

# Prototype LED Lighting Control System

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## Abstract

For two centuries, incandescent light bulbs have been the primary source of lighting for homes and businesses around the world. These popular devices have an unfortunate property: they waste 98% of their electrical power by dissipating it in the form of heat. Lighting is one of the major categories of energy consumption worldwide, using 19% of the energy produced globally. Due to this large percentage, and the inefficiency of incandescent bulbs, an enormous amount of energy could be saved by switching to a more efficient form of lighting.

It has been postulated that mixing the light from multiple Light Emitting Diodes (LEDs) is one of the most efficient ways to generate white light. LED technology has attracted ample attention in recent years from industries for use in various applications, such as LCD backlighting, and general illumination. LED technology has advanced significantly in recent years, although despite these advances, there remain limitations. By their nature as a semiconductor device, LEDs are susceptible to a number of manufacturing variables that affect operating properties such as quality and intensity of the light. Currently, there are only a few effective methods for controlling these variables, such as lot sorting, or using more precise and expensive manufacturing processes.

The objective of this project was to design a system that could produce white light with a greater consistency and tighter tolerance than is readily available with typical LEDs. This was implemented by using an optical feedback system to monitor and adjust four colors of LEDs to create the correct balance to produce white light. The optical feedback allowed the system to measure the light and adjust for the actual output of the LEDs, regardless of their variation from the nominal. These variations include chromaticity and intensity, which are affected by factors such as junction temperature, bias current, and manufacturing variables. The current prototype of this system demonstrates the mixing of red, green, blue and amber LEDs to balance to white light. The LEDs are driven by color, with the ability to scale the number LEDs of each color as desired. Each color is driven by a current source that is controlled by a pulse width modulated square wave at 1.5kHz. The sensor is in place and functioning to adjust the LEDs to create a qualitative white light output, with a variable intensity and color temperature.

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## Executive Summary

A study at the National Institute of Standards and Technology (NIST) in 2005 compared the color rendering and efficiency of various light sources. Incandescent bulbs had extremely poor efficiency but they outperformed fluorescent bulbs for color rendering. White phosphor-LEDs had the best features of both incandescent and fluorescent lighting. They are very efficient and have high color rendering. The best performing light source we were interested in was a mixture of Red, Green, Blue and Amber (RGBA) LEDs. This method can create a white light source with efficiency and color rendering higher than the other three options currently available to consumers. For this reason we chose to further investigate RGBA lighting. Like most silicon devices LEDs cannot be perfectly manufactured. Their characteristics can vary wildly due to the manufacturing process. Intensity and wavelength can then further vary due to operating temperature and the life cycle of the product. To compensate, manufacturers of white LEDs use batch sorting to minimize the difference between their LED models. This helps alleviate manufacturing variance but does nothing for variation caused by temperature or operating life. With the RGBA approach the LEDs could be precisely mixed to create white. If the wavelength and intensity of each color channel could be detected during operation, all of the variables affecting the wavelength and intensity of the LEDs will no longer matter, since the LEDs could be blended together properly to account for these measured offsets.

To realize this lighting method using the solution of optical feedback we acquired a small sensor containing two photo diodes on a single piece of silicon. This sensor is capable of detecting the wavelength and intensity of a monochromatic light source. A control loop was devised where data was taken from the user and processed to control four independent current sources that each drove a series string of colored LEDs. These LEDs shined upon a sensor that collected data for the processing unit to readjust the drive level of the LEDs.

This prototyping method proved successful. The device was capable of creating white light with adequate color rendering by reading the wavelengths and intensities of the LEDs during operation. The light source was able to be adjusted by the user, who had control over intensity and color temperature.



## 1. Introduction

Lighting is a major source of electricity consumption, using about 19 percent of globally generated electricity.[1] It is estimated that about half of lighting in homes around the world is provided by incandescent light bulbs,[1] which have an energy efficiency of only about 5%. Incandescent bulbs use the majority of electricity to heat a filament to a white-hot state in order to produce light, so much of the energy is wasted as heat. Considering the amount of energy consumed in lighting, utilizing more efficient methods of lighting will conserve a significant amount of energy.

The Energy Independence and Security Act of 2007 mandates that by 2012 the inefficient 100-watt incandescent light bulb may no longer be commercialized.[2] According to bill, by 2012 to 2014, all light bulbs must use 25 to 30 percent less energy than they did at the time, and must be 70% more efficient by 2020.[2] In the current market, compact fluorescent light bulbs (CFLs) meet this efficiency standard. It has been postulated that replacing one regular incandescent light bulb with a compact fluorescent light bulb in every U.S. household will save enough energy to light more than 2.5 million homes for a year.[Error! Bookmark not defined.] From an energy saving aspect, CFLs seem to be a good candidate to replace the incandescent light bulb.

Despite the energy savings, the environmental impact of CFLs has been brought into question. CFLs use electricity to excite a gas within a glass tube, which then fluoresces to produce ultraviolet (UV) light that is invisible to the human eye. This UV light reacts with mercury and a phosphorescent chemical compound to produce visible light. The mercury content of CFLs can be a big problem since breaking or incinerating CFLs can release mercury into the air. Mercury is hazardous metal that can accumulate in the soil, water, fish, and fish eating animals, including humans. Recycling CFLs has been emphasized in big companies, but rigid infrastructures for recycling CFLs and strict law enforcement on recycling will be needed to ensure that it is common practice. Lighting executives see CFLs as a transient technology for its limitations, including the inability to dim, the unpleasant color of the light, and the minimum five milligrams of mercury content.[3]

It has been proposed that light emitting diodes (LEDs) are potentially the most energy efficient and environmentally friendly lighting sources currently available. Michael Farrel, a president of Sentry Equipment Corporation in Oconomowoc, Wis., recently replaced the new factory's exterior and most of its interior lighting with LEDs.[3] He mentioned that the company spent \$12,000 more than what would

have been required to light the facility with a mixture of incandescent and fluorescent bulbs, but using LEDs, the company has been saving \$7000 in its yearly operating cost. Moreover, the building will not need to change a bulb for next 20 years, and the additional initial investment used will be recovered in less than two years.[3] Although, the high initial cost of LED bulbs will hinder the appeal to the general consumers, LED's long life span and higher efficiency suggest that it will be the next generation's major lighting source. The experts do not expect the conventional light bulbs to disappear anytime soon. It will take some time for LED to bring its price down and to penetrate into the general households, but the on-going research shows that it has the potential to be used for general lighting purposes and is well worth investigating.

## 2. Research

The National Institute of Standards and Technology (NIST) and the Department of Energy have done extensive research on using LEDs for lighting. Their experimental results suggest that using LEDs to produce white light has potentially the highest luminous efficacy and the best color rendering ability. In other words, LEDs can produce the most natural light while using the least energy, when compared with other conventional lighting techniques. In this section, the terminology related to colorimetry will be defined and explained. The study of colorimetry was useful in this project since visionary phenomenons played an important role in designing the optical feedback system.

### 2.1.LED Operation

LEDs are optoelectronic diodes, a family of semiconductor. They have been widely used in almost every form of electronics, mainly as the output indicator of power, and also can be found in traffic lights and signs on buildings. Recently, LEDs have emerged as the energy efficient source for LCD back lightings, and now, as a light source for the general illumination purposes. In this section, the general overview of the operating mechanism of LEDs will be introduced.

LEDs consist of a chip of semiconducting material doped with impurities to create a p-n junction. When the p-n junction is forward biased, current flows easily from the p-side (anode) to the n-side (cathode), but just like a regular diode, current does not flow in the reverse direction. A diagram of a typical LED structure is shown in Figure 2–1.

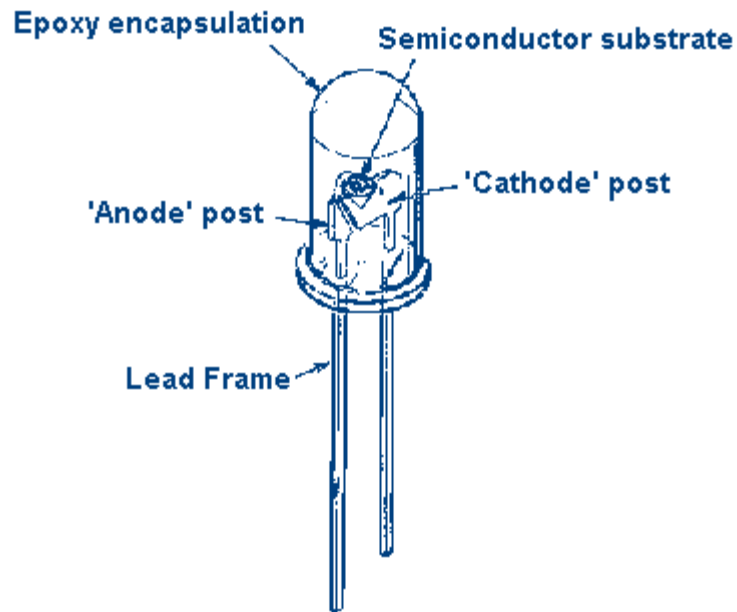


Figure 2–1: LED Components<sup>1</sup>

The basic operation of an LED is similar to that of a regular diode. When a p-n junction diode is forward biased, large numbers of majority carrier electrons on the n-side are injected over the reduced potential hill into the p-side quasineutral region,[4] and the similar phenomenon occur on the p-side, as holes are injected into the n-side quasineutral region.

As the carriers from each side move, some of them go through recombination. In indirect semiconductors like silicon (Si), the recombination takes place predominantly through R-G center, and energy is released as heat during the process.[4] In contrast, in direct semiconductor like gallium arsenide (GaAs), the major recombination takes place through band-to-band recombination. In this case, the energy is released in the form of photons and as they escape from the diode, the LEDs light up. This process can be shown in Figure 2–2. More details in mechanisms and physics involved in the recombination process can be found in literatures.[4]

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<sup>1</sup> [http://www.merg.org.uk/led/merg\\_led\\_02.gif](http://www.merg.org.uk/led/merg_led_02.gif)

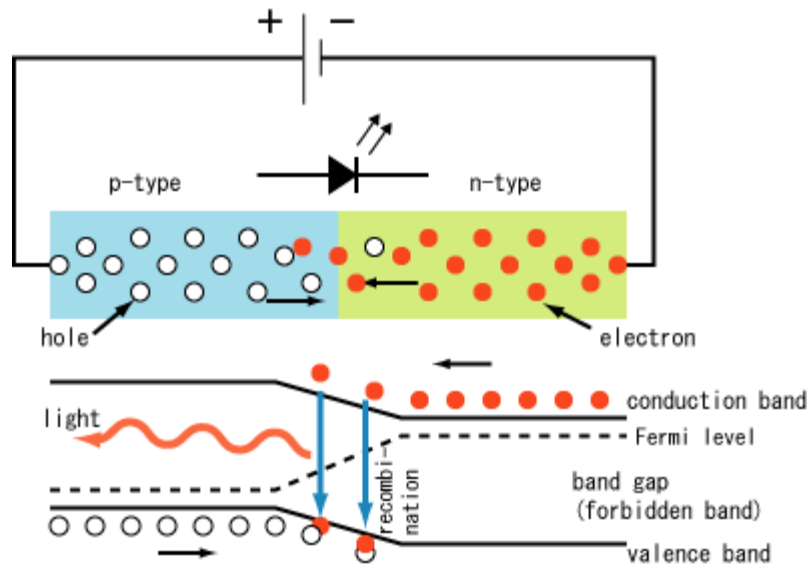


Figure 2-2: R-G Recombination Process

## 2.2. Light Measurements

Colorimetry is the science and technology to quantify and describe the human color perceptions.[5] In this section, the quantification of the color rendering properties of light sources will be discussed, and the measurements of light that provide standards for the industry will be introduced.

## 2.3. Tristimulus Values and Color Matching Function

The visual range of wavelength for human perception is between 380nm and 780nm. When all the monochromatic radiation of equal power within a vicinity of the wavelength bands are matched with the combination of the red(R), green(G), blue(B) primaries, the color matching functions are obtained. The color matching function CIE 1931, shown in Figure 2-3, is the standard used in the industry and colorimetry.

