Automated LED Dimmer Compatibility Tester

ECE 4012 Senior Design Project

Section L08A, Team We-Dim-Bulbs (sd19p07)
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Executive Summary

As LED bulbs become the predominant part of lighting solutions, they are expected to have the dimming capability like their predecessors, e.g. incandescent. However, due to the incompatibility between driver circuits inside LED bulbs and dimmers, consumers and manufacturers face the flicker problem where the brightness of a LED bulb fluctuates at certain dimming levels. In order to support consumers with such issue, Eaton Corporation, one of the largest power management companies, test their dimmers and provide lists of LED bulbs that are compatible with their products. Until now, the compatibility test was done manually on a pair of dimmer and LED bulb at a time costing the company significant amount of time and resource to test multiple combinations of dimmers and LED bulbs. To aid Eaton with their efforts, the Team-We-Dim-Bulbs designed and prototyped the Automated LED Dimmer Compatibility Tester (ALDCT) which automatically performs the compatibility tests on two Eaton dimmers with any four LED bulbs increasing the number of tested pairs by factor of eight while keeping the testing time to short 10 minutes. During the testing, the ALDCT measures the average intensity of light (average illuminance), percent flicker (fluctuation in light intensity), flicker frequency, and determine the visibility of flicker at different dimming levels (dimmer's conduction angles). Then, the tester outputs a tabulated test results, measurements mentioned above, as a CSV file. Overall, the Automated LED Dimmer Compatibility Tester, designed and prototyped by Team-We-Dim-Bulbs, has significantly increased throughput of tested pairs allowing Eaton to provide better customer service and bring constructive feedback on their research and development at cost of $1,037.

Automated LED Dimmer Compatibility Tester

1. Introduction

To increase output of compatibility test by factor of eight while keeping the test duration of short 10 minutes, the Team-We-Dim-Bulbs is requesting $xx funding to develop the Automated LED Dimmer Compatibility Tester (ALDCT).

1.1 Objective

The objective of Team-We-Dim-Bulbs' project was to develop the Automated LED Dimmer Compatibility Tester (ALDCT) which is capable of automatically testing up to two dimmers and four LED bulbs at a single testing session, measuring and outputting the average intensity of light (average illuminance), percent flicker (fluctuation in light intensity), flicker frequency, and visibility of flicker at different dimming levels (dimmer's conduction angles) in a tabulated format as a CSV file. The ALDCT significantly increases the productivity of compatibility test by factor of eight (two dimmer and four LEDs) while keeping the test duration at short 10 minutes; which is long enough for a good coffee break.

1.2 Motivation

Until now, the project sponsor, Eaton Corporation, was testing the compatibility between their dimmers and dimmable LED bulbs in the market manually which involved a technician adjusting the dimmers to certain dimming levels (conduction angle) using an oscilloscope, measure percent flicker with an expensive flicker meter (Asteria light meter [1]), visually inspect the LED bulb for visible flicker, then record the result in a spreadsheet. The manual testing mentioned above is inefficient and expensive process due to human involvement. To increase the productivity and alleviate the overhead cost of the compatibility test, Eaton reached out to Georgia Tech which led to Team-We-Dim-Bulbs developing a prototype of the Automated LED Dimmer Compatibility Tester (ALDCT) which automated the repetitive parts of compatibility testing, improved the throughput by factor of 8, and significantly reduced human involvement. Furthermore, the ALDCT project was industry specific meaning there was no existing product or solution that was available in the market.

1.3 Background

The LED-Dimmer incompatibility is one of the biggest challenges presented to LED and dimmer manufacturers these days. To solve this issue, Eaton Corporation provides their customers with a list of LEDs that are compatible with their dimmers. And, to produce this list, Eaton currently uses a manual testing system operated by a technician where he or she spends hours to perform the compatibility tests.

To detect flickering and measure the corresponding flicker percentage, Eaton utilizes a flicker meter, an oscilloscope, and visual inspection performed by the operator. First, the Tektronix oscilloscope MSO 5204B is used to visualize the input and the output (conduction angle) power of the dimmer [2]. Then, using the oscilloscope the operator adjusts the dimmer to reach a certain dimming level (conduction angle). Next, a light meter called Asteria, a high-speed optical measurement device by Admesy, is used to measure the flicker percentage (fluctuation in light intensity) and illuminance (average light intensity) of a dimmed LED bulb [1]. Furthermore, the LED bulb is inspected by the operator for visible flickers; this is done because high percent flicker does not correlate to visible flickers. Finally, the measurements are recorded on a spreadsheet manually for each dimming level, then compatibility is determined.

2. Project Description and Goals

The Automated LED Dimmer Compatibility Tester (ALDCT) designed and prototyped by the Team-We-Dim-Bulbs consists of three modules: control module, actuation module, and sensing module. These modules come together to automate the LED-dimmer compatibility test successfully acquiring following key measurements at different dimming levels to meet Eaton's testing requirements:

- Conduction Angle [°] (Dimming level)
- Average Illuminance [Lux] (Average light intensity)
- Percent Flicker [%] (Fluctuation in light intensity)
- Flicker Frequency [Hz] (Periodicity of flicker)
    - Flicker Frequency was not required by Eaton.
- Visibility of Flicker [Visible/Non-Visible]

While meeting Eaton's compatibility test data requirement, the team's prototype also achieved the goals proposed previously except for one:

- Fully automated testing procedure. (Achieved)
- Capability of testing eight LED bulb-dimmer combinations in one setup. (Achieved)
- Measuring average illuminance and percent flicker with low cost hardware. (Achieved).
- Generation of test result documents in accordance with Eaton's reporting standard.
    - While ALDCT outputs a CSV file of measurements that meets Eaton's data requirement, it does not meet Eaton's reporting format. Further data processing is required.

3. Technical Specification & Verification

The Table 1 below lists the proposed and final technical specification of the ALDCT.

Table 1. The desired and final technical specification of the ALDCT.

Feature Description	Proposed Value	Verified Value
Power Input	120 VAC, 60 Hz	120 VAC, 60 Hz
Number of Dimmers Supported	2	2
Type of Dimmers Supported	Push-Button, Slide	Push-Button, Slide
Number of LEDs Supported	4	4
Maximum Measurable Light Intensity *	50,000 Lux	700 Lux, 50,000 Lux*
Maximum Measurable Flicker Frequency *	2 kHz	2 kHz*
Visible Flicker Detection	Yes	Yes
Test Result Output Format	CSV/XLSX	CSV
User Interfaces (I/O)	Keyboard, Mouse, Monitor (GUI), USB	Keyboard, Mouse, Monitor (GUI), USB

Please see below for features with asterisk:

- The designed ALDCT photo-sensor has two different photodiodes with different gains for low (up to 700 lux) and high (up to 50,000 lux) light intensity measurement. The 50,000 lux measurement was verified by moving the light source towards the photo-sensor after verifying the linearity of the photodiodes.
- The flicker frequency was verified by switching a single red LED with a signal generator.

Lastly, the physical dimension of ALDCT was no longer considered as a technical specification to meet other significant specification, e.g. user interface - monitor.

4. Design Approach and Details

4.1 Design Approach

The Automated LED Dimmer Compatibility Tester (ALDCT) designed and prototyped by Team-We-Dim-Bulbs consists of three modules: control, actuation, and sensing. [Fig. 1] below shows the high level view of the prototyped tester, and [Fig. 2] shows the actual prototype.

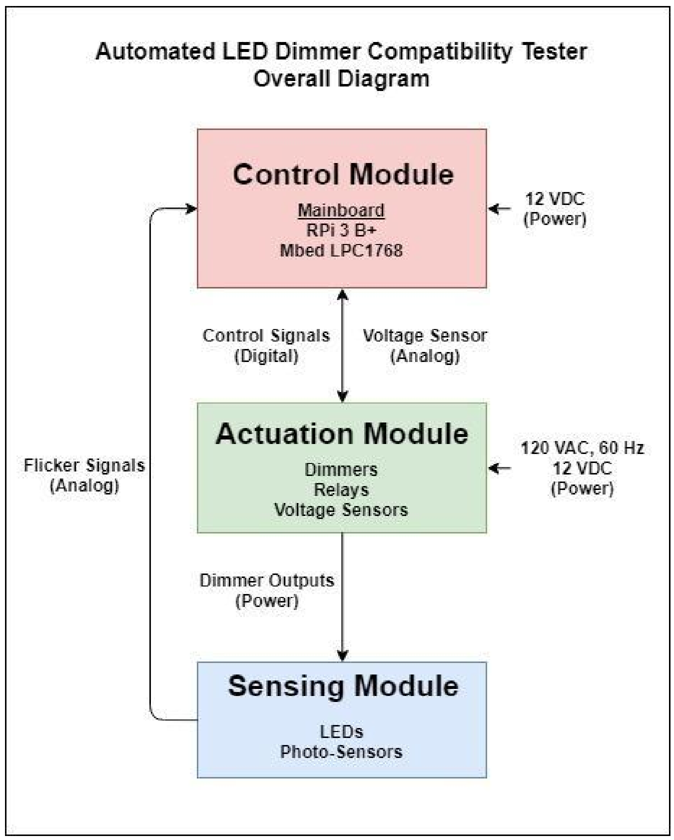

Figure 1. The high level view of ALDCT.

The control module is responsible for sending control signals to components in the actuation module, acquiring and analyzing signals from photo-sensors in the sensing module, and interacting with the ALDCT operator via inputs (i.e. GUI, keyboard, mouse) and outputs (i.e. plots, test result csv file).

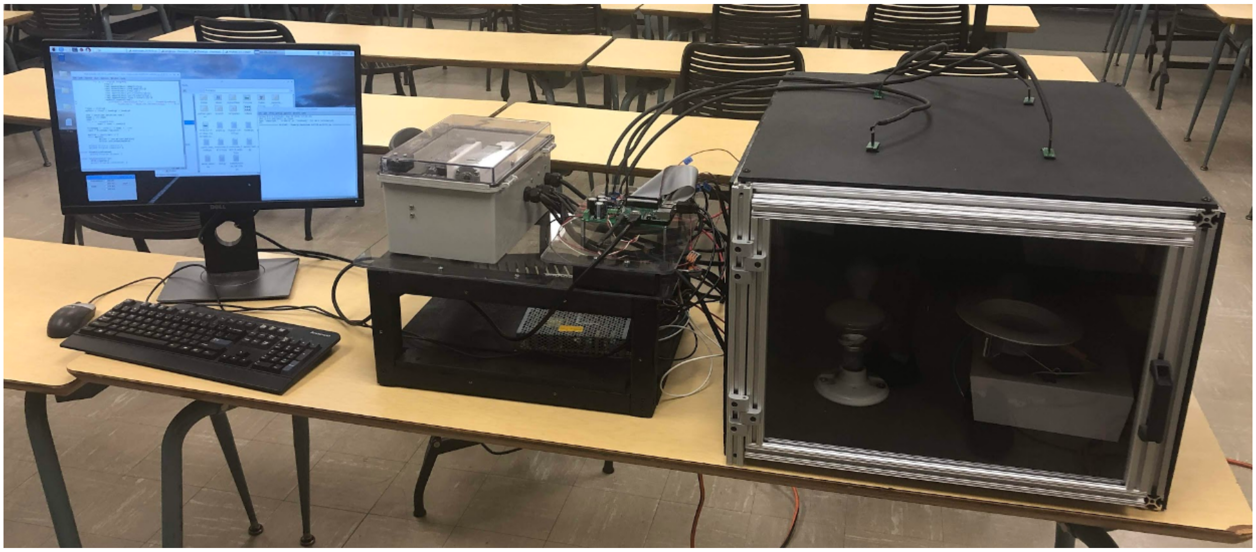

Figure 2. A picture of ALDCT prototype with all modules combined.

