# Project Report – Cover Page

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<thead>
<tr>
<th>University/College Name</th>
<th>Rensselaer Polytechnic Institute</th>
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<tr>
<td>Team Name</td>
<td>RPI Smart Lighting</td>
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<tr>
<td>Team Member Names</td>
<td>Hayleigh Sanders</td>
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<tr>
<td></td>
<td>Timothy Castiglia</td>
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<tr>
<td>External Affiliation/Business Partner</td>
<td>Robert Karlicek</td>
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<tr>
<td>Project Name</td>
<td>Automated Power Conservation and Color Temperature Control</td>
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<tr>
<td>Environmental area/opportunity addressed</td>
<td>Smart Home - Reduction in Energy Consumption</td>
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Please provide a brief one paragraph summary of your project:

This project seeks to reduce the total power consumption due to lighting in a commercial and residential setting through automated LED lighting intensity and color temperature adjustments. An LED lighting array is controlled by a microcontroller and I2C color sensor to obtain the RGB data needed to adjust both the brightness and temperature of its output to both conserve power and provide better lighting conditions for human activity.
Automated Power Conservation and Color Temperature Control

Problem Statement

Efficient lighting has long held the interest of sustainability efforts due to the prolific nature of electric light sources and their significant impact on total power consumption. The U.S. Energy Information Administration reports that residential and commercial lighting claims approximately 11% of the total U.S. electricity consumption for the year 2014. LED lighting has been developed as an energy-efficient alternative to traditional lighting sources like incandescent and compact fluorescent bulbs. An LED bulb typically operates at around 6-8 watts and is capable of producing light at an intensity comparable to a 60 watt incandescent light bulb. Likewise, LED lights have an average life expectancy of 50,000 hours. They run at a lower temperature than conventional light sources and do not contain dangerous materials like mercury. Despite this efficiency, these lights are not fully utilized in the commercial and residential sector. Two significant barriers in the usage of these lights are their relatively high cost and harsh light quality. This project attempts to provide a solution addressing both barriers to the use of LED lighting in the commercial and residential sector.

The high cost of LED lighting is due in part to the rare Earth materials and more intensive process required to manufacture them. However, the cost of LED lighting has dropped steadily as production efficiency has risen with increasing demand. The simplest possible design was sought to minimize the total cost of this project due to the inherent high cost of efficient color mixing arrays and drivers.

Lighting quality is usually described in terms of color temperature. This value ranges from 1,000 Kelvin to 10,000 Kelvin on the visible spectrum. Light with a low color temperature
appears warm and orange, while light with a high color temperature appears harsh and blue. A problem with current LED lighting systems available for commercial use is their lack of tunability with regard to color temperature. This makes them less desirable than their less-efficient counterparts currently on the market because they appear harsh and inappropriate for room lighting. This project seeks to develop a cost-effective LED lighting system capable of automatically adjusting its light intensity and color temperature in order to curb power consumption and encourage use through compatibility with the human circadian cycle.

**Project Summary**

This project is a novel approach to LED lighting systems with the intention of power conservation to reduce the pollution generated by electricity production. The lighting system design automatically adjusts its brightness and color temperature relative to outdoor lighting conditions with the use of an Arduino microcontroller and I2C color sensor routed to the LED array. The color sensor is meant to be attached to a window to detect the RGB properties of ambient light entering a room to determine lighting needs. The LED array output brightness is programmed to be inverse to that of the brightness detected by the sensor, so that the LEDs become bright in low ambient light conditions (i.e. night) and dim in high ambient light conditions (i.e. daytime) to take advantage of natural light. Likewise, the LEDs replicate the color temperature of the ambient light detected by the color sensor to produce light compatible with the human circadian cycle for any given minute.

The use of alternative lighting systems for the purpose of power conservation has been varied. For example, automated light tuning in response to ambient conditions for a number of applications has been proposed in the patent application “Automated Dimming Methods and
A 2006 study on energy management attempted to address the use of automated light adjustment under dynamic conditions. An automated dimming system using ambient lighting conditions detected with a sensor was proposed in the patent “Automated lighting and building control system”.