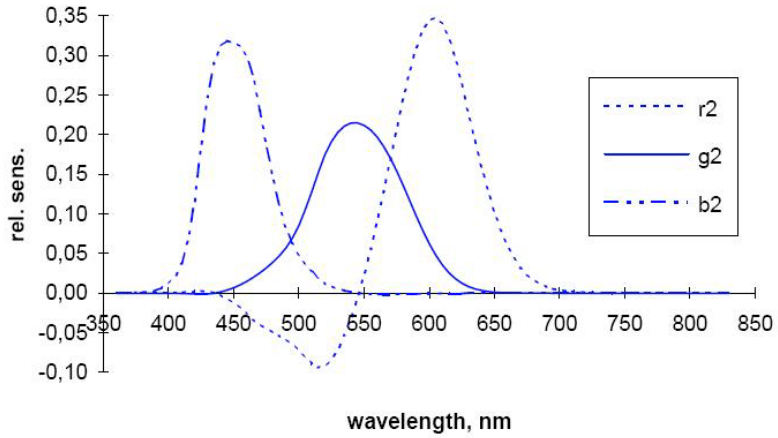


Figure 2-3: Color Matching Function of the CIE 1931 Standard Colorimetric Observer [5]

All color matches are additive,[5] hence the rule of superposition applies. For example, when there exists two light sources, one with wavelength  $\lambda_1$ ,  $\{C(\lambda_1)\}$  and  $\lambda_2$ ,  $\{C(\lambda_2)\}$ , a third light can be created simply by adding the two sources:

Given,

Equation 2-1

$$C(\lambda_1) = R_1[R] + G_1[G] + B_1[B]$$

Equation 2-2

$$C(\lambda_2) = R_2[R] + G_2[G] + B_2[B]$$

Then,

Equation 2-3

$$C(\lambda_1) + C(\lambda_2) = \{R_1[R] + R_2[R]\} + \{G_1[G] + G_2[G]\} + \{B_1[B] + B_2[B]\}$$

Given the spectral power distribution of a source, the R/G/B tristimulus values of that source can be calculated by extending the addition to all monochromatic components within a range of wavelengths:

Equation 2-4

$$R = k \int_{380nm}^{780nm} P(\lambda)\bar{r}(\lambda)d\lambda, \quad G = k \int_{380nm}^{780nm} P(\lambda)\bar{g}(\lambda)d\lambda, \quad B = k \int_{380nm}^{780nm} P(\lambda)\bar{b}(\lambda)d\lambda$$

K is a constant that can be used to convert the colorimetric (photometric) quantities to radiometric ones. The luminance of a color matched by the amounts of R red units, G green units and B blue units can be expressed as:

Equation 2-5

$$L = 1.0000R + 4.5907G + 0.0601B$$

In other words, the constant k can be chosen in such a way that if  $P(\lambda)$  is a radiometric quantity, the L value will be a corresponding photometric quantity. ( $P(\lambda)$  [=] W/(sr·m<sup>2</sup>), L [=] cd/m<sup>2</sup>)

## 2.4.Color Temperature

Color temperature is a characteristic of light that is widely used in the lighting products to describe the color of the light sources. The color temperature describes the chromaticity of a light source as a temperature in Kelvin, in reference to the temperature that an ideal black-body radiator will need to reach to emit the light with same chromaticity. Mathematically, this convention is related to Planck's law[6] and Wien's displacement law. Planck's law describes "the spectral radiance of electromagnetic radiation at all wavelengths from a black body at temperature T,"[6] and the Wien's displacement law states that "there is an inverse relationship between the wavelength of the peak emission of a black body and its temperature."

## 2.5.Color Space

The R/G/B color space can be easily conceived using simple vector calculus. Let a color be represented by an n dimensional vector, in a given spectrum space with n dimensions. The coordinates of this vector will be the power values at the n wavelengths. The three dimensional color space can be considered as a sub-space of this spectrum space, where any three independent vectors can be used as basis vectors of the color space. The vector transformation done by CIE:[5]

Equation 2-6

$$X = 2.76888R + 1.75175G + 1.13016B$$

Equation 2-7

$$Y = 1.00000R + 4.59070G + 0.06010B$$

Equation 2-8

$$Z = 0.00000R + 0.05651G + 5.59427B$$

The chromaticity coordinate is defined as following:

Equation 2-9

$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z}, \quad z = \frac{Z}{X+Y+Z}$$

Since  $x+y+z = 1$ , the coordinate can be explained using two of the three stimulus. The chromaticity chart is shown in Figure 2-4. The edge of the chromaticity chart represents monochromatic light sources, and the plane inside of the chart represents the color which can be constructed by mixing monochromatic light sources. The color temperature corresponding to different types of white color was also converted into the chart, which can be seen in the locus line around the white color region shown in Figure 2-4.

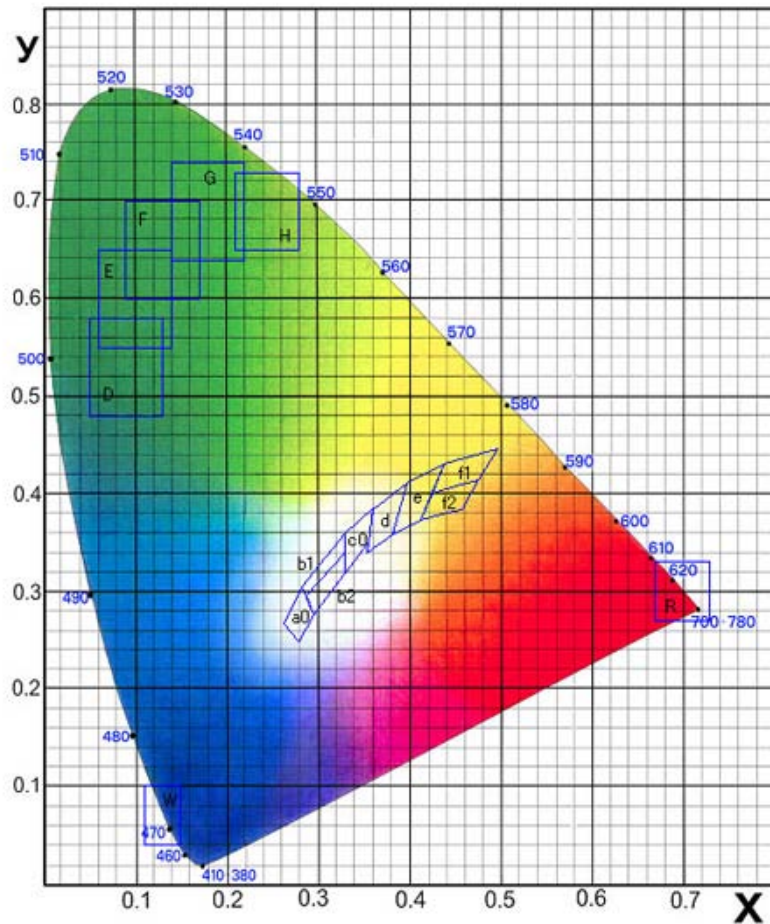


Figure 2-4: Chromaticity Chart [7]



## 2.6. Lighting Solutions

Color rendering is one of the most important characteristics of light sources for general lighting, and it describes the ability of a light source to provide natural color to objects under illumination.[8] The Color Rendering Index (CRI) is an international metric used to represent color rendering of a light source. CRI can be calculated by measuring color difference as illuminated by a source of interest, and by a reference source. Color difference can be measured by using chromaticity chart. The reference light source is the Planckian radiation for test sources with a correlated color temperature (CCT) less than 5000K, or a phase of daylight for test sources having CCT greater than 5000K.[8] If the resulting CRI is equal to 100, the color difference between the two sources is zero. Lower CRI values mean lower color rendering abilities. A source that has poor color rendering ability is not useful for general lighting. According to U.S. Energy Policy Act (EPA 1992), the lamps for generating light must have good color rendering ability and a CRI of 82 or better.[9]

Another important characteristic of a good light source is its luminous efficacy, which is measured in Lumens per Watt (Lm/W). Lumens, the SI unit for luminous flux, is a measurement of the perceived intensity of a given light. For example, a standard 100W incandescent light bulb used in North America emits about 1700 lumens; therefore, its luminous efficacy can be calculated to: 17 Lum/W. The maximum luminous efficacy of a radiation source is 683 Lm/W, which is for a green light at a wavelength of 555nm. When compared to this maximum, the luminous efficiency of an incandescent light bulb is about 2%.

However, the incandescent light bulb does provide good color rendering. CRI and luminous efficacy are in trade-off relationship.[8] It can be seen in sun light illumination, that color rendering is best achieved by broadband spectra distributed throughout the visible region. This is contrasted by the peak of luminous efficacy being achieved by monochromatic radiation at 555nm.[8] Therefore, the practical solution for energy efficient lighting should be optimized for both CRI and the luminous efficacy.

According to the research from NIST, the optimum solution appears to be using multi-color LEDs. This method performs well in both the CRI and luminous efficacy aspects.

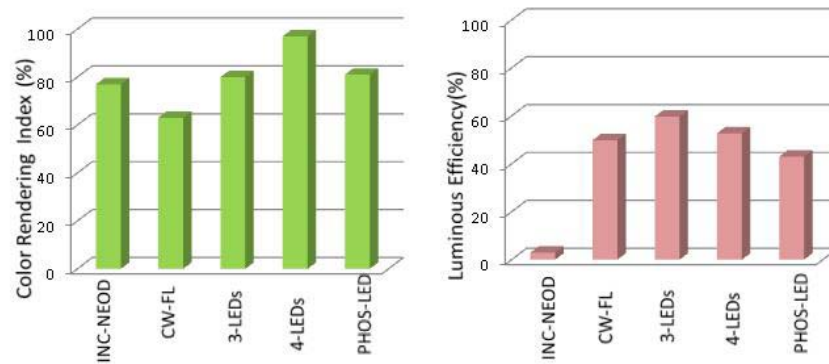


Figure 2-5: Comparison of Different Light Sources

The NIST research concludes that a multi-color LED solution has the highest color rendering performance of all the sources studied. The research also shows that the mixed color LED solution has a high energy efficiency. A system using four colors of LEDs (red, green, blue and amber) also appears to have a very high luminous efficacy. These measurements may not be the absolute rating of different sources. Yoshi Ohno, the eminent optics scientist at NIST who led the experiment, expressed the needs for a better way to quantize the color rendering performance than what was used for his experiment.[8] It is also important to note that data collected under these laboratory settings do not necessarily reflect the ratings of commercial products. The results from the NIST research certainly demonstrates the potential for multi-color LEDs to be the optimal solution for the 'bright' future. When other qualities such as durability, compactness, dimming application, flexibility and environmental impact are considered, it becomes even more apparent that LEDs are an optimal lighting alternative. However, while the multi-color LEDs technology has advantages of color flexibility, high color rendering potential, and high luminous efficacy, it also has disadvantages, which must be overcome before it can be implemented practically. The major disadvantage is that the individual LEDs behave differently with operating temperature, drive current, dimming, and the operating time.[10] The system efficiency of LEDs change over the operating time, and the spectrums of the individual LEDs shifts as a function of current and the junction temperature. This behavior means that additional control systems are required to maintain the desired color consistency.[10]

Another one of the major issues with LED applications is that their temperature can increase drastically; this is proportionally related to the current, which is proportionally related to the brightness of the light. One of the problems with the increase in junction temperature is that it

reduces the lifespan of the lamp severely. With multicolor LEDs, the issue becomes more problematic as the change in junction temperature will shift the spectrums of each LED beyond the tolerable range. Adding control systems to compensate for this issue raises the cost of lamp, which is already an issue by itself. For larger applications, a complicated system will be required to dissipate heat, so combining multiple LEDs into a fixture seems to be counterproductive to the original idea.[11]

Despite of the disadvantage, however, further improvements in energy usage and the price seem to be promising. LEDs have doubled in energy efficiency and brightness in the past two years, and the price has dropped an average of 20% every year since the 1970s.[11] It will take some time for the technology to mature enough to make LEDs significantly competitive with CFLs, but the future outcomes seem to be optimistic.

## **2.7.Current White LED Market**

Many companies have initiated investigations into the LED market. Since it is a newly adapting technology, companies have the potential to gain an advantage by becoming a "legal monopoly" in offering fully-integrated LED lighting products.

C.CRANE currently have LED light bulbs available from \$14.95~\$44.95, using 32W ~ 60W of power to produce a luminous efficacy equivalent to a 100W incandescent light bulb that emits 1700 lumens.[12] However, the C.CRANE products do not have dimming functionality yet, but they are estimated to last up to 30,000 hours.[12]

Cree is another leading company in the LED industry. The LR4 model from Cree is rated to use 10.5W to 11W input power, and have high quality of white light whose CRI is 94, and CCT is 2700K or 3500K. The model is also dimmable to 20%. The life span of Cree products are estimated to be 50,000 hours.[13]

Lamina Ceramics, NJ.,in 2006 launched an interesting product: a white light solution using red, green and blue LEDs. Titan, Lamina Ceramics' RGB white LED engine, has two categories. The low-profile Titan series have 3,000K CCT, 25W input power and produce 600+ lumens in a 2 inch square area.[14] The other model, which is more advanced, is the Titan Daylight white model. It produces 1,200+ lumens, and has a 4,700K CCT, which is comparable to the CCT of daylight. This

model also produces 16 million saturated and blended colors.[14] Even with these high-technology LED lights, the same drive limitations remain (18).