Next, the actuation module consists of electromechanical components that are controlled by the control module, voltage sensors to measure output of dimmers, and buck converters to power the stated components.

Lastly, the sensing module is a box made with aluminum bars and black side panels which encloses four E26 light bulb sockets and four photo-sensors for acquiring the key measurements mentioned in section 2 of this paper.

In the following sections, the prototyped ALDCT's hardware and implemented software are discussed in detail.

4.1.1 Hardware of ALDCT

4.1.1.1 Control Module

The control module is the brain of ALDCT. It sends control signals to actuation module, acquires data from signals coming from different sensors, and interacts with the ALDCT operator with I/O implemented with the module.

The major components of control module are one Raspberry Pi 3 Model B+, one Mbed LPC1768, and a mainboard which incorporates the Pi and Mbed. The Raspberry Pi 3 was used due to its capability of being a standalone computer (full-blown OS) with 4 USB ports (keyboard, mouse, data transfer), a HDMI port (monitor, GUI), GPIOs (digital control signals), communication protocol headers (serial, SPI, I2C), and Internet access via Wi-Fi or ethernet [3].

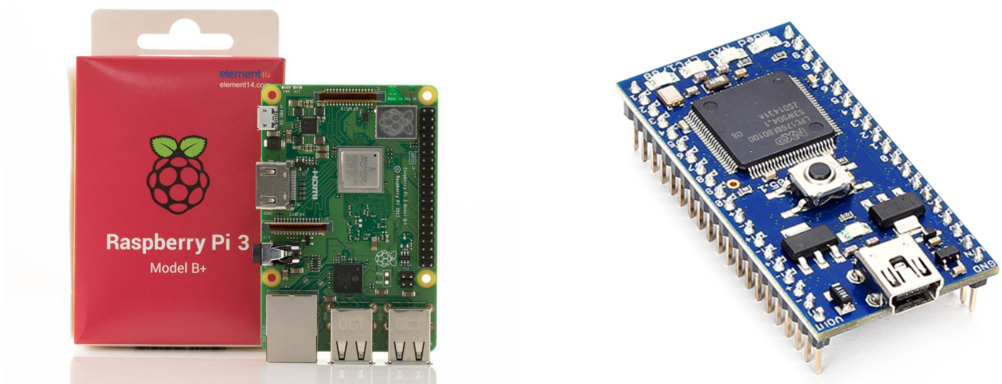

Figure 3. Raspberry Pi 3 Model B+ (left) and Mbed LPC1768 (right).

The Mbed LPC1768 was used since it has 6 channel 12-bit ADC and supports the communication protocols of Raspberry Pi [4]. Furthermore, a mainboard, shown in [Fig. 4] was made to incorporate the Pi and Mbed as a single module eliminating the messy connecting wires and making pin headers more accessible.

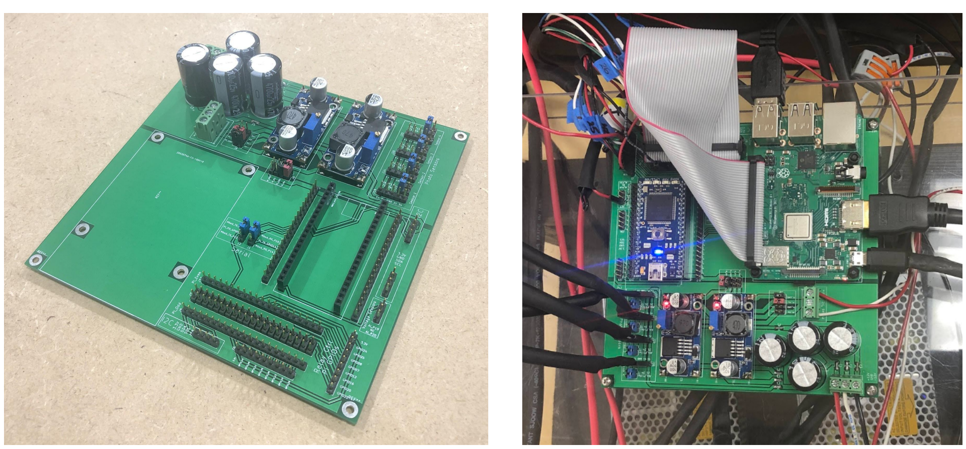

Figure 4. Unpopulated (left) and populated (right) mainboard.

The mainboard is made out of a two layer PCB with four input capacitors to smooth out the voltage ripples coming from power supply, two buck converters to provide 5V DC to Pi and Mbed, and, to provide powers to devices and photo-sensor headers, it receives +12V, 0V, and -12V DC from power supply. The board was laid out so that it provides power to Pi, Mbed, photo-sensors, and I2C devices, and connect all the necessary signal sources to Pi and Mbed. Please see Appendix A for schematic and layout of mainboard.

4.1.1.2 <u>Actuation Module</u>

The actuation module consists of a dimmer box, two dimmers, a linear actuator, two buck converters, two 8-channel relays, two limit switches, an adapter, and an actuator stand.

The actuation module is enclosed in a 8 in. × 8 in. × 13 in. dimmer box. The lid to the dimmer box is a transparent plastic, allowing the user to see inside the box.

Figure 5. AAL06-C2(left) SAL06 (right)

AAL06 and SAL06 are two dimmers that are manufactured by Eaton. AAL06 is a "smart dimmer single pole/multiple location" and requires neutral connection [5]. The neutral connection is intended to keep the microcontroller ON even if the dimmer is turned OFF. In this project, the AAL06 dimmer was hacked to replace the push buttons with a set of relays that are controlled by GPIO signals from Raspberry Pi. SAL06 is an “all load dimmer, single-pole/3-way” and is a mechanical dimmer with a switch and slider [6]. SAL06 only has three wires: the line, load, and the ground wire. The dimmer is controlled with a linear actuator that has an adaptor attached to the extension. The adapter was constructed from a 3D printer to accurately fit on the slider.

Figure 6. 12V standard linear actuator

The linear actuator used in the project is an “ECO-WORTHY 12V heavy duty linear actuator” and is controlled by voltage [7]. The actuator extends when +12V is applied and retracts when -12V is applied. The actuator is connected to two relays that are controlled by GPIO signals from the Raspberry pi.

The voltage sensors and relays require 5V and the linear actuator requires 12V. In order to provide the required voltages to the devices, two buck converters were set to output 5V and 12V respectively. The buck converters receive 24V from the power supply and set the to required voltages.

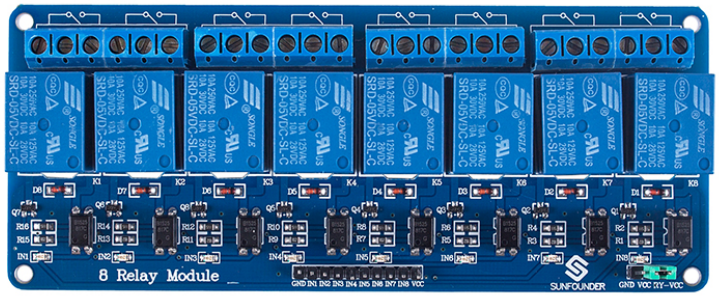

Figure 7. 8-channel relay module

Two 8-channel relays were used to control both dimmers and the linear actuator. The relays received the commands from the GPIO pin of the Pi and executed them by sending signals to either turn ON/OFF the dimmers or move the actuator up and down.

Due to the power of the linear actuator, we decided to add two limit switches to the actuation module to limit how far the actuator can travel. The upper level switch triggered whenever the actuator reached the maximum level and it cut off the moving forward signal from the Pi.The lower level switch did the same thing when the actuator reached the lower level. To support the linear actuator and set it at the same level as the dimmer, a stand was designed and 3D printed.

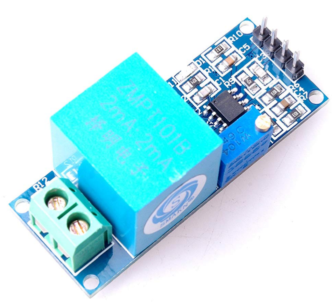

Figure 8. SMAKN active single phase voltage sensor.

Due to the location of dimmers, the active single phase voltage sensors by SMAKN [9,

Fig. 8] are placed in the actuation module enclosure which measure the output voltage of dimmers and bring the voltage down to ADC sampling range (3.3V Max). The voltage sensors are calibrated so that when 60 Hz, 120V AC, mains voltage is passed they produce 800mV amplitude 60 Hz sine wave with 1.8V DC offset. During the operation of ALDCT, the sensor output will be used to measure the conduction angle (dimming level) of dimmers. Although the smoothing effect of transformer introduces percent error (when compared to differential probe measurement) in measurement, it was chosen to isolate the ADC from the mains voltage.

4.1.1.3 Sensing Module

The sensing module consist of the LED box, the sensors, LED sockets, and the LED bulbs. The box is a 20in x 30in x 17in box. The frame was made out of 80/20 aluminum stick. Military graded starboard was mounted on the frame to create the box. Four LED sockets were mounted inside the box. Different LED types were placed in the sockets. Four sensors were fixed on the top of the LED box. Each LED had a sensor placed above it to measure the light intensity and the percent flicker. Once the sensor took the measurements, it sent them to the main board where the information was processed and formatted before it was displayed on the monitor.

In order to measure the light intensity signal (i.e. flicker signal, a photo-sensor was made using two photodiodes (BPW-21, BPW-34), a single package dual op-amp (TL082ACP), PCBs, and SMD passive components (resistors and capacitors). [Fig. 9] below shows the completed photo-sensor.