This project is unique because, while standard LED bulbs may be manufactured at fixed color temperatures and automated dimming has been implemented for commercial use to conserve power, no present commercially-available system integrates both the dimming and color temperature adjustment of an LED lighting system in an automated fashion based on an external ambient light source.

**Relationship to Sustainability**

This project has deep implications with regard to sustainability and societal benefit. The power consumption of the lighting system developed for this project is significantly less than that of conventional lighting sources like incandescent bulbs and compact fluorescent lights, which makes them both cheaper to operate and curbs the pollution created by electricity generation. LED lights last far longer than conventional sources before they need to be replaced, which cuts down on waste generation due to replacement. LED lights produce far less heat than these conventional sources, so they reduce the risk of an accidental fire or injury due to burning. They do not contain mercury or toxic gasses, which makes them far safer for the environment and human use than conventional lighting sources. Likewise, the system developed for this project automatically tunes its color temperature to that of outdoor light, which makes it more compatible with human activity.
The color tunability of the system was a slight tradeoff with regard to power efficiency. White LEDs are the most power-efficient lighting sources available, but they lack dynamic color tuning, which can only be achieved with the use of a color mixing array of red, green and blue LEDs. The light output to power input ratio of red, green and blue LEDs is not as high as that of white LEDs and is intrinsically dependant on the elements used to create the LED.

**Materials and Methods**

Color tunability was achieved through the use of three Saber Z4 square color mixing arrays. Each array contained four LEDs: one red, one blue, and two green. Two green LEDs were incorporated into the array for better color mixing due to the way light is perceived by the human eye. The color mixing arrays were fixed to an aluminum heatsink with thermal tape. A waveguide was held very close to the surface of the LEDs on the mixing array to ensure proper light dispersion due to the fact that, unlike incandescent lights which radiate light in all directions, LEDs are only capable of emitting directional light. The waveguide has a textured surface that allows directed LED light entering its side to bounce around inside and exit the textured surface in a uniform manner.
Referring to Figure 1, four LED drivers were powered by a 24Vac transformer. Each color channel (red, blue, and two green) was powered by a 1000ma LUXdrive AC BuckPuck LED driver with internal dimming. The maximum supply current of each driver was adjusted to 300ma using an onboard dimming potentiometer. The Arduino Nano microcontroller was powered using the 5V internal reference voltage supplied by one of the drivers. The control input of each driver was connected to a corresponding PWM output on the Arduino, which was programmed to send a PWM signal corresponding to the correct current at which to drive each color channel. A Taos TCS34725 I2C color sensor was wired to the Arduino in order to provide RGB data to its control algorithm in order to send a PWM signal to each driver corresponding to the correct current needed for each channel to produce the desired color temperature and intensity configuration.

The color sensor returns data for the red, green and blue intensities of detected light. These values were used to determine the color temperature of the ambient light using a function in the Arduino driver file for the TCS34725 sensor. Given a color temperature, this light can be recreated on the color mixing array with red, green and blue LEDs using the relationship between RGB values and color temperature established by previous research. Figure 2 shows the graphed data of the color temperature and brightness (a PWM value from 0 to 255) of red, green and blue LEDs.
The color temperature range of interest for room lighting applications is 1000K to 6500K. A regression analysis was performed on the RGB relationship to color temperature due to the limited space on the Arduino, making it unable to refer to an entire lookup table and obtain sensor data at a reasonable rate. This analysis was used to approximate values for blue and green given a red value, shown in Figures 3 and 4. The logarithmic regression equations for green and blue are shown in the top right corner of each respective figure.
Using a preliminary build of the model, an integration sphere was used in order to determine the power consumption of each channel. The sphere is pictured below in Figure 5 with the LED mixing arrays inside. Figures 6, 7 and 8 show the data resulting from tests at various currents up to a maximum current for each LED channel. The maximum current for each channel was determined through experimental optimization by adjusting the arrays so that they produced enough white light to illuminate a completely dark room.
Team Member One Contribution: Her contribution consisted of designing and building the electrical system, ordering parts, determining the physical power requirements of components, and designing tests to obtain experimental data.