There are a number of other companies, such as General Electrics (GE), Philips Electronics, Siemen's Osram Sylvania unit and a Japanese firm called Nichia that are developing innovative technology for LED lighting solutions.[14] The U.S. Government is also encouraging the research and development of LED technology by having funded 70 LED projects.[14]

### 3. Methodology

In this section, each module of the project will be explained with details in specifications that were considered in choosing components and design. The system was divided up to the current source, digital controller, and the sensor.

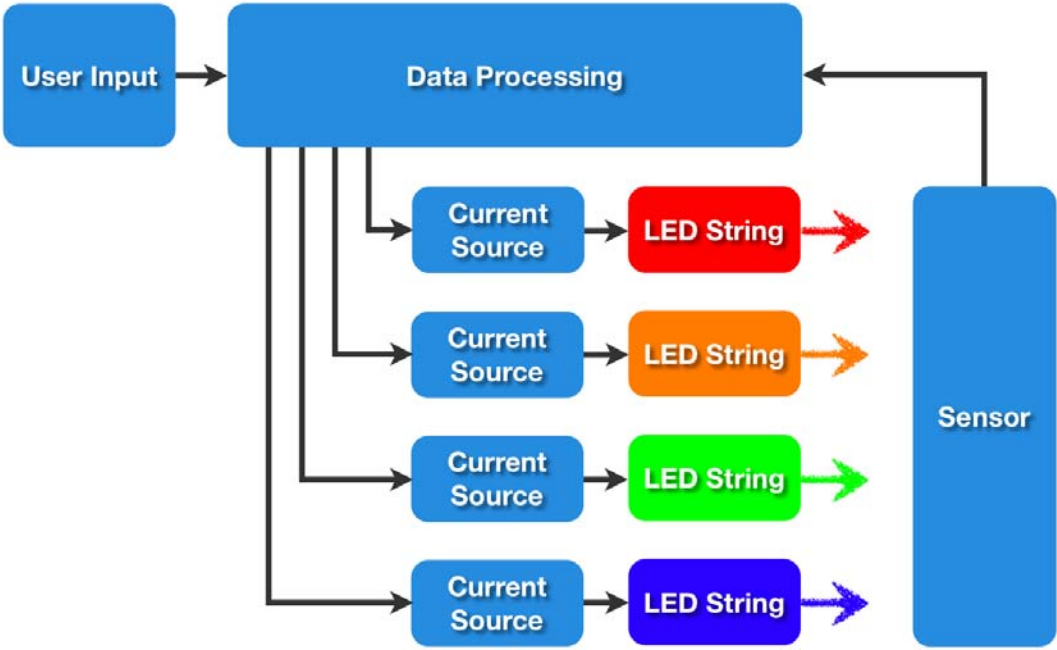


Figure 3–1: Block Diagram of Device

#### 3.1. Microcontroller

Several key parameters were considered when selecting a microcontroller for the project. The Micro Processing Unit (MPU) needed to be capable of accepting analog input voltages from the sensor feedback module. It also needed to be capable of outputting analog voltages to the current sources. A timer and digital output pins capable of pulse width modulating the current sources at 1kHz was also required. Finally, the MPU need additional inputs for user control, preferably two analog inputs. One input for adjusting brightness and one for adjusting color temperature. Memory and clock speed were not a huge concern, as almost all modern microcontroller have enough memory to store the program and are fast enough for simple math calculations. Lastly, the most important factor considered was the group members' familiarity with the microcontroller and the availability of support for it.

Table 3–1: Microcontroller Consideration Parameters

Specification	Purpose	Dependence
<b>Two Channel ADC</b>	Collecting data from sensor feedback.	Required
<b>Four Channel DAC</b>	Controlling bias current of LED current sources. One per current source.	Required
<b>Timer w/ Four Digital Outputs</b>	PWM of LEDs. One per current source.	Required
<b>Clock Speed</b>	Processing Data	Negligible
<b>Memory</b>	Storing Program	Negligible
<b>Group's Familiarity</b>	Faster setup times.	Strongly Considered
<b>Available Support</b>	Help troubleshooting.	Strongly Considered

### 3.2.Current Source

LEDs are fundamentally diodes, and as such, are best driven with a current source. This is due to the exponential response of diode current with respect to the diode’s forward voltage. This means that a small change in voltage will result in a large change in current. If the current is parameter being controlled, however, then the voltage will vary significantly, but it won’t matter. For this reason we decided to use a current source to drive the LEDs, and simply supply enough voltage for all the LEDs to operate.

It was necessary to have feedback in the system to maintain a constant current for the LEDs. We decided this would be accomplished with the use of op-amps. The main component to be determined was the transistor that would drive the current. A pair of op-amps would be used for the feedback and control portion. One op-amp would provide the control current or voltage for the transistor, while the other pre-scaled the feedback signal, so that a smaller measurement could be used.

Table 3–2: Current Source Specifications

Specification	Purpose	Dependence
Supply up to 70mA of current	To drive the different LEDs	Required
Switching the current in PWM	To control the perceived intensity of each color LED	Required
Operate PWM at >1kHz	To prevent the cycles of the pulses from being noticeable by the human eye.	Required
Withstand >> 4V continuously across the transistor	During the ‘off’ portion of the cycle, much of the LED supply voltage will drop directly across the transistor	Required
Tolerate 0.5W power dissipation	Worst case scenario voltage across and current through	Required
Ability to operate on 3.3V single rail power supply	To simplify overall system design by reducing the number of different power supplies needed	Strongly preferred
Require low voltage drop to maintain proper operation region	Reduce power dissipated in the transistor when ‘on’	Preferred

The specifications in Table 3–2 apply primarily to the selection of the transistor. The options we considered were BJT and MOSFET transistors. Both types of transistors met the requirements of current drive, switching speed, power dissipation and voltage tolerance in the current drive path. The deciding factor was drive voltage. A MOSFET typically has a threshold voltage of 1.2V, or higher in large power MOSFETs. BJTs, on the other hand, have a typical threshold voltage of around 0.7V. This made a BJT the optimal choice for this application, because we only had a 0-3.3V swing available from the control op-amp. We wanted as much of that range as possible available to use for

fine control of the drive current. The drawback of BJTs is the risk of the transistor saturating and therefore slowing the PWM transitions of the current.

The implementation of the PWM required an extra mechanism. We decided that a PNP BJT setup would best accomplish this function. The transistor was placed with the collector connected to the inverting input of the control op-amp, which is also where the feedback from the current sensing was connected. The emitter of this transistor was tied to the 3.3V power rail. This way, when the base of the transistor received a high voltage signal, the transistor would be off, and would not affect the feedback function and control of the current. When the transistor was driven with a low signal at the base, the transistor would turn on, and override the feedback with a 3.3V signal. This caused the control op-amp to drive the output all the way down in an attempt to reduce the feedback signal. This would turn the current drive BJT off, and create the low portion of the PWM cycle.

### **3.3.Optical Feedback**

LED's light output changes as a function of the junction temperature, regardless the color of LEDs. It has been obtained from some experiments that a LED's light output can vary by a maximum of 150% over the range of operating current.[1] Thus, it is important to design the optical feedback system to ensure that the light output remains constant, with minimum variance required, in order to provide adequate light quality. One way to measure the change in light output is measuring the change in the wavelength of the light source. The design specification for the maximum change in the wavelength allowed was given by the CIE standard.

The heart of the optical feedback modulation was the sensor. The sensor needed to be chosen with careful considerations for accuracy, precision, range of data acquisition, and measurement type. The main function of the sensor was to receive the output from LEDs and to convert the information such that the microcontroller could quantify it and provide necessary adjustment to stabilize the output light. The system can be simply described by a block diagram as in Figure 3–2.



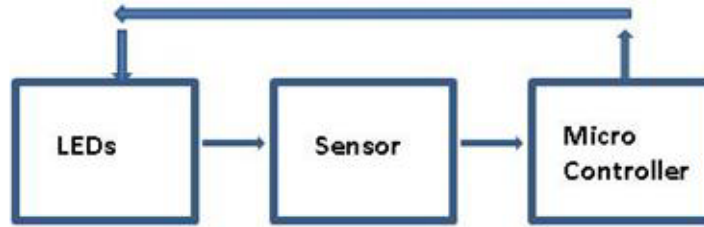


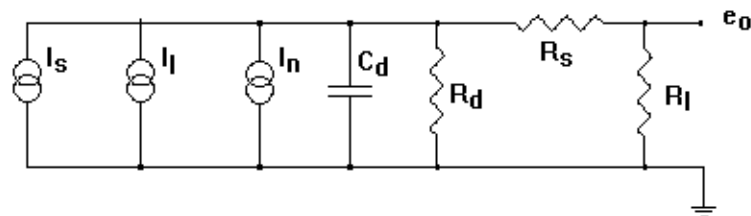
Figure 3–2: Block Diagram of Optical Feedback

### Photojunction Sensors

Photojunction sensors, such as photodiodes and phototransistors, are "semiconductor devices that convert the electrons generated by the photoelectric effect into a detectable electronic signal." [7] The photoelectric effect occurs when photons lose energy to electrons in a material. In a semiconductor material, the energy transferred from the photons can enable an electron to move from the valence band to the conduction band of the material. When an electron moves from the valence band to an electron band, a hole is created in the valence band (electron-hole pair). When an electric field is applied, each charge in the pair will drift toward the opposite electrode on the surface and produce the signal.

### Equivalent Circuit

A circuit representation for a photodiode is shown in Figure 3–3.



- $I_s$  = signal current
- $I_l$  = leakage current
- $I_n$  = noise current
- $C_d$  = diode junction capacity
- $R_d$  = diode parallel shunt resistance
- $R_s$  = diode series resistance
- $R_l$  = load resistance

$$e_o = [I_s + I_l + I_n] [R_l R_d] [R_l + R_d + R_s]$$

Figure 3–3: Equivalent Circuit for a Photodiode

## I-V Characteristics of Photodiodes

When there is no illumination, the I-V characteristic of a photodiode is essentially same as that of a standard diode given in the equation (standard diode equation). However, as the illumination is imposed on the device, the curve shifts downward by the amount of current generated by the incident light,[7] as shown in Figure 3–4. The lower right hand quadrant is where the photodiode operates under the photovoltaic mode. When the device is operating with low or no load resistance, it is said to be in "current mode." [7] In the current mode, the output is linear with incident light intensity.[7] Another operating mode is "voltage mode", where there is a high load resistance. Voltage mode operation exhibits an exponential relationship between the output and the incident illumination.[7] Just as the standard diode, the lower left-hand quadrant shows the reversed bias mode of operation, where the output is nearly linear with the incident intensity.

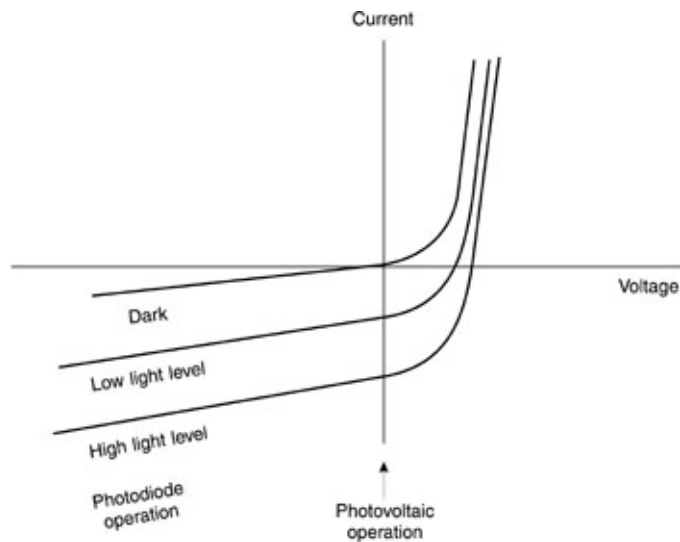


Figure 3–4: VI Characteristics of a Photodiode

## 4. Implementation

In this section, the procedure involved in implementation of each modulation will be discussed - from choosing the components used in the system to the design of actual algorithms and circuits.

### 4.1.LEDs

#### Options

The most important criteria for the LED selection in this project was an appropriate design to provide good color blending. Also, high luminous efficacy is important as the intensity needs to be controlled in a wide range as the output light is adjusted by the feedback loop. Power dissipation specification was also considered significantly to reduce the effects of junction temperature increase.

After reviews between the products manufactured by KingBright, Lumex, and Cree, a product from KingBright was chosen for this project. The WP7679C1 (Figure 4–1) model from KingBright possesses the characteristics desired by this project. The design of the bulb is adequate for a clean arrangement of LEDs in the array and for positioning to produce stable output light for mixing of colors and the sensor.