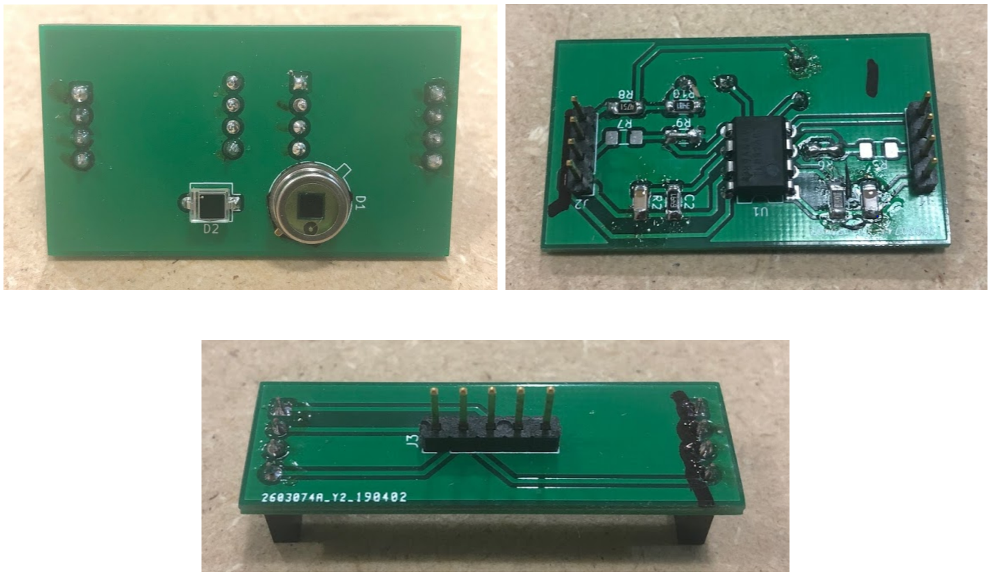

Figure 9. The pictures of photo-sensor assembly (top - photo-sensor, bottom - connector).

The photodiodes are reverse biased by 5V to insure linearity of photocurrent per lux (verified 10 nA/Lux for both photodiodes). Then, transimpedance amplifiers were used to convert the photocurrent signal to voltage signal. The diodes have different gains (BPW-21 has gain of 75,000 Ω, BPW-34 has gain of 6,490 Ω) to allow measurement of low light intensity (up to 700 Lux) and high light intensity (up to 50,000 Lux). Then, the feedback capacitors were chosen to ensure no attenuation in gain up to 2 kHz while preventing resonance, and op-amp's (TL082ACP) gain bandwidth product of 3 MHz were verified to be suitable for the application by referencing transimpedance amplifier guide by John Caldwell [10]. With the completed photo-sensors, the ALDCT acquires the light intensity signals through Mbed which are then processed with signal processing algorithm on the Pi. For the schematic and layout of photo-sensor, see Appendix B.

4.1.1.4 <u>Power Supply</u>

Figure 10. Mean-Well RS-150-12 12 VDC 12.5 A power supply.

To ensure the common voltage reference between Pi, Mbed, and photo-sensors while providing both +12V and -12V supply to photo-sensors' op-amps, two Mean-Well 12V DC switch mode power supplies are connected in series to form +12V, common, and -12V.

4.1.2 <u>Software of ALDCT</u>

4.1.2.1 <u>Controls and Graphic User Interface</u>

One main code is used to run the ALDCT program. The main code calls several other python codes containing Raspberry Pi GPIO pin numbers and functions. Upon running the main code to the program, a graphical user interface python code is called.

The graphical user interface consists of two check buttons for the two dimmers implemented, four checkboxes for the LEDs used, and a start button to continue the main program. The implementation of checkboxes gives the user more flexibility on which dimmer and LED combination he or she would like to test. If no LEDs are selected when the start button is pushed, the program will print a statement notifying the user that it will not run.

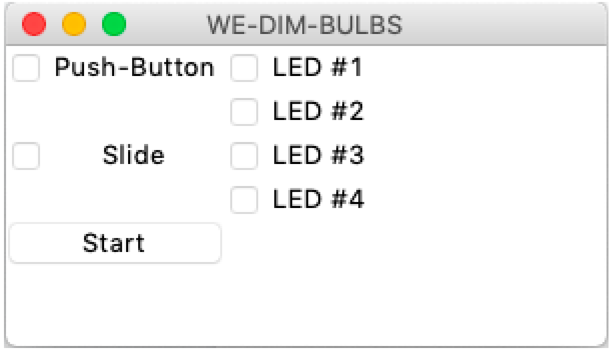

Figure 11. Graphical user interface as seen on Mac OS.

For the main program, an increment-based testing procedure was implemented. At the beginning of the test, the program will run a mandatory bypass procedure where each selected LED will be directly connected to the power source without dimmer assistance. The bypass procedure determines each LEDs maximum brightness at a conduction angle of 180 degrees. After completing the bypass procedure, the program proceeds to test each LED and dimmer combination individually.

Each dimmer is given eight increment levels to test. 0.85 seconds increases the push button dimmer by one increment, and 1 second increases the slide dimmer by one increment. Key measurements are taken with each increment before proceeding. Upon switching LEDs, the corresponding dimmer resets to its minimum setting to restart the test.

4.1.2.2 Data Acquisition

The Mbed's ADCs are utilized to sample the output signals of voltage sensors for conduction angle and photo-sensors for key flicker measurements mentioned in section 2. It was verified that with careful planning the Mbed is capable of sampling frequency of 2 MHz.

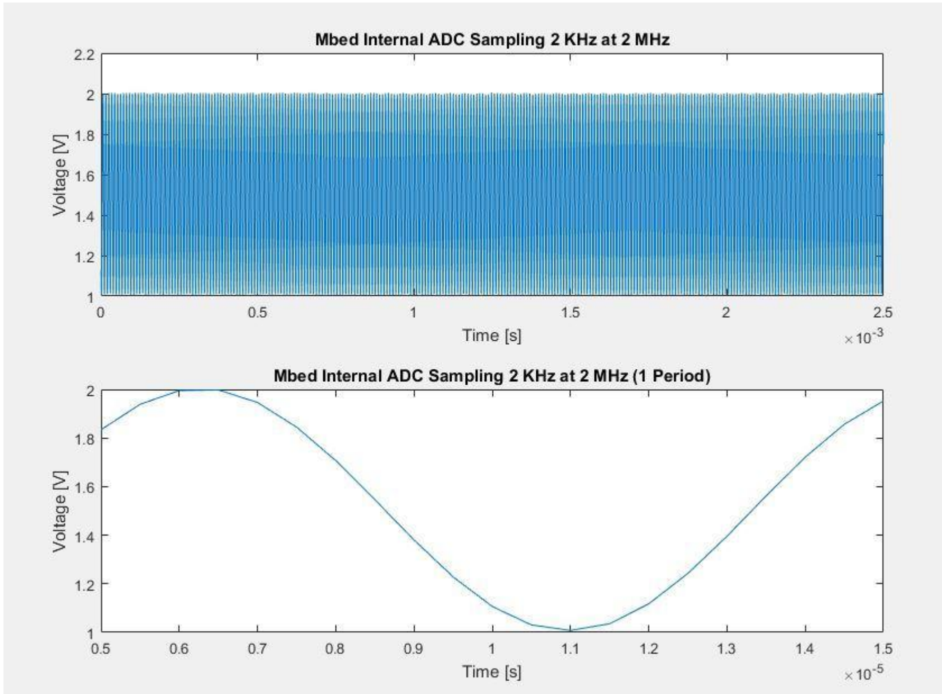

Figure 12. Verification of Mbed's sampling rate.

For dimmer output voltage measurement for conduction angles, the ADC samples at 12.5 kHz for 40 ms period giving 500 samples. For photo-sensor signal, the ADC samples at 25 kHz for 80 ms period giving 2000 samples. The sampled data is then transferred to Pi from Mbed through serial connection at baud rate of 460,800. Once sampled data is transferred to Pi and saved into an array, the array is passed through signal processing function to determine the values of key measurements. For Mbed and Pi's serial communication code, please visit website's resources section.

4.1.2.3 Digital Signal Processing and Data Analysis

The major evaluation criteria for the Automated LED Dimmer Compatibility Tester is the light flicker, in other words, the fluctuation in the detected waveform from the light source. The user can determine if the LED-Dimmer pair is compatible with each other by looking at the flicker or the fluctuation level. ALDCT tests the flicker level with several different increment levels for dimmer so that the user can have more information to analyze on the compatibility. Each increment level is recorded as conduction angle which represent the dimming level applied at the scale of 180 degrees. (i.e. conduction angle of 0 is the LED is totally dimmed and there is no light coming out, and 180 means no dimming effect is applied on the LED). EATON pushbutton dimmers and slider dimmers forward-cut the input signals to reduce the light level.

4.1.2.3.1 <u>Conduction Angle</u>

<u>Smoothing The Input Signal</u>

In order to detect more accurate data points for the conduction angle measurement, the Weighted Moving-Average filter was used to smooth out the input signals. WMA filter smooth out the noisy signal by convolution of the given data points with the weighting function shown below, where n is number of data points, p is corresponding voltage value for

$$\text{WMA}_M = \frac{np_M + (n-1)p_{M-1} + \cdots + 2p_{(M-n+2)} + p_{(M-n+1)}}{n + (n-1) + \cdots + 2 + 1}$$

our case, and M is weighted running mean for n samples. [11] In other words, WMA applies different weighting coefficients on the chosen window to reconstruct the filtered signal.

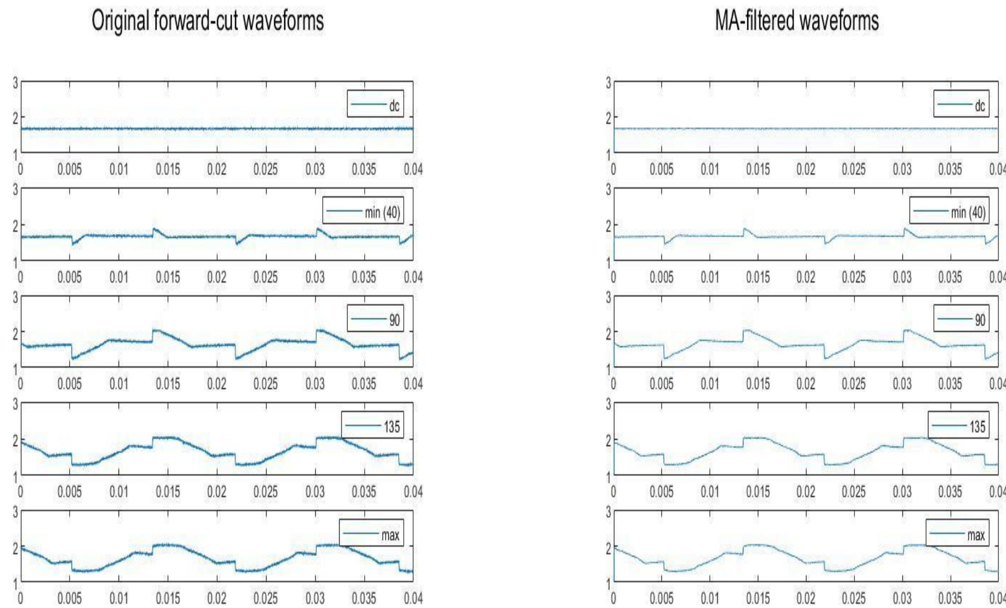

Figure 13. Comparison between original and filtered signals

The LHS of [Fig. 13] shows the DC voltage level and input waveforms at the conduction angle of 40, 90, 135 and 145. RHS of the figure is each corresponding WMA-filtered signals. The filtered signals exhibit less spikes or small signal fluctuations over time.

