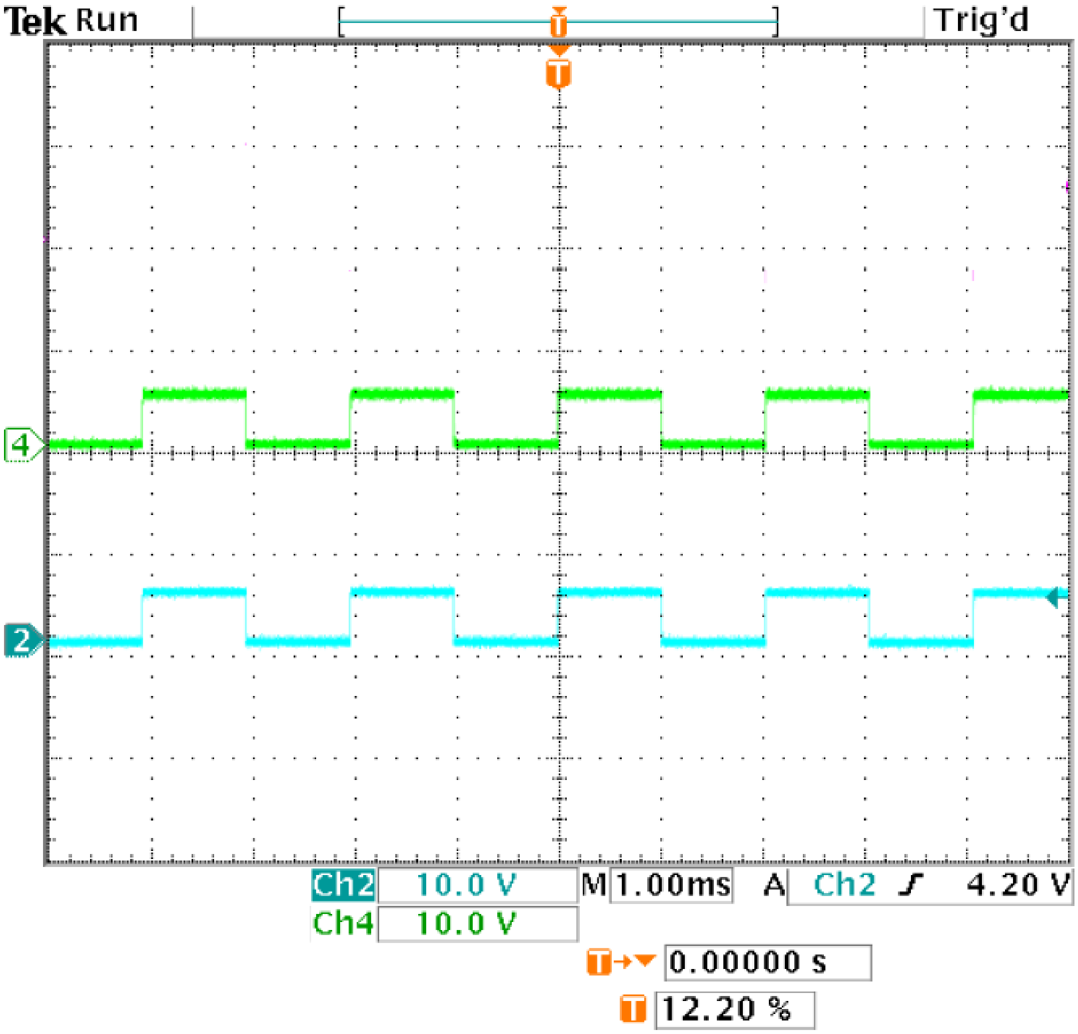

Figure 15: Input PWM Signal