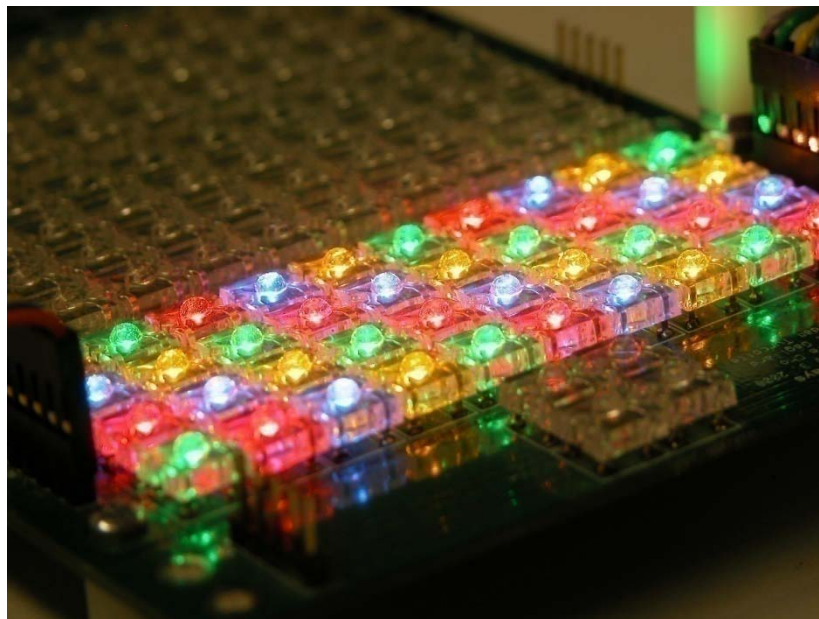


Figure 4–1: Kingbright Super Flux LEDs

There is a LED product available with three different colored dies fabricated on the same piece of silicon substrate. When tested, however, its ability to produce the white light was concluded to be inadequate to be used for general illumination, as shown in Figure 4–2.



Figure 4–2: Poor Color Blending from RBA Single Lens LED4.1.2 Microcontroller

## 4.2. Microcontroller

### Options

While there are many families of microcontrollers on the market our group narrowed down the choices to two families. The MSP430 by Texas Instruments and the ADUC70xx by Analog Devices.

The group agreed that the ADuC7026 would meet all of requirements discussed in section 3.2. The device has four 12-Bit Digital to Analog Converters (DACs), twelve 12-Bit Analog to Digital Converters (ADCs), and four timers. The 40MHz clock and 62kB of flash memory were also more than adequate. The processor retails for about \$9. A functional block diagram of Analog Devices ADuC7026 Analog Microcontroller is shown in Figure 4–3.

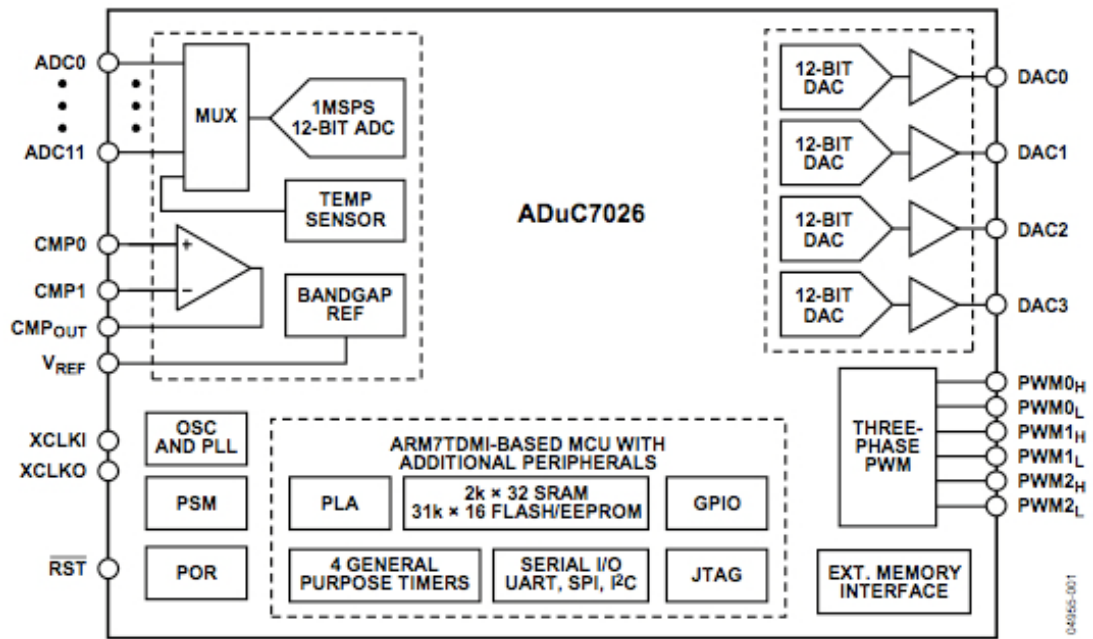


Figure 4–3: ADuC7026 Functional Block Diagram

Every group member has had experience programming the MSP430 family of microcontroller. It was agreed that the MSP430F1611 was an appropriate model for the intended application. The device has two timers that will work for the PWM application. It also has eight 12-Bit ADCs but only two 12-Bit DACs. The device needs at least four DACs for controlling each of the four current sources. There are no MSP430 models that have four onboard DACs. Lastly the 8MHz clock speed and 48kB of flash memory were more than adequate for the project. The device retails for about \$11. A functional block diagram of Texas Instruments MSP430F1611 Microcontroller is shown in Figure 4–4. For the MSP430 to be a viable option an external four channel DAC would need to be connected to the device so the processor could control four current sources, one for each color LED (Red, Green, Blue, and Amber). Analog Device's AD5324 was selected this task. The device has 12-bits of resolution and is capable of function at the 3.3V supply that all other devices are operating at. While the device does retail for a pricey \$6, it was selected, because it could be obtained as a free sample for this project. A functional block diagram of the AD5324 is shown in Figure 4–5.

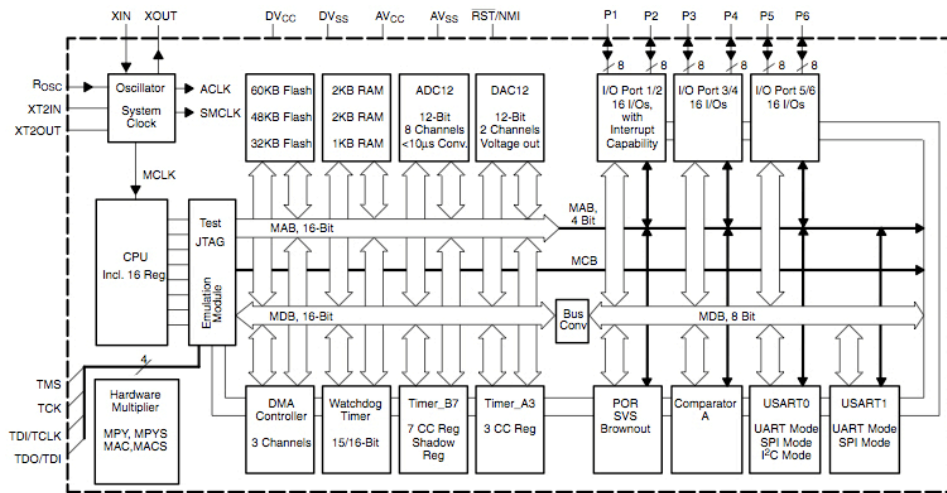


Figure 4–4: MSP430F1611 Functional Block Diagram

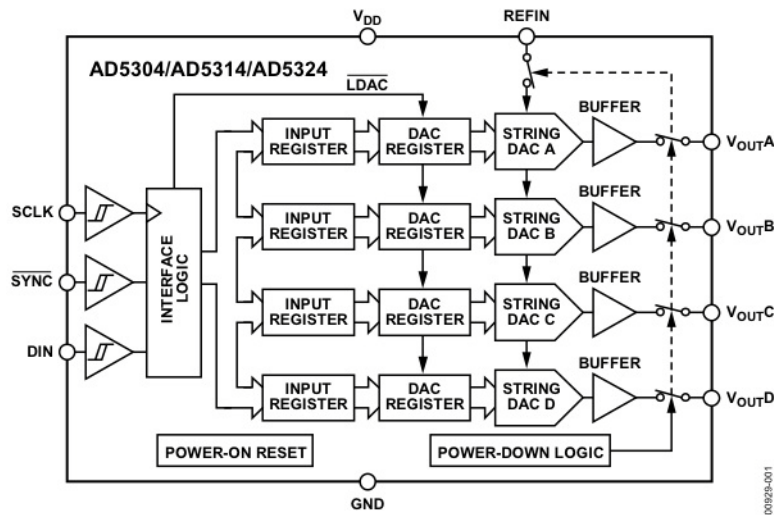


Figure 4–5: AD5324 Functional Block Diagram

## Selection

The most important factor in the selection process was our group's familiarity with the microcontroller and available support for it. A j-tag programmer for the MSP430 could be checked out of the WPI ECE shop for free while an ADUC70xx j-tag programmer would have to be purchased separately. The ECE department also had available licenses for IAR Embedded Workbench for the MSP430. This piece of software, with appropriate license, is capable of compiling and flashing large C programs to the MSP430 family of devices. A similar program would also be needed for compiling and flashing code to the ADuC7026. For these reasons the

MSP430F1611 microcontroller was selected for the project in conjunction with the AD5324 external DAC.

### Schematic

In Figure 4–6 is the schematic of the microcontroller circuit implemented in this project. The jtag header for programming and debugging is header J22. Header J3 allows for the sensor log-amps to be attached to the MSP430's ADCs for data acquisition. The small three pin header J21 is used as a jumper. This was added for debugging purposes. The two status LEDs, U259 and U260 were also added for debugging. Two potentiometers, each with their own status LEDs inside, were added to allow the user control over the intensity and color temperature of the white light source. Two crystals are also attached to the microcontroller which operates at an 8MHz clock frequency. Three traces connect the MSP430 and the AD5324. The AD5324's four analog output channels each attach to one of the current sources' analog input voltage nodes. Finally, four 1.5kHz PWM signals from Timer-B on the MSP430 connect directly to each of the current sources' PWM input nodes.

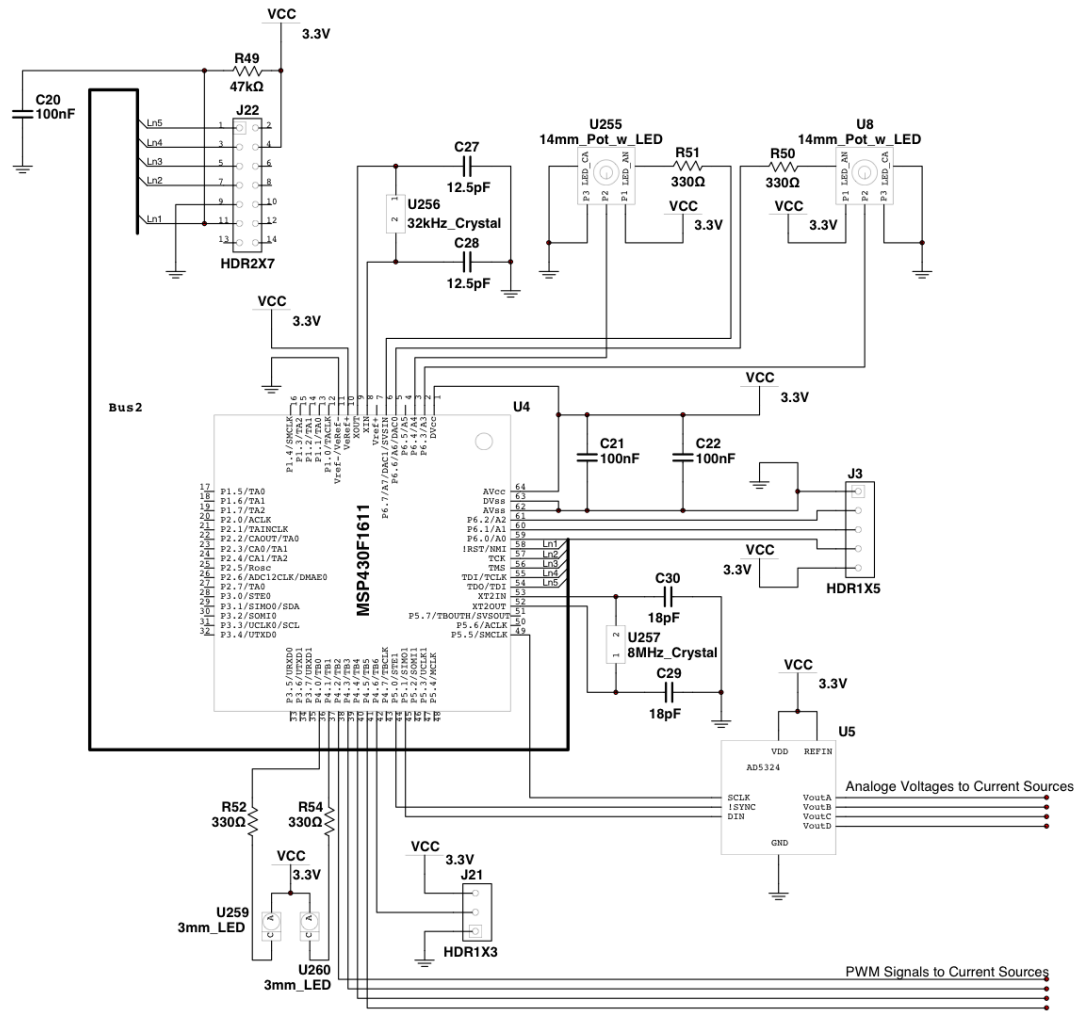


Figure 4–6: Microcontroller Schematic

### 4.3. Current Source

There were several specifications considered in choosing an architecture and design for the current source. Table 4–1: Current Source Specifications & Reasons summarizes these criteria.