Rising Edge Detection

Rising edge detection is an important part as it gives the initial index for the conduction angle measurement. The edges are detected through differentiating the entire signal and spotting the significant gradient-changing location. [Fig. 14] is the plot of each filtered signal's differentiated form. The spikes, shown as green triangle points in the figure, represent the sudden changes in the gradient as for the situation of rising edges or forward-cut edges.

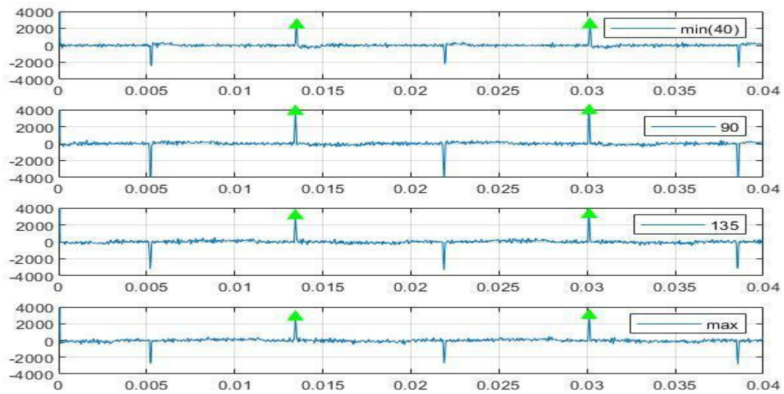

Figure 14. Rising edge detection of input signals

Angle Measurement

The first rising edge is the index where the measurement will be taken. The halfway index between two rising edges will be the index of falling edge. We have assumed the number of points between the rising edge and the falling edge would be 180 degree conduction angle. The forward-cut conduction angles will have DC-crossing point in between the rising and falling edge. By calculating the number of indices between the rising edge and the DC-crossing point respective to the distance between rising and falling edge, it is possible to obtain the conduction angle in the scale of 180 degree.

Table 2. Conduction angle measurements and errors

Oscilloscope (degree)	Python (degree)	Error (%)
40 (min)	37.9856	5.01
90	90.8654	0.96
135	139.3269	3.21
145 (max)	151.0791	4.02

Table 2 shows the comparison between the oscilloscope measurement and signal-processed calculation of conduction angle. Considering that the oscilloscope measurement is human-based and includes the human-measurement errors, the signal-processed conduction angle calculation is reasonably accurate.

For the situation of full sine wave, or the signal that is not dimmed or forward-cut, there will be only one rising edge at the very front segment of the filtered signal. In the case of detecting only one rising edge, the system automatically outputs 180 degree as conduction angle.

4.1.2.3.2 Flicker

Pre-Filtering

Since some of the detected flicker signals had random spikes, the Hampel filter was used to filter out the outliers. Hampel filter is similar to weighted median filter; the median of the moving data window is obtained and is weighted on each data frames with estimated standard deviation for Gaussian data, which is 1.4826.

```python
def hampel(vals_orig, k=20, t0=3):

    vals1=vals_orig.copy()
    vals = pd.DataFrame(vals1)
    L= 1.4826
    rolling_median=vals.rolling(k).median()
    difference=np.abs(rolling_median-vals)
    median_abs_deviation=difference.rolling(k).median()
    threshold= t0 *L * median_abs_deviation
    outlier_idx=difference>threshold
    vals[outlier_idx]=((vals[outlier_idx]-1)+(vals[outlier_idx]+1))/2
    vals2=vals[0].tolist()
    return(vals2)
```

Figure 15. Python implementation of Hampel filter

[Fig. 15] shows the python implementation of Hampel filter. The filter order was chosen to be 20 in order to filter out the outliers as much as possible. Higher order of filtering introduced unwanted distortions.

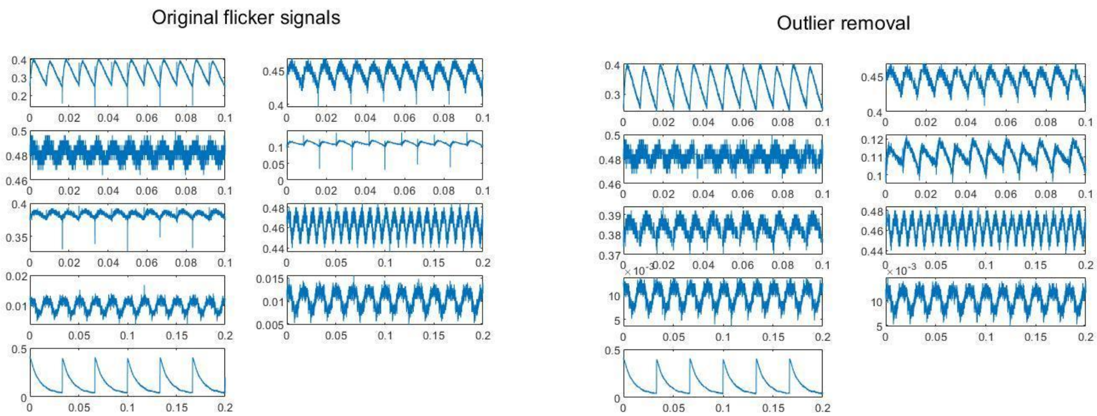

Figure 16. Comparison between original flicker signals and Hampel-filtered signals

Peak and Trough Detection

[Fig. 16] shows the examples of flicker signals and the filtered signals. The major outliers are removed, but small fluctuations are still visible. In order to remove these fluctuations, same as the conduction angle measurement, the WMA filter was used to smooth out the flicker signals.

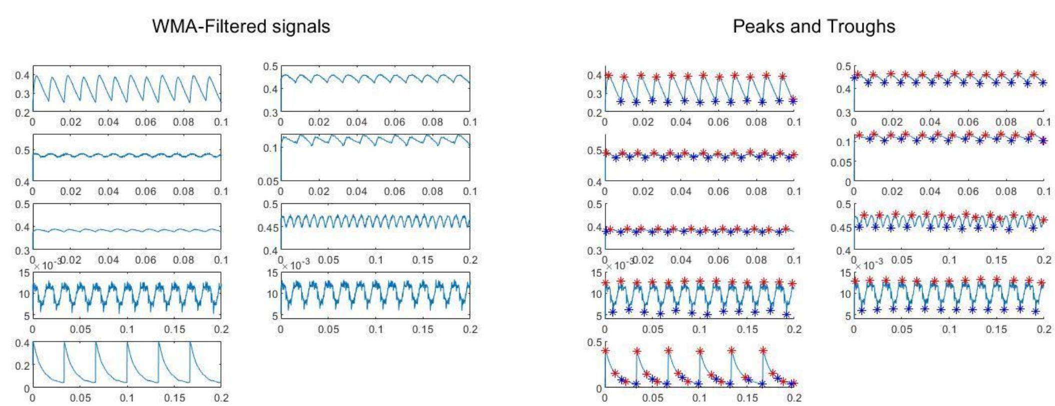

Figure 17. Filtered flicker signal and extreme points detection

Since the length of sampled data is 2000, the peak detection frame was chosen to be the length 120 to enoughly detect all the extreme points. The red dots in [Fig. 17] are the detected peaks and the blue dots are the detected troughs.

Light Intensity, Flicker percentage, Flicker frequency

The calculation of each flicker criteria is shown in [Fig. 18]. Average voltage level was calculated as the average of maximum and minimum value and later divided by the value of 0.00075 to calculate the light intensity. Flicker frequency was calculated as inverse of the time distance between two adjacent peaks. [12] Flicker percentage was calculated with the standard industry flicker measurement equation. The system outputs 0 for all three criteria if the LED is not compatible with the testing dimmer and does not go on and there is no flicker to detect.

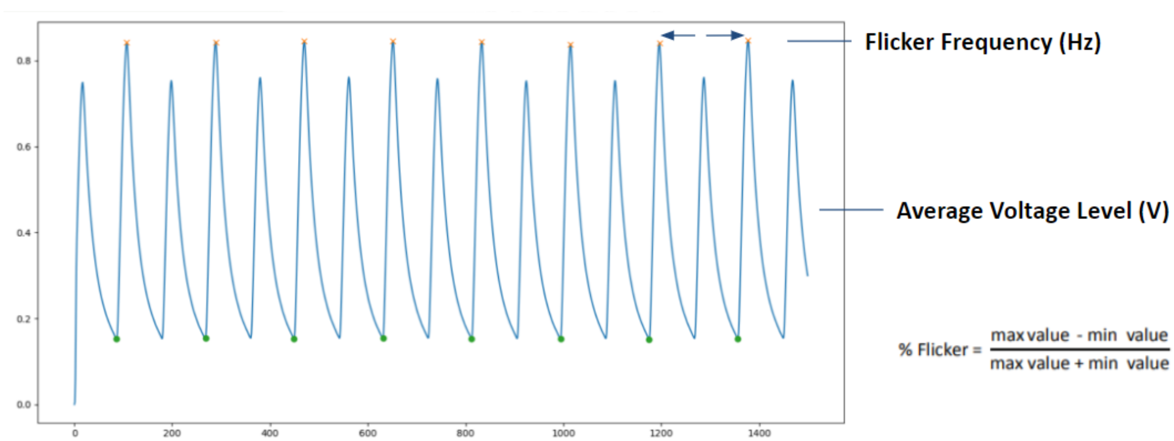

Figure 18. Example of flicker signal and each flicker measurement criteria

Visibility

The visibility was a challenging criterion because each person perceives the light flicker differently. Therefore the visibility detection was standardized through analysis of flicker data obtained from 8 different LED bulbs. The average frequency threshold that human can perceive the light as visible is 60Hz, so the visibility outputs as ‘visible’ when the flicker frequency is lower than 60Hz. For flicker frequency above 60Hz, the visibility is determined depending on the average voltage level; for higher average voltage level, the flicker percentage should be high enough to be visible, but for lower voltage level, the flicker is visible only with small flicker percentage. Details and implementation are shown in [Fig. 19]. Visibility is outputted as N/A when LED doesn’t go on and there is no flicker to detect.

```
if flickerfreq>=60:
    if averagevolt>=0.05:
        if flickerper>65:
            visibility = 'visible'
        else:
            visibility = 'non-visible'
    else:
        if flickerper>35:
            visibility = 'visible'
        else:
            visibility = 'non-visible'
else:
    visibility = 'visible'
```

Figure 19. Example of flicker signal and each flicker measurement criteria

4.1.2.4 <u>Test Result Output</u>

After the whole test process is done, the output CSV file is created in the same folder where the test script is run as shown in [Fig. 20]. The timestamp of the system runtime is added to the output filename, so the CSV file is named as “Output_current_timestamp.”