Team Member Two Contribution: His contribution consisted of the software design and statistical analysis side of the project. He researched the relationship between color temperature and RGB values in order to determine how to set the RBG LEDs for the appropriate color temperature.

Results, Evaluation and Demonstration

The table below gives a summary of the efficiency of the lighting system compared to other common sources of light. Lumens per watt, the amount of light emitted per watt of supplied power, were used as a measure of efficiency. These calculations were performed at similar lumen values for the other light sources. The lighting system is far superior to incandescent and compact fluorescent sources, but not quite as efficient as a white LED array.

<table>
<thead>
<tr>
<th></th>
<th>Color Tunable LED System</th>
<th>Incandescent Bulb</th>
<th>Compact Fluorescent</th>
<th>White LED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency (lm/W)</td>
<td>242.8977</td>
<td>8.6</td>
<td>46</td>
<td>260-300</td>
</tr>
</tbody>
</table>
The total power consumption of the lighting system was then estimated by fitting the power consumption of the design to RGB sensor data. The color sensor was fixed to a window and allowed to record RGB data for a 24-hour period at one minute intervals. Using the current needed for each channel to produce its maximum brightness as an upper bound reference point, the instantaneous RGB values were converted to a PWM value from 0 to 255, which correspond to the control signals sent from the PWM pins of the Arduino to each LED driver. The power consumption for the system was then calculated taking into account the 1.4 Watts of power consumed by the Arduino and the .0125 Watts of power consumed by the color sensor.

![Power Consumption vs. Time](image)

*Figure 10: Power consumption over a 24 hour period*

The system consumed an average of 3.85 Watts per hour over a 24 hour period. The implications of this finding are summarized in the following table:

<table>
<thead>
<tr>
<th></th>
<th>Color Tunable LED System</th>
<th>Incandescent Light Bulb</th>
<th>Compact Fluorescent Light</th>
<th>Standard White LEDs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Watts per hour</td>
<td>3.85</td>
<td>60</td>
<td>13-15</td>
<td>6-8</td>
</tr>
<tr>
<td>Electricity cost over a 30 day period (Upstate New York power rates)</td>
<td>$0.21</td>
<td>$3.31</td>
<td>$0.71-$0.82</td>
<td>$0.33-$0.44</td>
</tr>
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</table>
Despite its high up-front cost, the color tunable LED system used far less power than its commercial counterparts. The system should pay for itself once the long lifetime of LEDs is taken into account. Scaling the system for compatibility with any room size would be simply a matter of adding more LEDs to each channel and/or increasing the current to each channel.

The system will be demonstrated in-person at the competition. It will be displayed on a table and its automated color tuning abilities will be demonstrated by exposing the sensor to various light conditions.

**Conclusions**

In conclusion, the automated color-tunable LED lighting system demonstrated high efficiency relative to conventional lighting sources. Its ability to adjust its brightness relative to ambient light allowed it to consume less power on average than a standard white LED bulb, which made up for the loss in efficiency due to color tuning. The system was able to automatically adjust its brightness and color temperature in a way that standard, commercially-available lighting systems cannot. The high up-front cost of the system may be a deterrent to residential use, unless it is viewed as an investment that will last a long time, like a refrigerator. Despite this, the flexibility of the design makes this application ideal for both residential and commercial use. Future testing would need to include system readings from a wall-mounted power meter in order to account for the power overhead contribution of the LED drivers and 24Vac transformer. This test was prevented due to a lab accident involving the loss of one blue LED on the mixing array and a driver. While the LED drivers are highly efficient, their power loss cannot be ignored if the most accurate results are desired.
References


4. Ray James King, “Automated lighting and building control system” Publication number US20100176733 A1. 15 July 2010