Table 4–1: Current Source Specifications & Reasons

Specification	Purpose	Reasoning
Supply up to 70mA of current	To drive the different LEDs	The red and amber LEDs required 70mA of current, and the blue and green LEDs required 50mA
Switching the current in PWM	To control the perceived intensity of each color LED	LEDs are best controlled by a current source, so the current would be used to implement PWM
Operate PWM at >1kHz	To prevent the cycles of the pulses from being noticeable by the human eye.	1kHz is the absolute minimum speed to operate the PWM at. Higher frequencies are even better
Withstand >> 4V continuously across the transistor	During the 'off' portion of the cycle, much of the LED supply voltage will drop directly across the transistor	When 'on' the transistor must have enough voltage (Vce) to stay in the Forward Active Region, where it behaves as a current source. When 'off' the transistor will have the majority of the LED supply voltage across it, since there is negligible current
Tolerate 0.5W power dissipation	Worst case scenario voltage across and current through the LED strings	This is assuming one of the sources started driving 100mA, and the voltage across the transistor was 5V. Both of these values are exceptionally high.

<p><b>Ability to operate on 3.3V single rail power supply</b></p>	<p>To simplify overall system design by reducing the number of different power supplies needed</p>	<p>We wanted the entire control system to run on a single, efficient, power supply. This simplified the system, and reduced conversion losses when voltages would need to be changed.</p>
<p><b>Require low voltage drop to maintain proper operating region</b></p>	<p>Reduce power dissipated in the transistor when 'on'</p>	<p>A lower voltage required to keep the transistor in the Forward Active Region would mean a lower voltage across the transistor when 'on'. This reduces the power dissipated in the transistor</p>

**Architecture Selection**

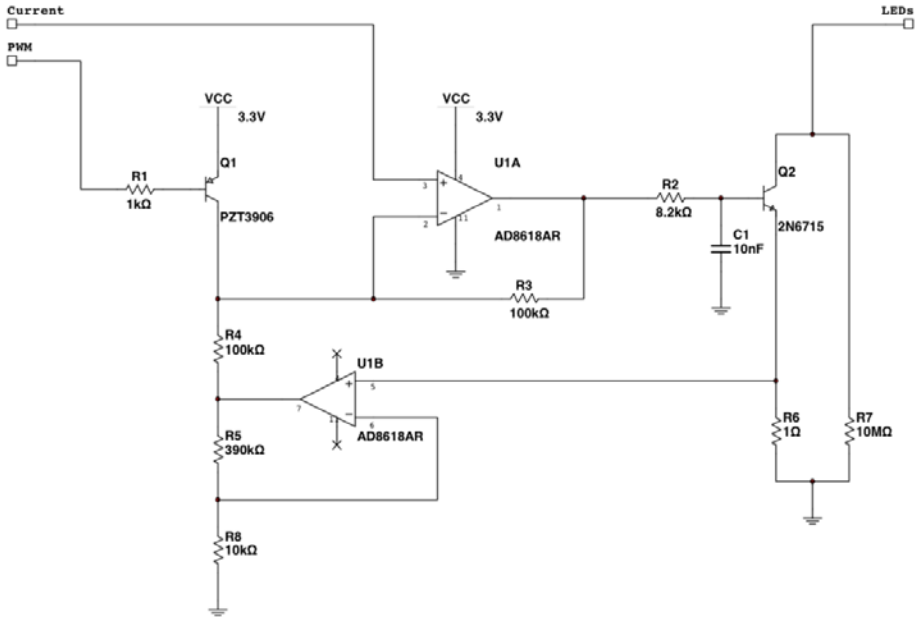


Figure 4–7: Schematic of LED Drive Current Source

Figure 4–7 shows the final schematic for the current source that was used to drive the LEDs. We needed a control system with feedback in order to maintain a consistent current level through the LEDs. The current also needed to be controlled by a signal that ranged from 0V to 3V, which is the limit of the DAC output channels. This suggested an op-amp circuit to drive a transistor. The op-amp was configured with negative feedback for control. The op-amp also had gain in the feedback, to scale the control voltage to the range that is required by the transistor.

We then needed a small resistor in the LED current path to measure the current for feedback to the op-amp. The main drawback with this current sense resistor is that it will be dissipating power whenever the LEDs are ‘on.’ To minimize this effect, we added the second op-amp. This op-amp went inside the feedback path, and provided gain to scale the current-sense voltage before it reached the control op-amp. This allowed us to use a smaller resistor than we would have otherwise needed, thus reducing power loss.

The capacitor on the base of the NPN BJT is there to form a low-pass filter that smoothes out the base voltage and prevents spikes in the current waveform. The PNP transistor implements the PWM control of the current by overriding the feedback signal with the supply rail of 3.3V to turn the LED current ‘off.’

### **Component Options and Selection**

We narrowed the options for transistors down to two: the 2N2222A and the NZT6715. We then compared key features each to determine which was best suited to our application. The two transistors are comparable in voltage limits and current gain. Figure 4–8 and Figure 4–9 show the DC current gains of the two transistors. The 2N2222A had a slightly higher gain at the currents of interest to us (50mA and 70mA), with a value of approximately 275. The NZT6715 had a gain approximately 250 at the same current levels. Both transistors could withstand 40V continuously across the collector to emitter. The deciding factor in favor of the NZT6715 was the fact that it could tolerate a full watt of power dissipation and 1.5A of collector current, whereas the 2N2222A could only safely dissipate 625mW of power and could only supply 1A of current. While even the capability of the 2N2222A would suffice for our application, we decided to use the NZT6715 for its extra buffer tolerance, and to allow for possible future expansions.

## NZT6715 Typical Pulsed Current Gain vs Collector Current

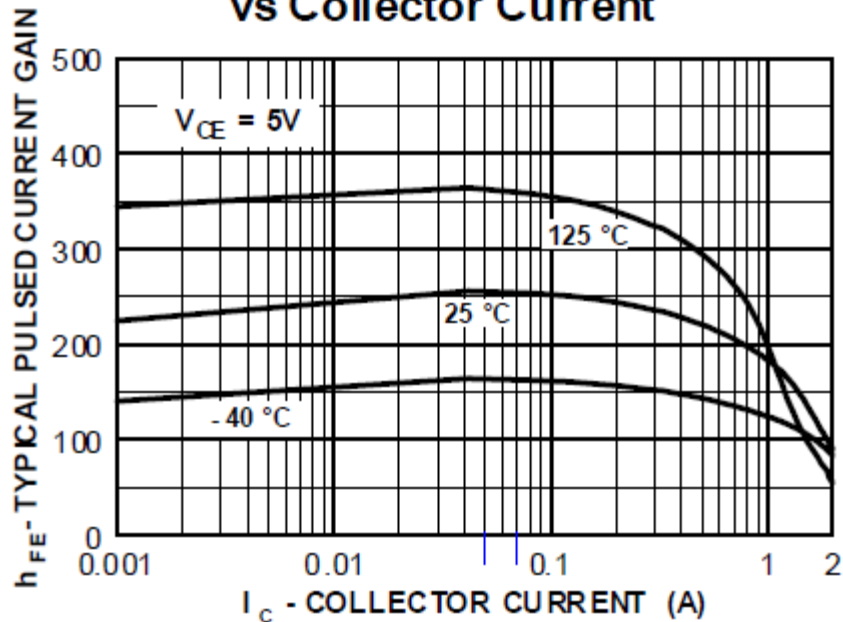


Figure 4-8: DC Current Gain of NZT6715 Transistor

### PN2222, PN2222A

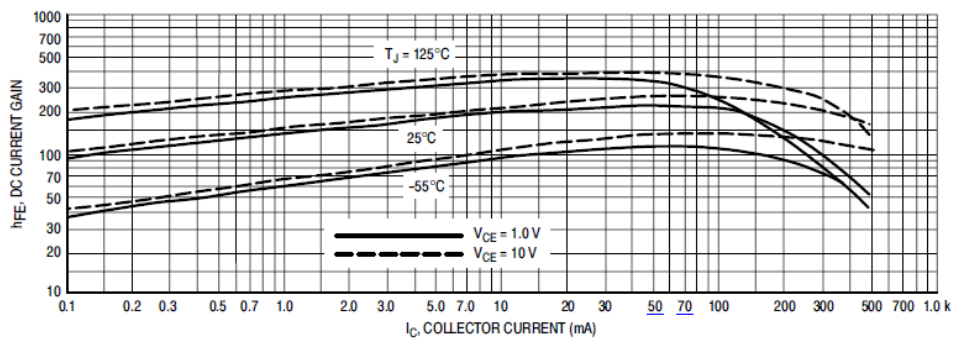


Figure 4-9: DC Current Gain for 2N2222A Transistor

Once we had chosen the transistor, we could then choose an op-amp to drive it. We had the LMC6494 available in the lab, however, it did not leave as much margin around our requirements as we would have liked. The main problem with this op-amp was that it would not operate at 3.3V single supply. The other parameters of this op-amp were adequate for initial testing, and in that stage, a dedicated power supply was simple to provide. Having a higher voltage supply would not be convenient once we transferred the design to a PCB. For our

alternative, we found the AD8618 op-amp. This device was able to operate with a single supply rail of 3.3V. It also provided numerous advantages over the LMC6494 in general specifications. The AD8618 had a much higher slew rate, and could get closer to the supply rails with its output. The AD8618 could provide 150mA source or sink at its output, where the LMC6494 could only provide 20mA. The higher current output is very beneficial when driving a BJT.

#### 4.4.Sensor

WS-7.56 wavelength detector from the Pacific Sensor Inc., was used for this project. The sensor was chose for its economical price, facile output measurement, and simple conversion of wavelength information to electrical output. The sensor is constructed on a silicon die with two photodiodes facing each other back-to-back in vertical configuration. A picture of sensor is shown in Figure 4–10.

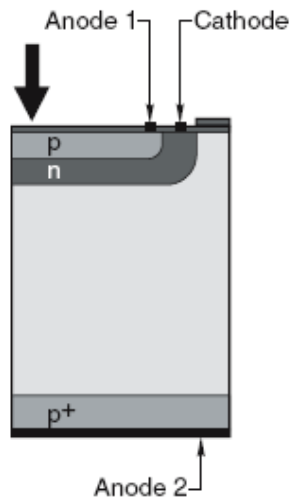


Figure 4–10: WS-7.56

One of the photodiodes is more sensitive to lower wavelength (400~700nm) and the other is more sensitive to higher wavelength (700~1000nm). Having different spectral responsivity, each diode produces unique photocurrent corresponding to the wavelength of the light source illuminated on the sensor, as shown in Figure 4–11.

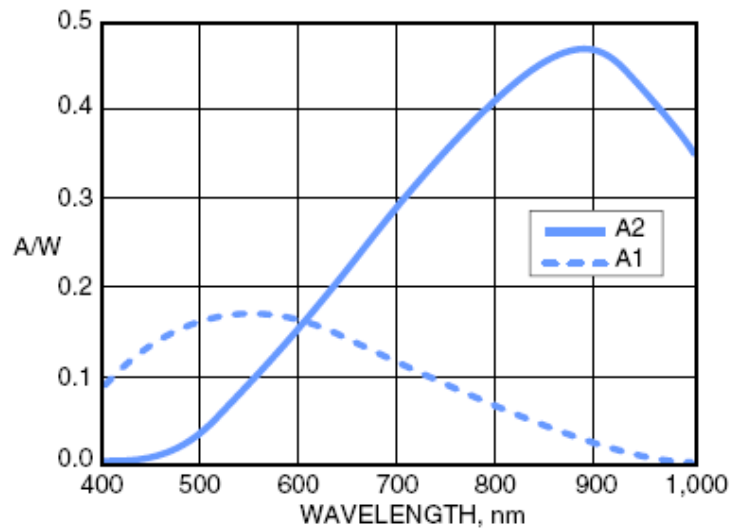


Figure 4-11: Spectral Resposivity of WS-7.56

ADL 5310 dual logarithmic converter was used to convert the output of sensor into a logarithmic scale. Then, the quotient of two sensor waveforms was found by taking the difference of the outputs of the logarithmic converter. This calculation was performed using the microcontroller unit.