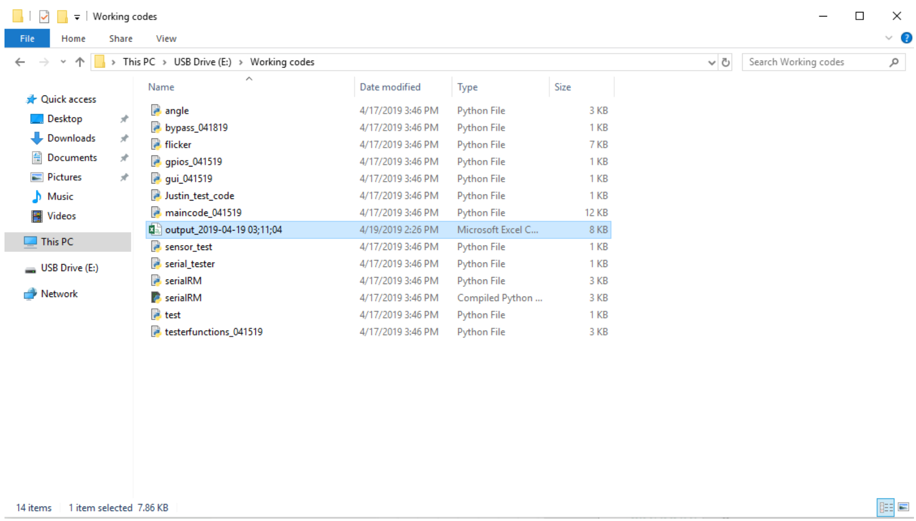

Figure 20. The output CSV file stored in designated folder

The contents of the output file is shown in [Fig. 21]. The left column shows the type of dimmer and the LED number being tested for seven different increment steps. The top row shows all the measurement criteria including conduction angle, light intensity, % flicker, flicker frequency and visibility.

	A	B	C	D	E	F
1		Conduction Angle	Lux	% Flicker	Visibility	FlickerFrequency
2	Bypass - LED #1	180	465.9849019	13.23020425	non-visible	187.9699248
3	Bypass - LED #2	180	744.2944625	39.23961278	non-visible	106.8376068
4	Bypass - LED #3	180	986.9798533	19.58143612	non-visible	102.0408163
5	Bypass - LED #4	180	2146.385715	43.37222398	non-visible	200
6	Push Button Dimmer - LED #1 - Min	47.36842105	0	0	N/A	inf
7	Push Button Dimmer - LED #1 - Step 1	42.35294118	0	0	N/A	inf
8	Push Button Dimmer - LED #1 - Step 2	54.11764706	133.3598274	39.52088177	non-visible	102.0408163
9	Push Button Dimmer - LED #1 - Step 3	66.31578947	382.3159838	38.94116116	non-visible	104.6025105
10	Push Button Dimmer - LED #1 - Step 4	52.10526316	442.7995167	18.37928136	non-visible	187.9699248
11	Push Button Dimmer - LED #1 - Step 5	74.80519481	459.0811283	13.28231766	non-visible	123.1527094
12	Push Button Dimmer - LED #1 - Step 6	87.63157895	459.8818522	12.51881414	non-visible	189.3939394
13	Push Button Dimmer - LED #1 - Step 7	134.5794393	458.7330913	12.48899543	non-visible	102.4590164
14	Push Button Dimmer - LED #2 - Min	40	439.8579481	71.03777688	visible	102.4590164
15	Push Button Dimmer - LED #2 - Step 1	56.84210526	286.2446805	50.35545229	visible	102.0408163
16	Push Button Dimmer - LED #2 - Step 2	75.78947368	636.8263167	70.23434562	visible	102.0408163
17	Push Button Dimmer - LED #2 - Step 3	85.26315789	299.5700252	20.82754144	non-visible	101.6260163
18	Push Button Dimmer - LED #2 - Step 4	99.47368421	617.4660435	50.93823212	non-visible	143.6781609
19	Push Button Dimmer - LED #2 - Step 5	112.9411765	593.3141498	40.5366913	non-visible	101.6260163
20	Push Button Dimmer - LED #2 - Step 6	122.3529412	584.1585226	37.3028377	non-visible	102.0408163
21	Push Button Dimmer - LED #2 - Step 7	138.8235294	501.4280383	24.3532186	non-visible	101.6260163
22	Push Button Dimmer - LED #3 - Min	47.05882353	18.19871358	11.62660363	non-visible	102.0408163
23	Push Button Dimmer - LED #3 - Step 1	56.47058824	56.76884665	5.154926047	non-visible	99.60159363
24	Push Button Dimmer - LED #3 - Step 2	65.88235294	120.0507747	7.05916968	non-visible	100.4016064
25	Push Button Dimmer - LED #3 - Step 3	82.89473684	280.0981689	4.728040488	non-visible	100.8064516
26	Push Button Dimmer - LED #3 - Step 4	94.73684211	417.3398277	2.498985396	non-visible	101.6260163
27	Push Button Dimmer - LED #3 - Step 5	105.8823529	624.0125625	1.704275783	non-visible	106.3829787
28	Push Button Dimmer - LED #3 - Step 6	120.7894737	705.1442626	6.59308972	non-visible	99.60159363
29	Push Button Dimmer - LED #3 - Step 7	136.4705882	792.3732778	13.84307426	non-visible	102.4590164
30	Push Button Dimmer - LED #4 - Min	180	172.1220332	86.02731908	visible	104.1666667
31	Push Button Dimmer - LED #4 - Step 1	58.82352941	463.7276089	73.24874639	visible	104.1666667
32	Push Button Dimmer - LED #4 - Step 2	75.29411765	856.8574281	77.85056832	visible	104.1666667
33	Push Button Dimmer - LED #4 - Step 3	80.52631579	1094.218337	77.99240549	visible	103.3057851
34	Push Button Dimmer - LED #4 - Step 4	95.36423841	1322.130475	76.68396936	visible	103.7344398
35	Push Button Dimmer - LED #4 - Step 5	105.8823529	1460.786249	74.79322023	visible	105.4852321
36	Push Button Dimmer - LED #4 - Step 6	120.7894737	1598.875312	71.76354955	visible	105.4852321
37	Push Button Dimmer - LED #4 - Step 7	134.1176471	1737.596984	66.15730261	non-visible	105.9322034
38	Slide Dimmer - LED #1 - Min	180	0.876454282	99.9933477	visible	165.5629139
39	Slide Dimmer - LED #1 - Step 1	180	0.917269477	99.99046555	visible	192.3076923

output_2019-04-19 03;11;04

Figure 21. The contents of output CSV file

4.2 Codes and Standards

1. Standard NEMA SSL-7A contains the design criteria and measurement procedures for LED and forward phase cut dimmers. IES is also used for approved test method for lumen maintenance of LED light sources and optical waveforms. Those two standards were referenced during development of testing procedure of ALDCT.
2. CEC and EPA are used for dimming and flicker requirements on lamps. CEC is a generic standard that includes all dimmable lamps while EPA is more specifically used for LED lamps. Those two standards are referenced during development of flicker signal analysis algorithms.
3. UART Serial communication between Mbed and Pi where their UART hardwares require same voltage reference to recognize received data. To satisfy this requirement, the mainboard was made.

4.3 Constraints, Alternatives, and Tradeoffs

During the development of the ALDCT, many alternatives were considered.

1. AMS Light to Voltage Converter as Flicker Sensor:

   The considered AMS Light to Voltage Converter IC was an all-in-one light detector with an amplifier inside meaning the gain of the converter is fixed which caused saturation at converter's output and slow response to change in light intensity.

2. Differential Amplifier with Voltage Dividers for Dimmer Output Measurement:

   The topology proposed in project proposal to measure voltage of dimmer output consisted of a differential amplifier with two voltage divider. This was a big safety concern in case of voltage spikes and protection of microcontroller (Mbed). Therefore, the team compromised with slight percent error in conduction angle measurement due to smoothing effect of transformer with isolation of microcontroller from mains voltage.

3. Optocoupler Zero Crossing Detector and Schmitt Trigger for Phase Cut Angle:

   The team tried optocoupler zero crossing detection and schmitt trigger to detect rising and falling edges to calculate conduction angle. However, the dimmers' outputs did not exactly cross zero due to capacitive characteristics of LEDs and the required threshold voltages for schmitt trigger differed from one LED to another, making those two approaches near impossible realize.

4. Bit-Scope as ADC:

   The Bit-Scope, an oscilloscope compatible with Pi, was considered, but had look for another alternative due to the high price and inactive manufacturer.

5. MOSFET Switch as Push-Button Mimicker:

   At the beginning, MOSFET switches were considered for push-button replacement allowing Pi to mimic push-button press. However, there was a concern that the push-buttons on dimmers may not be isolated from mains voltage which meant possibility of damaging Pi in case of fault in dimmer.

The few major constraints of the project were to sense dimmer output voltage with low cost device and to control dimmer without major modification.

5. Schedule, Tasks, and Milestones

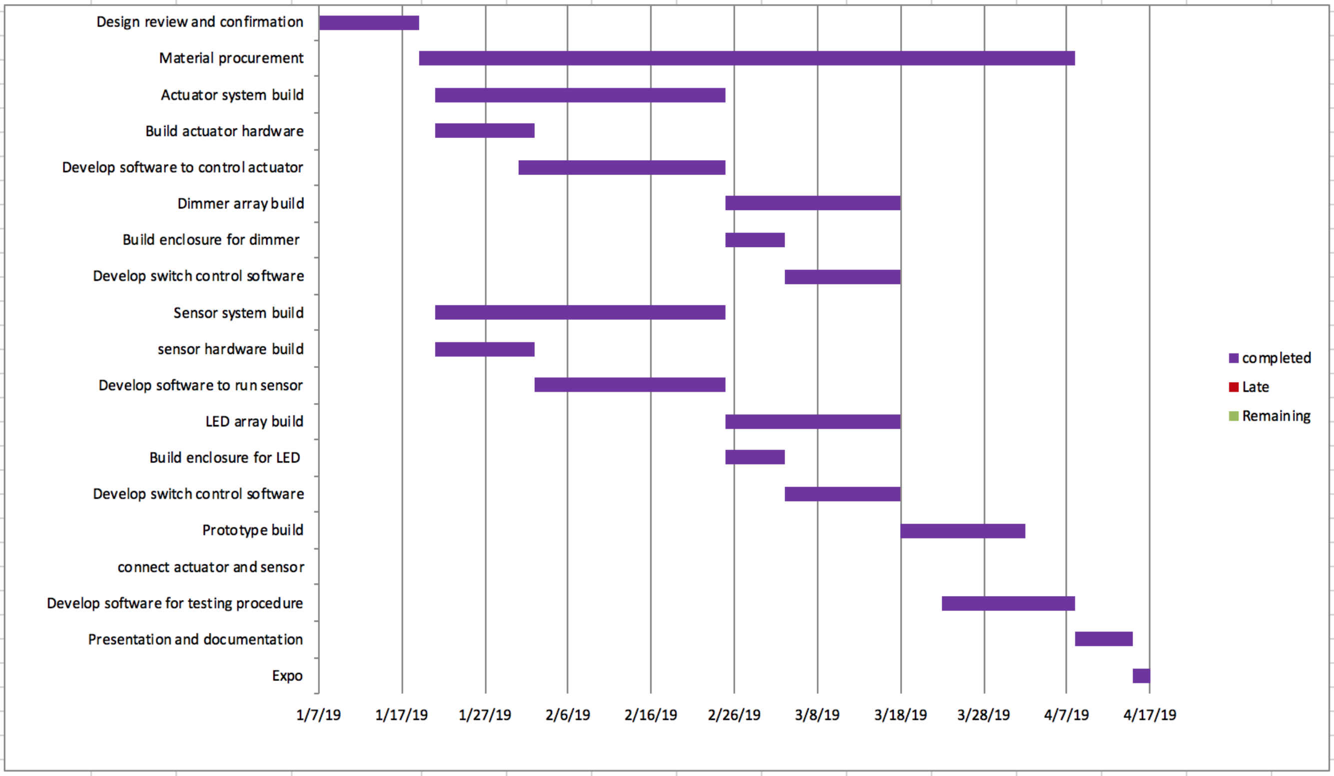

Figure 22. Updated Gantt Chart.

[Fig. 22] above shows the updated Gantt Chart of Team-We-Dim-Bulbs after the Capstone Expo. To describe the relative contribution of team members to the overall project following expression can be considered:

Geon Woo Kang = Justin Koudonou > Soo Kwon Ha = Ben Brown

In Appendix C, a table describing the difficulty and/or technical risk of the tasks with name of member assigned is made for a reference.

6. Final Project Demonstration

Following sections states the result of validation and demonstration. The documents mentioned in this section is available at team's website.

6.1 Validation of Project Specifications

Before the final demonstration, the modules of the ALDCT were tested to verify that their meeting the technical specification.

- The operation of actuation module was tested by sending control signals from the control module and sampling the voltage sensors' signals. The team verified that the control module can successfully control the dimming level by controlling the relays in actuation module and can measure the conduction angle of dimmer outputs using the voltage sensors with negligible percent error.
- The sensing module was tested by testing the photo-sensors. First, the linearity and intensity measurement were verified by cross checking with Adafruit lux sensor output resulting 2.4% difference in light intensity measurement while keeping the photocurrent linearity steady. Next, the maximum average light intensity measurement were verified by testing with the brightest bulb available for the low intensity (up to 700 Lux), then, by moving the light source towards the photo-sensor for high intensity (up to 50,000 Lux).
- After verifying each module, all the modules were put together to complete the prototype. Then, the team ran a long testing session (total of 18 hours) involving adjustment in software portion of the project to correctly output the measured data and test result.

6.2 Demonstration

The team gave final presentation to the advisor and sponsor which included videos of the ALDCT operating as intended and demonstrated the working prototype at the Capstone Expo where the team ran demo testing procedure which only tested minimum, 50%, and maximum dimming levels instead of all the increment steps. The team received positive feedback from both parties.

7. Marketing and Cost Analysis

7.1 <u>Marketing Analysis</u>

ALDCT is not for commercial sale, instead, it is a product solely for the purposes of Eaton. There is no similar product existing in the market, therefore, Eaton is currently running the compatibility test manually. The ALDCT is the one and only product that analyzes the LED-dimmer compatibility at this moment.

7.2 <u>Cost Analysis</u>

The total material cost of ALDCT is $1,037.00. Table 3 shows a breakdown of the material costs of the prototype.

Table 3. Equipment and Materials Cost

Control Module			
Parts Description	**Cost/Unit**	**Number of Units**	**Parts Cost**
Raspberry Pi 3 Model B+ Kit	$80.00	1	$80.00
Mbed LPC 1768	$55.00	1	$55.00
Mainboard (PCB, Header Pins)	$28.00	1	$28.00
Actuation Module - Dimmer Box			
Parts Description	**Cost/Unit**	**Number of Units**	**Parts Cost**
Enclosure	$40.00	1	$40.00
Linear Actuator	$51.00	1	$51.00
Linear Actuator Limit Switch	$2.00	2	$4.00
8 Channel Relay Module	$10.00	2	$20.00
Active Single Phase Voltage Sensor Module	$11.00	2	$22.00
High Voltage Safety Door Switch	$30.00	1	$30.00
Fixtures/Adaptors	$25.00	1	$25.00
Sensing Module - LED Box			
Parts Description	**Cost/Unit**	**Number of Units**	**Parts Cost**
Photo-Sensor (PCB, Op-Amp, Photodiodes, SMD Components)	$18.00	4	$72.00
80/20 T-Slot Frame (Bars, Fasteners, Hinges)	$150.00	1	$150.00
Starboard Sheet	$120.00	1	$120.00

E26 Light Bulb Socket	$2.00	4	$8.00
Other Parts			
Parts Description	**Cost/Unit**	**Number of Units**	**Parts Cost**
Mean-Well RS-150 12V Power Supply	$24.00	2	$48.00
LM2596 Buck Converter Modules (6 Pack)	$11.00	1	$11.00
Power Supply/Mainboard Shelf	$42.00	1	$42.00
Monitor	$120.00	1	$120.00
Keyboard & Mouse	$25.00	1	$25.00
Lever Nuts	$36.00	1	$36.00
Wires/Connectors (Connecting Wires, Power Wires, Jumpers)	$50.00	1	$50.00
		Total	**$1,037.00**

The total hours worked by the team members to develop the ALDCT is shown in Table 4. The hours for class lectures were excluded.

Table 4. Hours Worked by Members of Team-We-Dim-Bulbs

Task	**Ben**	**Geon**	**Justin**	**Soo Kwon**
Out of class meetings	16	16	16	16
Weekly meetings with advisor	11	11	11	11
Biweekly meetings with sponsor	7	7	7	7
Research	9	9	9	9
Presentation	2	2	2	2
Report preparation	12	12	12	12
Material collection	0	2	2	0
Hardware fabrication	5	60	60	5
Software coding	65	10	10	65
Assembly	5	7	7	5
Testing	10	10	10	10
Total	**142**	**147**	**147**	**142**

Assuming the labor cost of $30 per hour, the 142 hours of development for software engineer and 147 hours of development for hardware engineer will result in labor cost of $4,260 and $4,410 respectively, therefore the total labor cost sums up to $17,340. The fringe benefit is determined as 30% of labor cost, and overhead is determined as 120% of sum of parts, labor and fringe benefit costs. The total development cost for ALDCT is $43,350 as shown in Table 5.

Table 5. Total Development Costs

Component	**Cost**
Parts	$1,037
Labor/Development	$17,340
Fringe Benefits, % of Labor	$5,202
Subtotal	$22,542
Overhead, % of Material, Labor & Fringe Benefits	$20,808
Total	$43,350

The estimated profit of ALDCT is given in Table 6. It is assumed that 500 units are sold over 5 years at the price of $1,200, and the sales expense is 7% of the selling price. The total part cost will be discounted down to $1,000 for bulk purchase. The expected revenue is $600,000.00 with a profit of $242.50 per unit.

Table 6. One Year Eaton LED Tester Profit

Component	**Amount**
Parts Cost	$1,037.00
Assembly Labor	$10.00
Testing Labor	$10.00
Total Labor	$20.00

Fringe Benefits, % of Labor	$6.00
Subtotal	$1,063.00
Overhead, % of Material, Labor & Fringe Benefits	$818.50
Subtotal, Input Costs	$1881.50
Sales Expense	$161.00
Amortized Development Costs	$15.00
Subtotal, All Costs	$2057.50
Profit	$242.50
Selling Price	$2300.00

8. Conclusion

Team-We-Dim-Bulbs successfully prototyped a working Automated LED Dimmer Compatibility Tester (ALDCT) that can test two dimmers and four LEDs at once in 10 minutes. Although the accuracy of result must be further validated, the prototype operates as the team intended. For the future work:

- The accuracy of conduction angle measurement can be improved by utilizing more sophisticated device such as differential probe.
- The photo-sensor can be improved by adding programmable gain circuit with output voltage limiter to protect ADCs.
- The whole system will become robust by adding protection circuits for each sensitive device like Mbed.
- The signal processing and data analysis algorithm can be improved to the test results.
- The GUI can be improved to give better user experience.

Overall, Team-We-Dim-Bulbs met the expectation of the advisor and sponsor.

9. Leadership Roles

All members of Team-We-Dim-Bulbs were involved in documentation.

<u>Ben Brown</u> [Software Lead]

- Developed GUI and ALDCT procedure functions on Raspberry Pi.
- Co-Documentation Coordinator

<u>Soo Kwon Ha</u> [Signal Processing and Data Analysis Lead]

- Developed signal processing and data analysis algorithms for the key measurements.
- Designed and produced output format and contents.
- Co-Documentation Coordinator

<u>Geon Woo Kang</u> [Technical Lead]

- Designed and prototyped control module and photo-sensors.
- Designed the framework of overall system and divided into modules.
- Developed communication interface between Mbed and Pi in control module.
- Webmaster
- Co-Documentation Coordinator

<u>Justin Koudonou</u> [Team Leader]

- Designed and prototyped actuation module and LED box of sensing module.
- Designed and constructed various fixtures for electromechanical components.
- Expo Coordinator
- Co-Documentation Coordinator