#### 4.5.Initial Testing

LabVIEW DAQ was attached to control LEDs for selection testing and color mixing proof of concept. A variety of small LEDs were tested using LabVIEW during the selection process. The LabVIEW module was very helpful in accumulating large amounts of data for the LEDs we were considering. It allowed for automated control and measurement of the circuits, and could easily repeat the same measurements under the same or different test conditions. The LabVIEW controller also allowed for more certain test conditions for prototyping the current source.

Once we had a schematic designed, we needed to test it. The first version of the circuit was built on a solderless bread-board to allow for easy adjustments if needed. A computer running a LabVIEW application was used to provide the control signals at this stage in the process. This was done because, compared to using LabVIEW, it was impractical to interface the microcontroller with a bread-board. Using LabVIEW also removed one of the variables from the troubleshooting process. It is difficult to debug the programming of a microcontroller if there is not a working system for it to interface with. The LabVIEW application was easier to create and debug while the current source

was being finalized. Figure 4–12 shows two of the final four bread-boarded current sources, and Figure 4–13 shows the LabVIEW application used to control the current source.

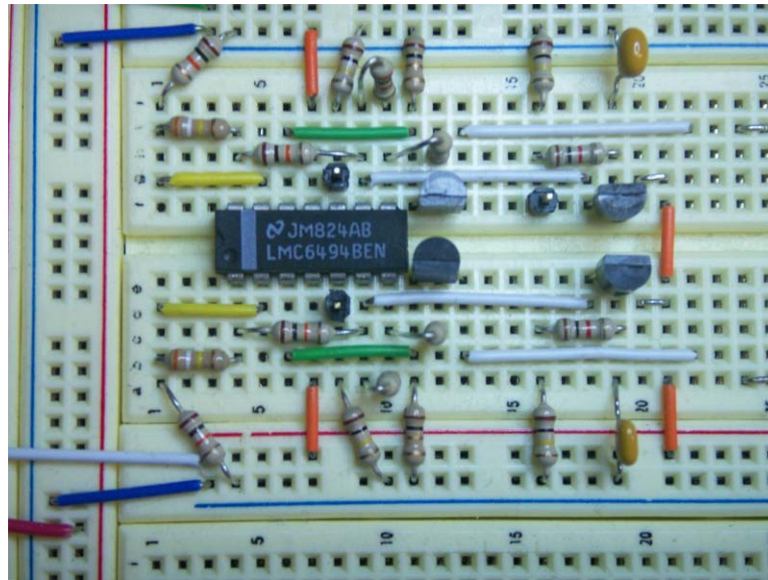


Figure 4–12: Two of the Four Current Sources on a Bread Board

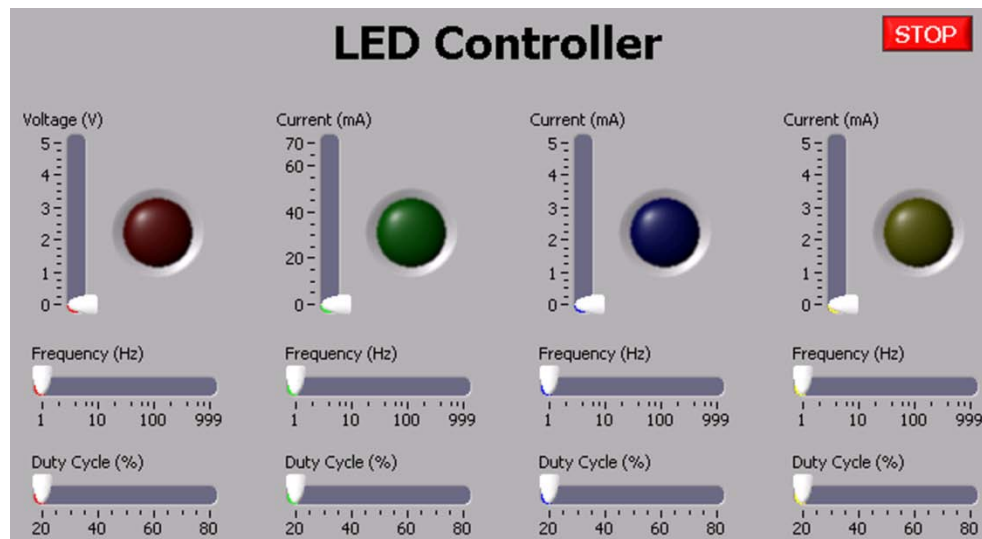


Figure 4–13: LabVIEW Interface for Manually Controlling the Current Sources

The LabVIEW application had controls to adjust the current through each color, the duty cycle of the PWM signal, and the frequency of the PWM cycles. We used this to determine the optimal operating conditions for each of the colors, so as to fine tune the current sources. Once we had finalized the current sources on the bread-board and determined that we could accurately control

the current and PWM with signals that are within the capability of the microcontroller, we were ready to design a PCB to recreate the circuit on.

#### 4.6. Printed Circuit Board

Once the breadboarded current source was verified to be working as desired, drafting of a printed circuit board began. The decision was made to order a duplicate board in case a mistake was made and repairs had to be performed afterwards. The board consisted of two sections. One contained the four current sources, data processing unit and voltage regulator, while the other section contained an array of holes for LEDs to be placed. The sensor feedback was not included in this revision of the printed circuit board. That part of the circuit was not yet completed and progress needed to be made on other facets of the project, particularly the implementation and programming the microcontroller and the current source. The boards were dual layered and made from the standard FR-4 material with 1oz copper plating, green solder-mask and white silkscreen. The layout was drafted in Ultiboard. Figure 4–14 and Figure 4–15 displays the drafted layouts of the control circuit and small LED arrays, while Figure 4–16 is a photograph of the populated LED Controller circuit. To create a densely populated board, demonstrating practical product scale, most components selected had surface mount packages. All of the resistors and capacitors selected were of package type 0805. Test points were placed on all data and communication traces to allow for simple testing and debugging.

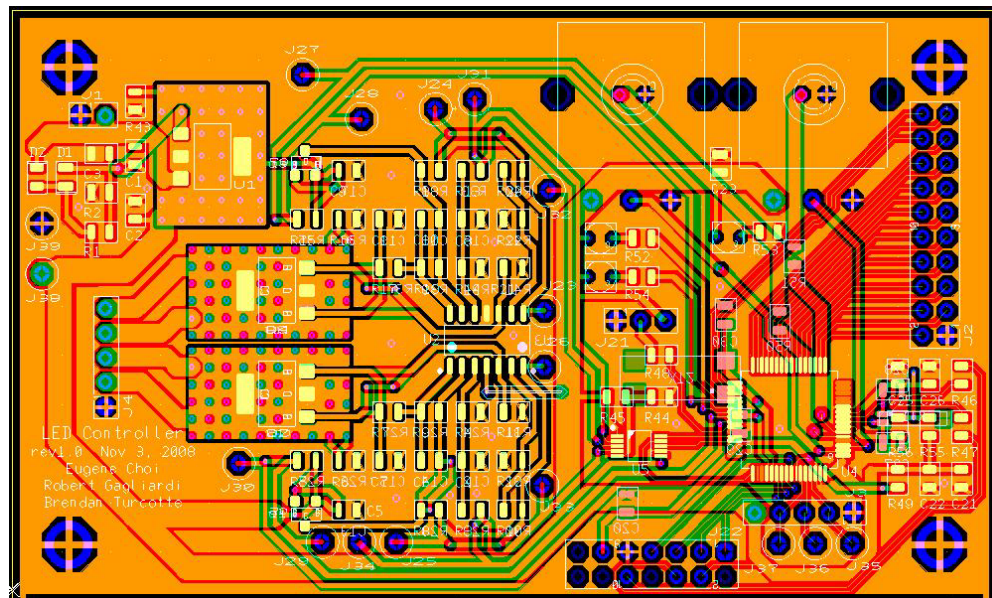


Figure 4–14: LED Controller rev1.0 - Printed Circuit Board Layout



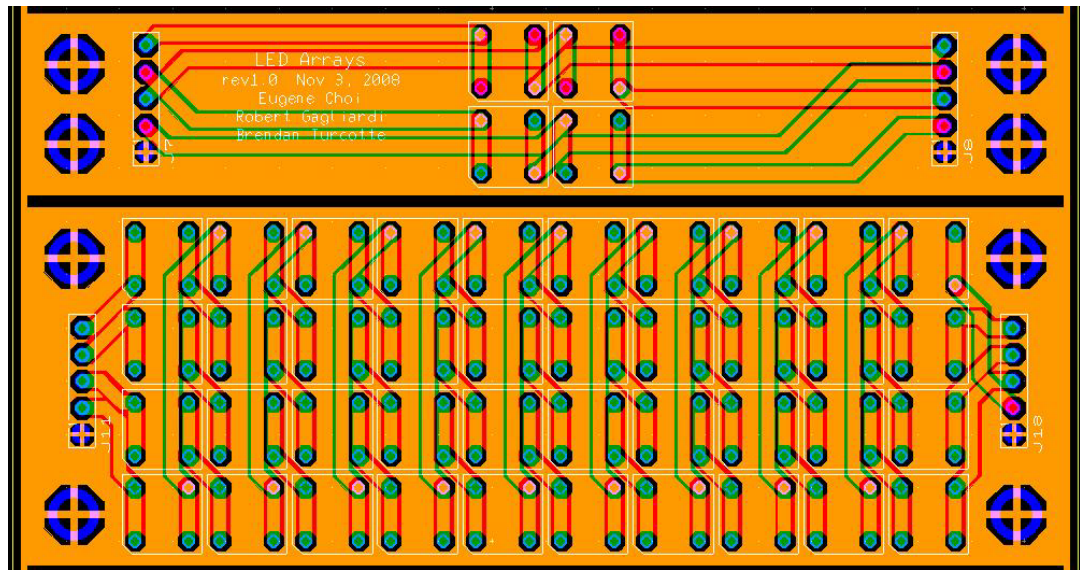


Figure 4-15: LED Array - Layout

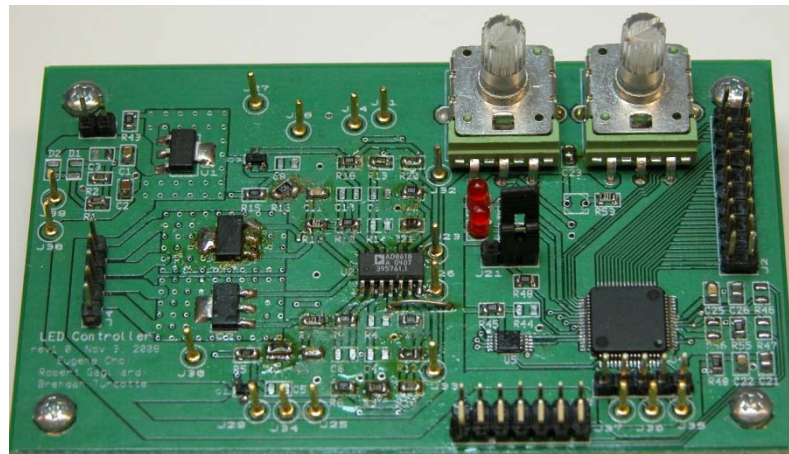


Figure 4-16: Photograph of Populated LED Controller rev1.0

### Voltage Regulator

For protection purposes a voltage regulator was placed on the board to provide a regulated 3.3V supply for  $V_{CC}$ . The MSP430, DAC, Op-Amps, Log-Amps and sensor all operate at this supply voltage. The schematic for the voltage regulator is shown in Figure 4-17. In Figure 4-18 is an image of the circuit layout. Notice the extra pads placed on the PCB. These allow for the addition of extra components in the circuit. This was done since the device was still in a testing phase and unforeseen circumstances may have forced the use of additional protection diodes or capacitors. Ultimately these components were not needed for the voltage regulator to function properly in our circuit. The schematic layout used to create the PCB with these extra pads is

shown in Figure 4–19. The extra copper area surrounding the LM317 was perforated with ‘vias’ for heat dissipation considerations, see Figure 4–16. This was ultimately an unnecessary feature.

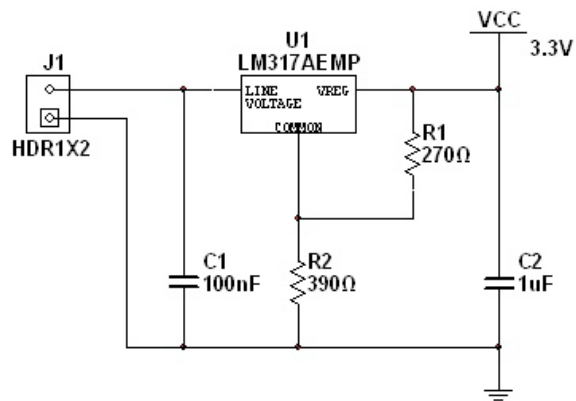


Figure 4–17: Voltage Regulator - Realized Schematic

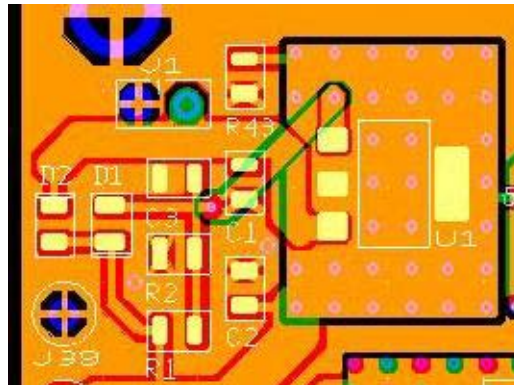


Figure 4–18: Voltage Regulator - Layout

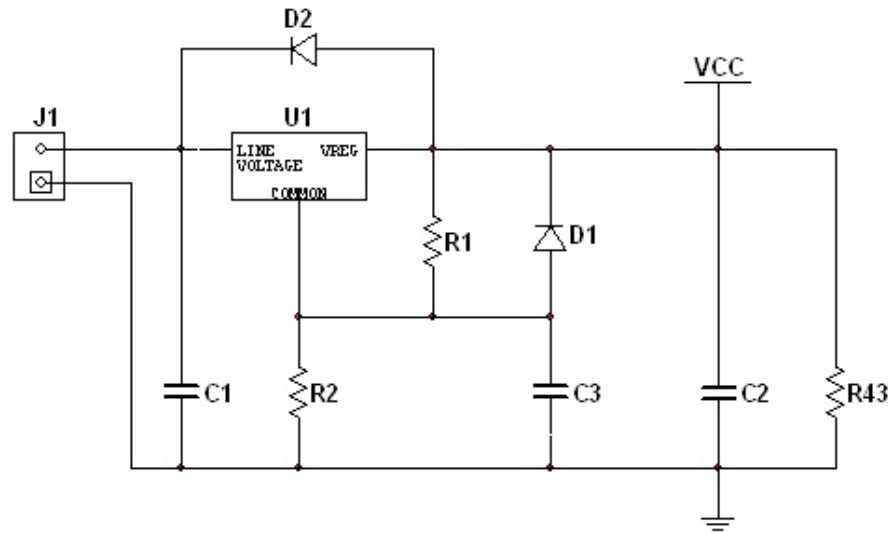


Figure 4–19: Voltage Regulator: PCB Schematic

### Microcontroller

The microcontroller circuit primarily sits on the top of the PCB, aside from a few resistors and clock crystals which are on the bottom. The microcontroller timing pins attach directly to the current source via traces while the external DAC connects the MSP430 to the analog inputs of the current source. The external sensor module not located to this board attaches via the single row five pin header located on the lower part of the board as shown in the Figure 4–20. The JTAG interface for programming and debugging the device is the two by seven header in the lower left hand corner. The largest header on the right was placed on the board to provide access to the MSP430's I/O pins for future peripherals such as a Keypad or LCD. This was ultimately not utilized. A power indicator LED resides in the center of the image, while two status LEDs are on the left side. A three pin header was placed on the board below these status LEDs for a jumper to set different modes of operation during testing. Finally two potentiometers were placed at the top of the board for user input. One is for adjusting intensity while the other for adjusting color temperature. Two status LEDs were placed under the potentiometers as additional indicator lights.

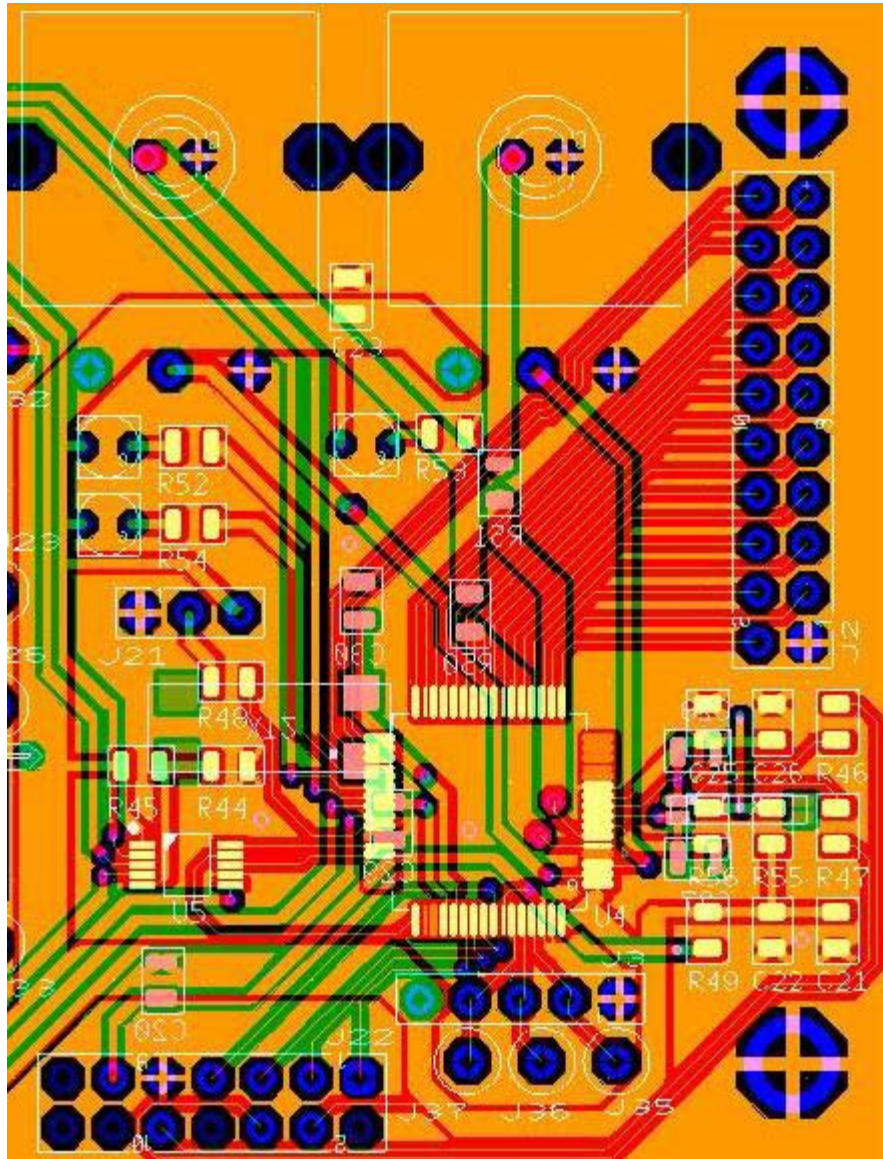


Figure 4–20: Microcontroller - Layout

### Current Sources

For this test board, four current sources were needed, one to control each of the series strings of colored LEDs (Red, Green, Blue, and Amber). Two current sources are visible on the top of the board in Figure 4–16. Notice how they are mirror images of each other and share the same op-amp chip. Since all surface mount components were used it was possible to place two more current sources mirrored on the opposite side of the board. This becomes more apparent when viewing Figure 4–21 of the layout in Ultiboard. Notice that extra pads are present in the board layout of the current source in comparison to the final current source schematic shown in

Figure 4–7. These extra pads were present to allow for future adjustment of the current source transfer function. The schematic of a single current source used to layout the board with extra pads is shown Figure 4–22. Test-points were placed at critical points for testing and debugging. A five pin single row header allows for attachment of LED chains to the current sources. As with the voltage regulator, the areas under the current source transistors were perforated with ‘vias’ for heat dissipation. This was a useful addition, because the area becomes warm to the touch during operation. If a second revision were to be made it would be wise to not place all four transistors so close together or directly on opposite sides of the board.

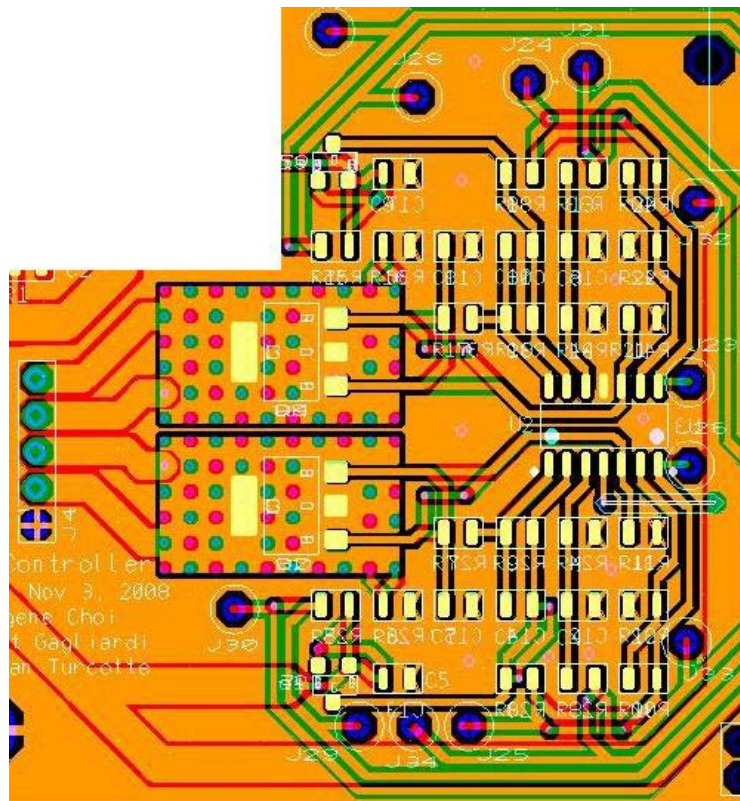


Figure 4–21: Four Current Sources - Layout

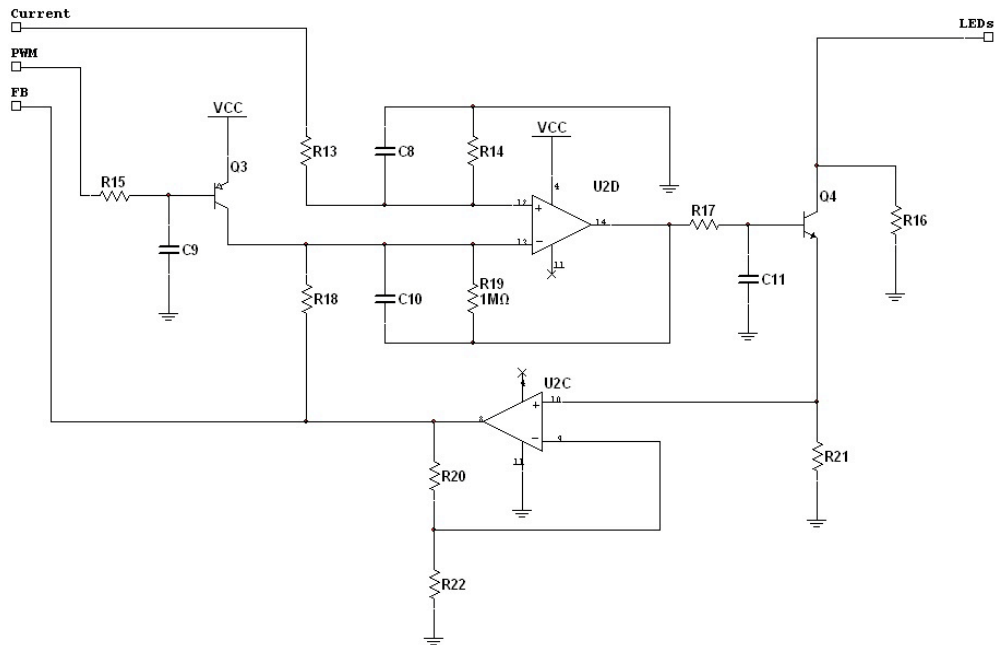


Figure 4–22: Current Source - PCB Schematic

## LED Arrays

The printed circuit board manufacturer producing the board for this project charged a fixed price per board with a maximum board area of 60 in<sup>2</sup>, so the remaining board area was designed to hold multiple strings of LEDs. One small array containing one of each color was made for testing and debugging. Six larger arrays of containing forty LEDs, or ten of each color were also laid out. At either end of the arrays are five pin headers for attaching the power supply voltage and current sources. Since the LEDs in each array are connected in series, the separate arrays can be chained in together in series using five wire jumper cables as long as the appropriate voltage supplies for the LEDs are used. The LEDs were place in a diagonal pattern to aid in color mixing. This diagonal pattern is clearly shown in Figure 4–1.