10. References

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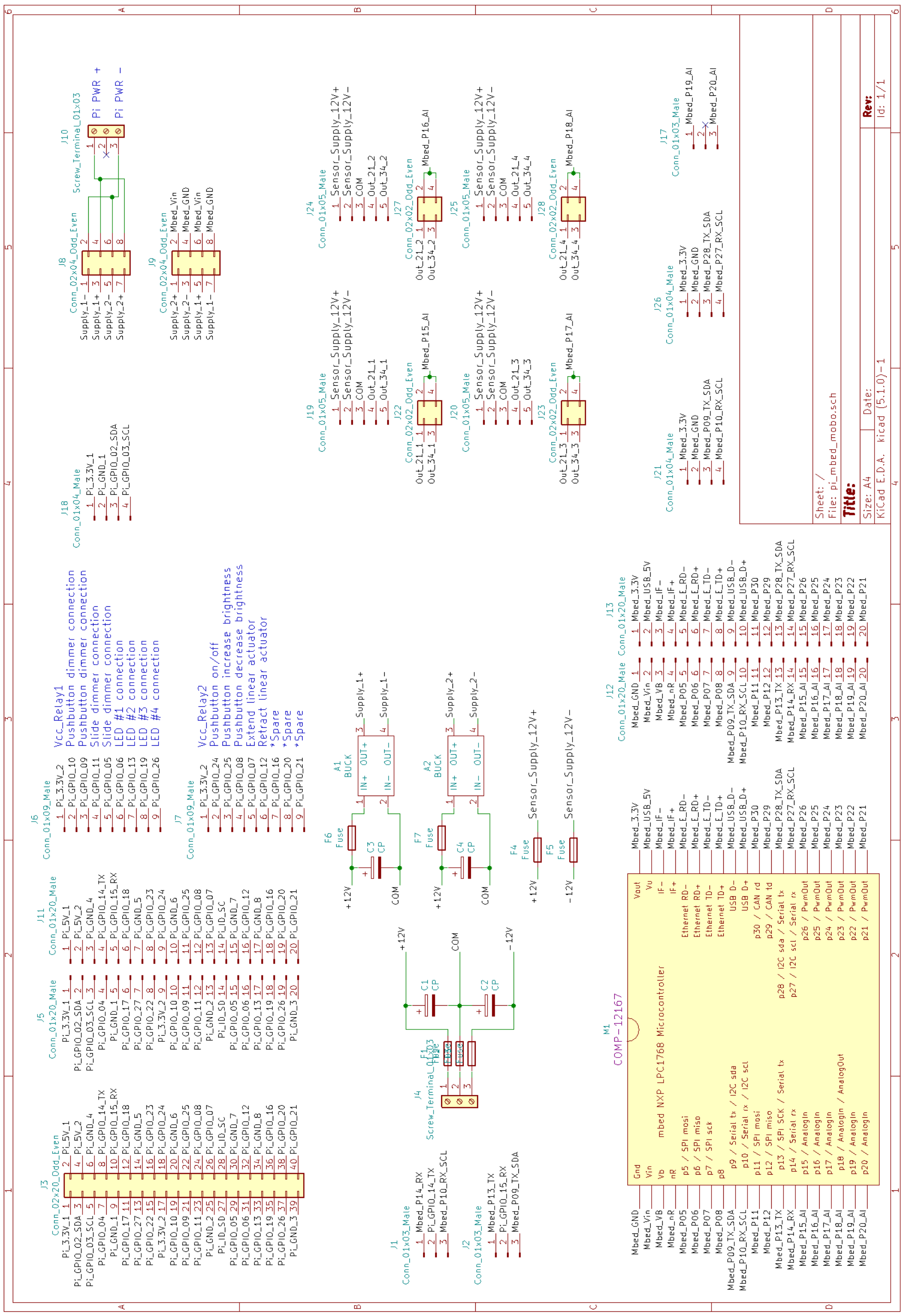
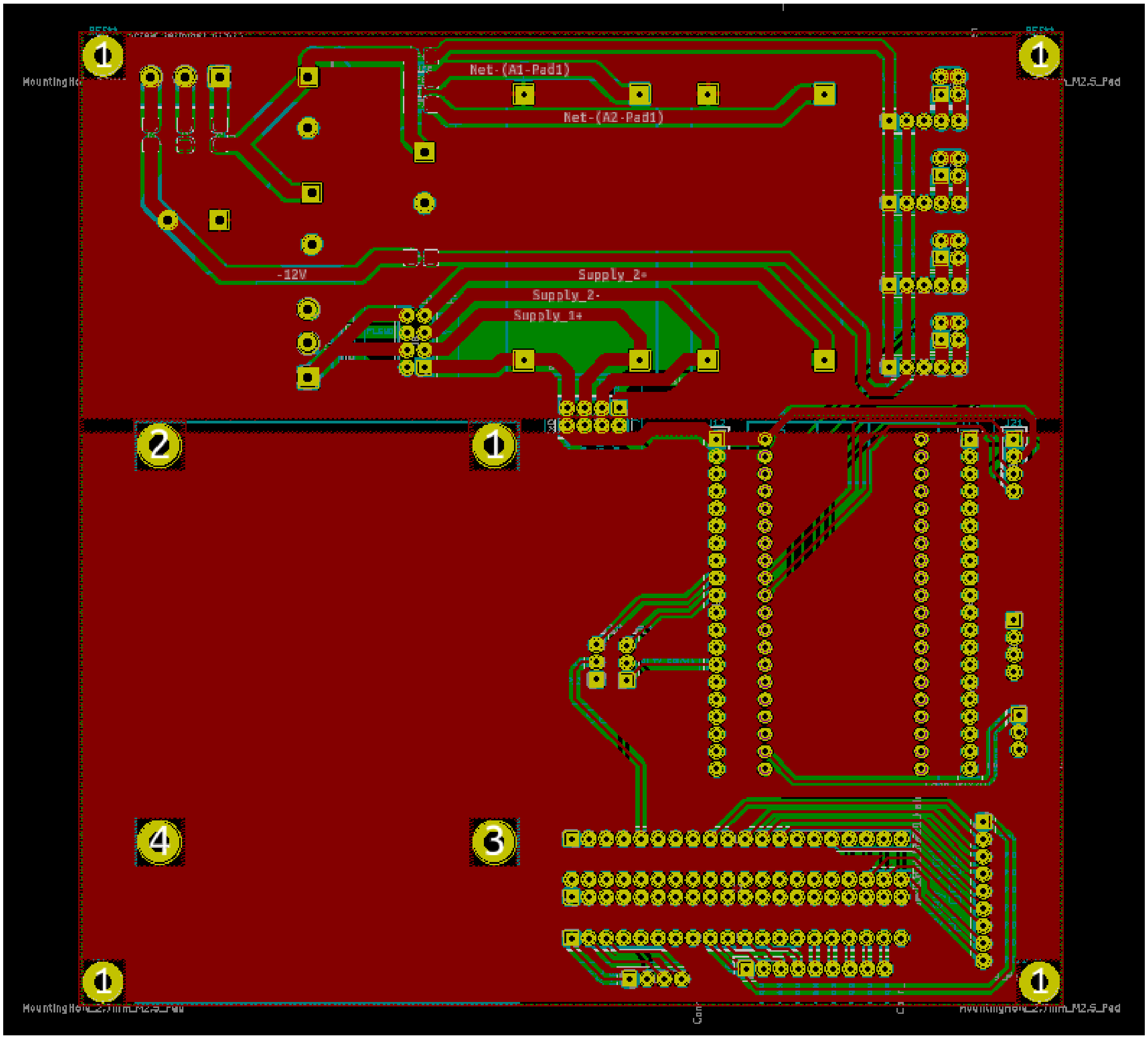
Appendix A

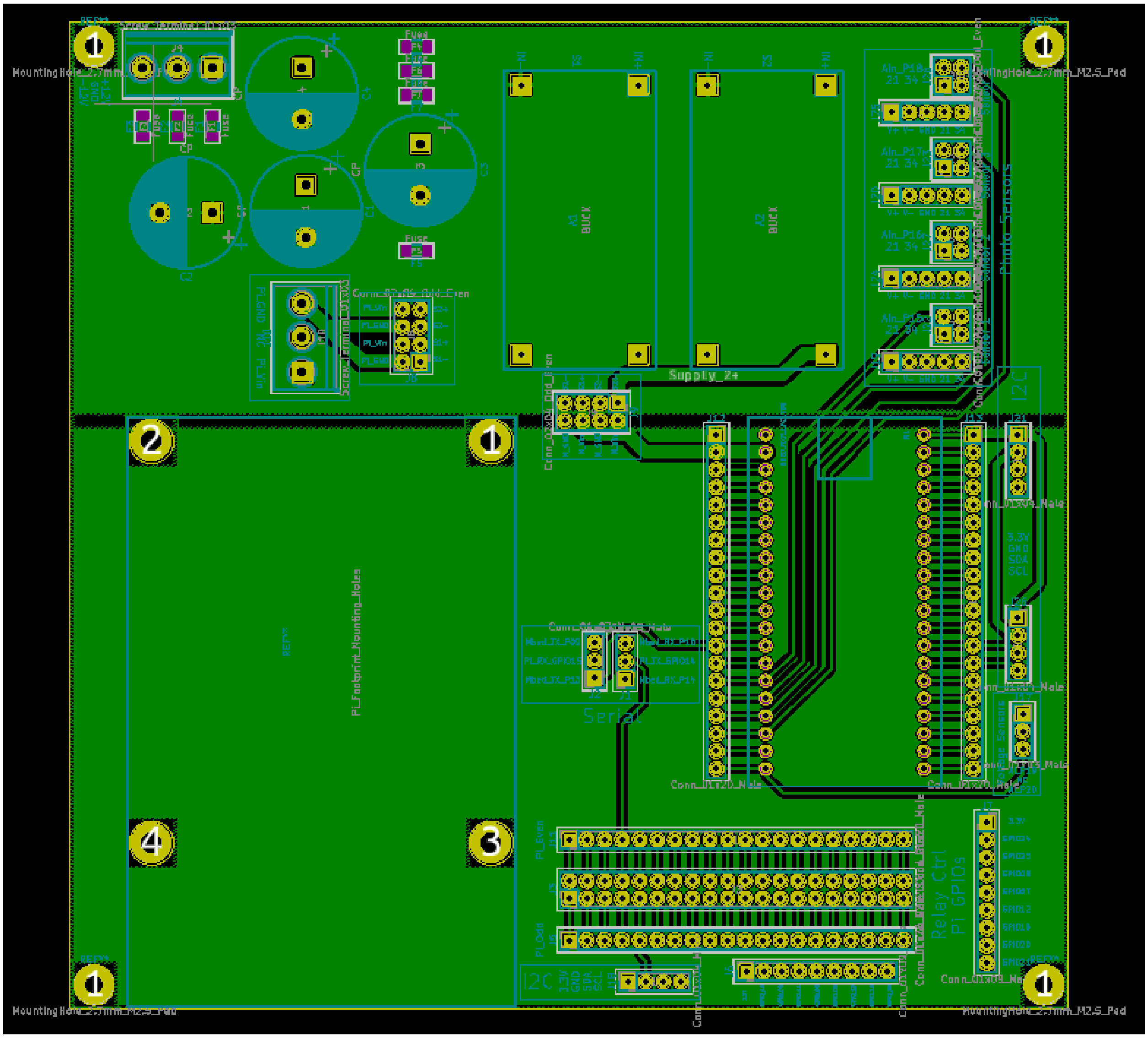
Mainboard Schematic



Mainboard Layout (Top Metal View)