### 4.7.LED Polling Method

In order to take measurements on a single color of LED, the other colors had to be turned off. The initial attempt of simply turning off all colors except the one to be measured was not successful. The time it took to turn off the other colors, measure the remaining one, and turn them all back on was long enough to be noticed by the eye, and thus the light flickered.

The second attempt was successful, and worked by taking advantage of some of the microcontroller features that had previously been overlooked. One method of timer operation is

performed by setting the channel high for a certain length of time, then setting the channel low for the remainder of the cycle. It is also possible for the timer and channel to behave in reverse. The channel would be set low for a time, and then be set high for the remainder of the cycle.

The isolation of one color at a time was accomplished by using a combination of both methods. The default method would be to set the channel low at first. The color to be measured would then be set to the other method, and the effective duty cycle would be the complement of the normal duty cycle (period – duty). This resulted in one channel being on for a time, then turning off, while the other channels are off for a time, then turn on. By setting a minimum duty cycle of 20%, we could ensure that there would always be an adequate span at the beginning of a cycle.

Figure 4–23 shows the scaled version of the voltage across the current sense resistor for each of the channels. Channel 1 (yellow) is the red LEDs, channel 2 (blue) is the blue, channel 3 (violet) is the amber, channel 4 (green) is the green LEDs. The blue and green chains are operating at 50mA while the red and amber chains operate at 70mA. The high portions of the waveforms correspond to the portion of the cycle when the LEDs are on.

Figure 4–23 and Figure 4–24 show the waveforms during a polling cycle. Figure 4–23 shows the waveforms while the amber LEDs are being polled. The apparent time shift in the amber waveform is due to the duty cycle inversion. In reality, the amber LEDs are being turned 'on' at a different time in the PWM cycle, but for the same duty period. This allows for one color to be measured at a time without disrupting the perceived operation.

Figure 4–24 shows the waveforms when the red LEDs are being polled. This appears different from the amber polling because the oscilloscope is triggering off of the red LED channel. This view provides a more convenient example of the duty cycle adjustments. The blue, green, and amber LED channels are unchanged from their normal operation. The beginning of each cycle occurs at the falling edge of these waveforms. The 'on' duty cycle appears at the end of each PWM cycle, and is specified by the duration of the 'on' pulse. The red channel is operated in complement to the others. For the polled channel, the 'on' pulse appears first in the PWM cycle, but it is defined by the same mechanic as the other channels. That is, the duty cycle is specified by the duration of the second half of the pulse, which is now the duration of the 'off' pulse. To account for this, the duty cycle for the polled channel is declared as  $[100\% - \text{'on' duty}\%]$ . The result is the waveforms as shown in Figure 4–24.

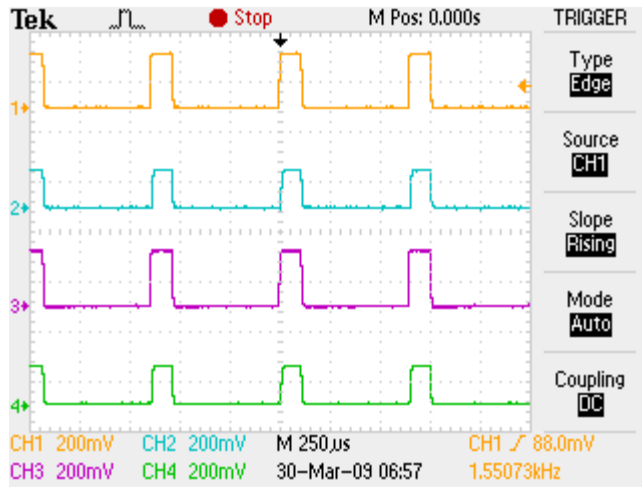


Figure 4-23: Normal Operation Waveforms for all Colors

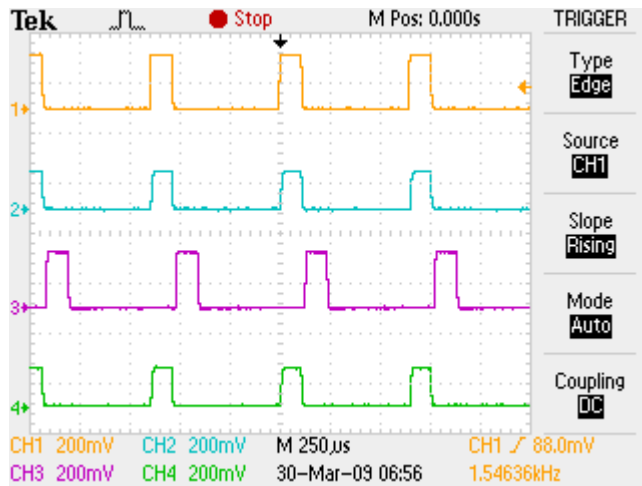


Figure 4-24: LED Channel Waveforms During Polling of Red



## 5. Calibration Algorithm

The algorithm to make use of the sensor data to mix the LEDs to white went through a number of stages before it was completed. Initially, the algorithm only sampled each color once, and assumed that the reading it received was for the correct color. This resulted in the light output changing significantly with each update cycle. We determined that this problem was caused by interference from the other LEDs and ambient light sources. The problem was aggravated by the imperfections involved with the measurements, so that the values received from consecutive reads of the same color were different, even if the LEDs had not changed significantly.

To solve these problems, we developed a new algorithm. First, we stored the expected wavelengths of the LEDs as reported by the datasheets. These would be used as a basis of comparison later. We then set a tolerance of how far the readings could vary and still be considered valid. The LEDs were then sampled as before, but the data was handled differently. Each color, one at a time, was sampled repeatedly until 10 good measurements were taken. A good measurement was determined by the tolerance and expected wavelength for that color. The microcontroller took the sensor reading and calculated the wavelength of the light measured. If that wavelength did not fall within the acceptable window, the data was ignored and the LEDs were sampled again. When a valid data point was measured, the wavelength and intensity were each incorporated into their own 10 value moving average. This smoothed out the variance in the readings and prevented wild adjustments. Once 10 valid measurements had been made, the system would move on to the next color and repeat this process.

Once all four colors had collected acceptable data, the adjustment calculations began. The wavelength data was only used to verify that the correct color was measured, while the intensity data from the valid measurements was used to determine the readjustment. The four valid moving averages of the intensities were sent through a function to determine the dimmest color. The other three colors were then scaled back in their PWM duty cycles to match the dimmest color. At this point all of the colors were calculated to be of equal intensity. Next these duty cycles were adjusted according to a program defined mixture for neutral white light. Now the duty cycles were correct relative to each other to generate white light, however, they were not likely at full available brightness, or at the specific intensity that the user selected.

The next step was to take the default white balanced duty cycles and shift them so that the brightest color was operating at maximum duty cycle. Once that was accomplished, the user input was considered. The user intensity was measured on a scale from 0 to 1, so the maximized white balance duty cycles were simply multiplied by this value. This scaled all duty cycles evenly to maintain the white balance at a different overall intensity.

The user color temperature was slightly more complicated to implement. The input for color temperature was measured on a scale from -0.17 to +0.16. These were used to scale the relationships between the four colors. This had to be considered in two parts: one for if the user wanted a cool light, and the other for if the user wanted a warm light. The cool light mode was easy, as the red and amber LEDs simply needed to be scaled down. The harder part was if the user wanted a warm light. If the user wanted a warmer light, but the duty cycles of the red or amber LEDs were already very high, the adjustment scale up would put them over 100%. In this case, the green and blue LEDs were instead scaled back. This had the same effect of mixing more red and amber than blue and green in the white mixture. If the red and amber duty cycles before temperature balance would fit the increase in duty cycle, then the red and amber were simply scaled up to change the balance.

The changes to the base neutral balance duty cycles occurred only once all the necessary valid data points were acquired. The user input, however, was considered far more often. Every time the sensor took a reading, the microcontroller also measured the potentiometers that we used for user input. If the readings were more than 10% away from the last reading, the user settings were recalculated using the last set base neutral duty cycles. The 10% buffer was needed because the ADC readings for the potentiometers had a tendency to drift slightly. The buffer ensured that the input was only considered if there was a definite change by the user.

## 6. Results & Analysis

The objective of this project was to produce white light by mixing Red, Green, Blue and Amber LEDs to create a consistent, accurate, white light. This was achieved with a feedback sensor that monitored the wavelength and intensity of LEDs. It must be noted that proper light measurement equipment was unavailable to the group. All results are based on subjective observations or data gathered from the sensor under test.

### 6.1. White Light

Through subjective observation white light was successfully created by mixing Red, Green, Blue and Amber LEDs appropriately, as shown in Figure 6–1. These levels of white were adjusted to mimic different color temperatures. An image of warm light is shown in Figure 6–2.



Figure 6–1: Photograph of Neutral White Light

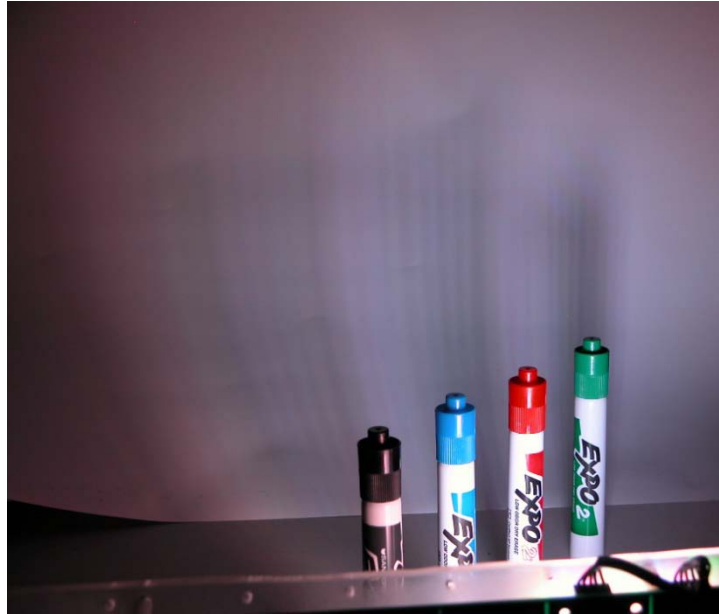


Figure 6–2: Photograph of Warm White Light

The intensity and color temperature were both capable of being adjusted by the user with two potentiometers. The different images above were taken by adjusting the color temperature knob. It was not possible to determine what the current color temperatures of the above images were or if the white light was even along the color temperature curve. A spectroradiometer would be needed to complete this task. It was possible however, to create almost any observable variation of white light by mixing the LEDs. In addition the color and intensity of light remained stable at the output specified by the user. This was determined visually and could be further substantiated with proper measurement equipment.

## 6.2.Shadows

One requirement of the system was that it must not have colored shadows that would annoy the user. These shadows are visible in Figure 6–3. To alleviate this problem a simple diffuser was created and placed over the LEDs. A piece of sanded plexi-glass was used to produce the shadows shown in Figure 6–1. A better diffuser could be designed specifically for this application by an optics engineer.



Figure 6–3: Photograph of Shadow Without Diffuser

Even with the diffuser the light source does not appear white when it is looked at directly. To solve this problem the light source could be placed so that the light is reflected off the back of a light fixture. This would prevent the user from ever directly looking at the light source.

Finally the entire system operates without any noticeable flicker to the user. The feedback mechanism is also unaffected by ambient light. The light will remain at a constant level and not deviate from it until the user adjusts either the intensity or color temperature.

## 7. Conclusion & Recommendations

This prototype provides reasonable evidence that this approach to lighting is feasible. With proper light measurement equipment data could be collected to verify these claims. With this new data a better calibration algorithm could be devised.

If another group was to continue this project we recommend they implement an AC adapter so that a large scale application would be possible. There are limitations to using a desktop power-supply. It is crucial that the group also obtain the use of a spectroradiometer to measure light. A proper diffuser should be designed or obtained as well. With these three additions the group should be able to create a working product capable of lighting a room to the standards set forth by the lighting industry. If the team wished to further improve the color rendering of objects they could expand the system from using just RGBA LEDs by placing more different colors of LEDs to fill in the spectral gaps between RGBA. This is similar to the role Amber plays. It fills the spectral gap between Red and Green to provide better color rendering.

In summary, the method of creating a consistent white light using RGBA LEDs has potential. The technique implemented in this project with a feedback sensor also works. This project has shown that it operates successfully at a subjective level. We suspect that this form of lighting may someday be sold as a commercial solution to home or business lighting.

## 8. References

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