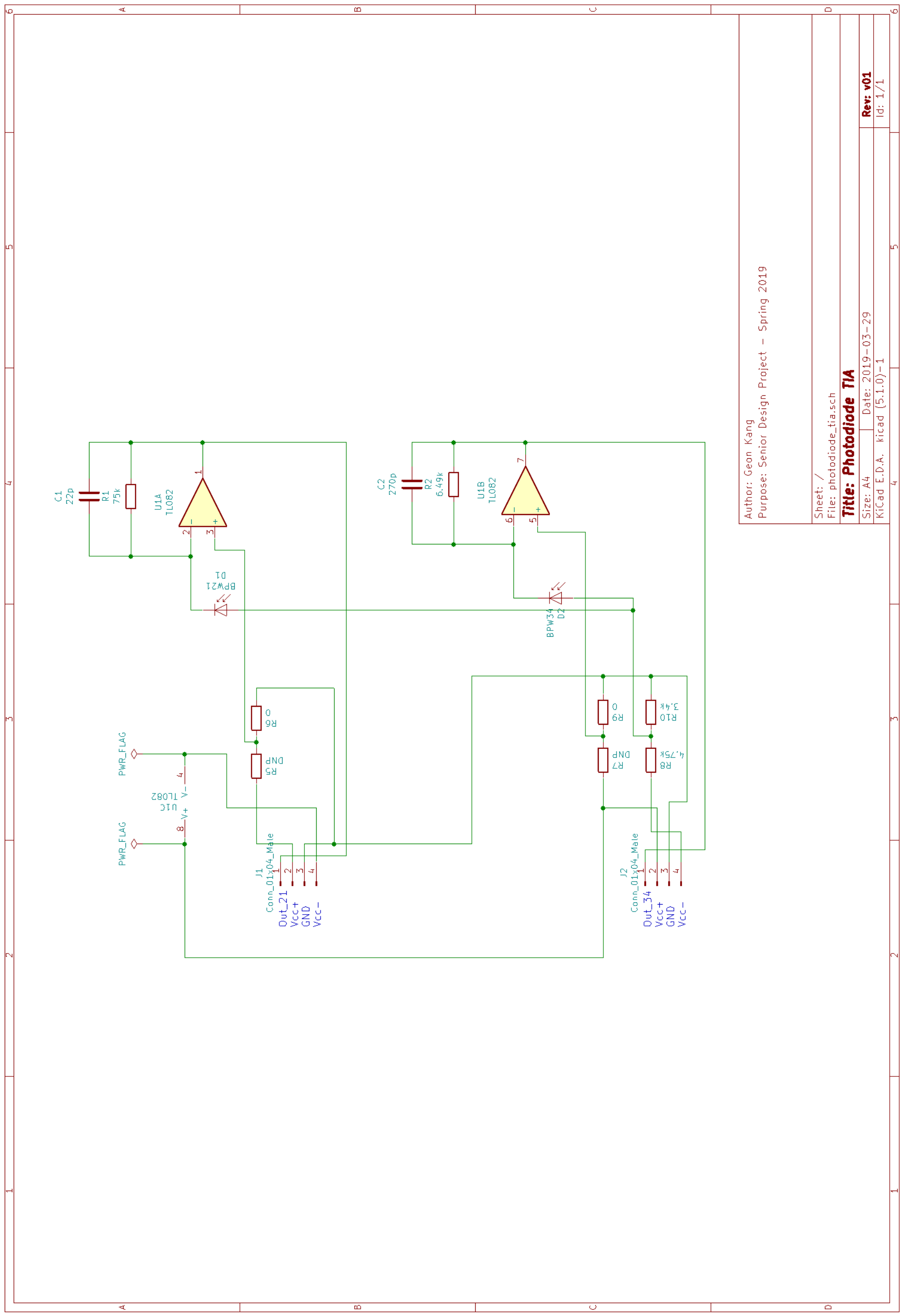
Mainboard Layout (Bottom Metal View)



Appendix B

Photo-sensor Schematics

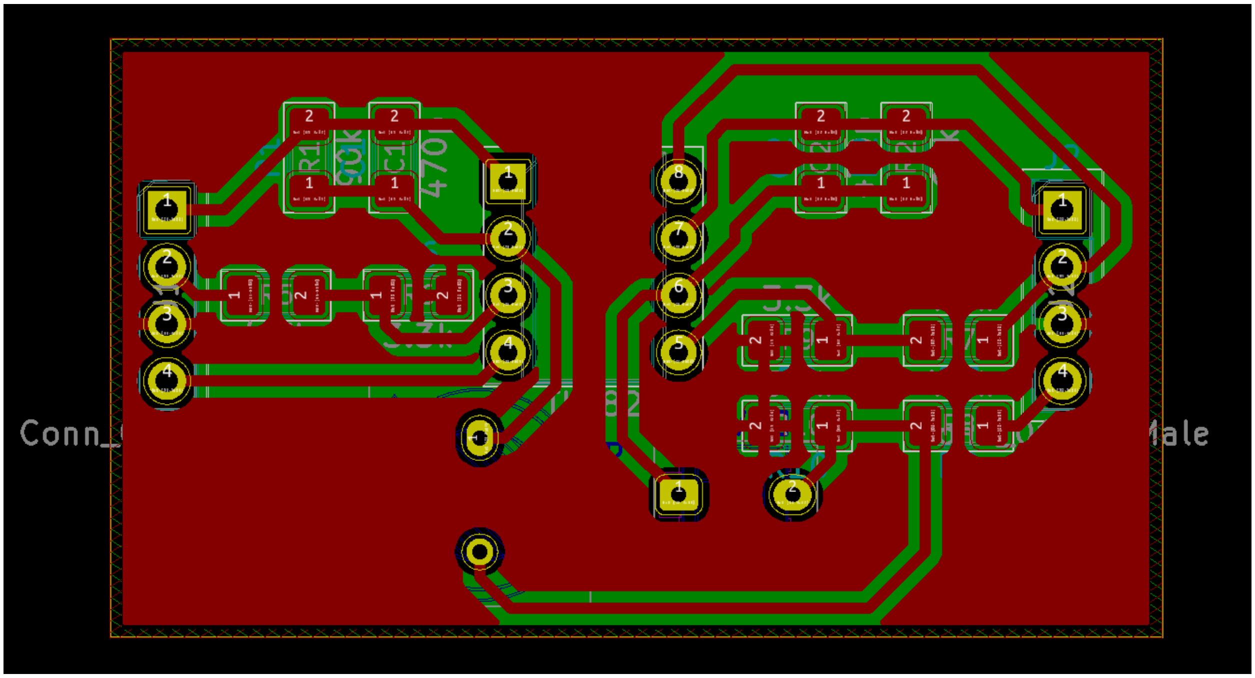
Photodiode Transimpedance Amplifier



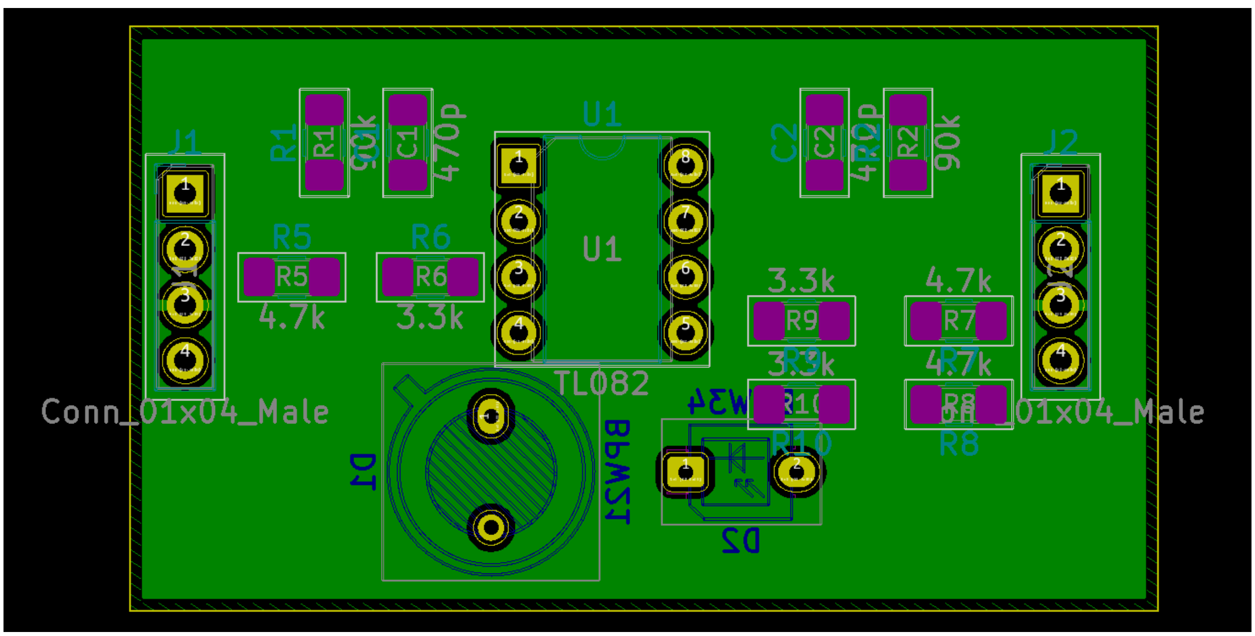
Photodiode Transimpedance Amplifier Connector

Photo-sensor Layouts

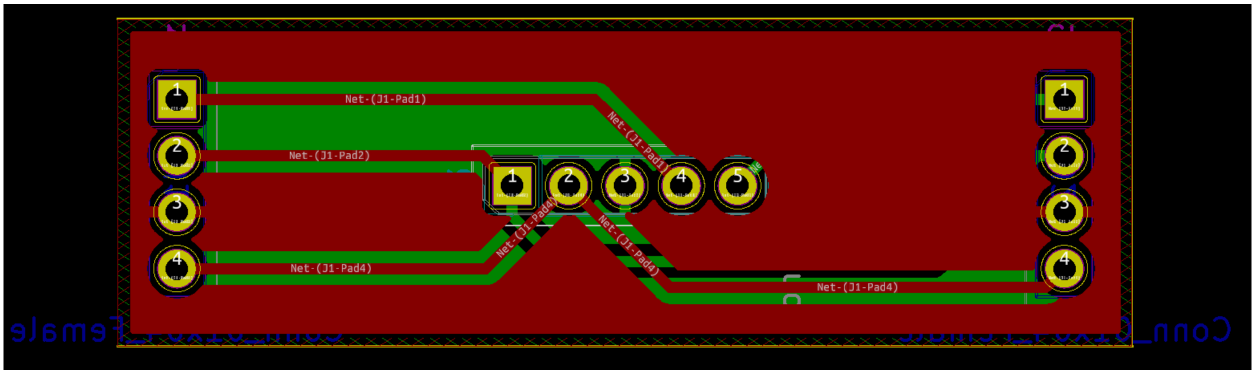
Photodiode Transimpedance Amplifier (Top Metal View)



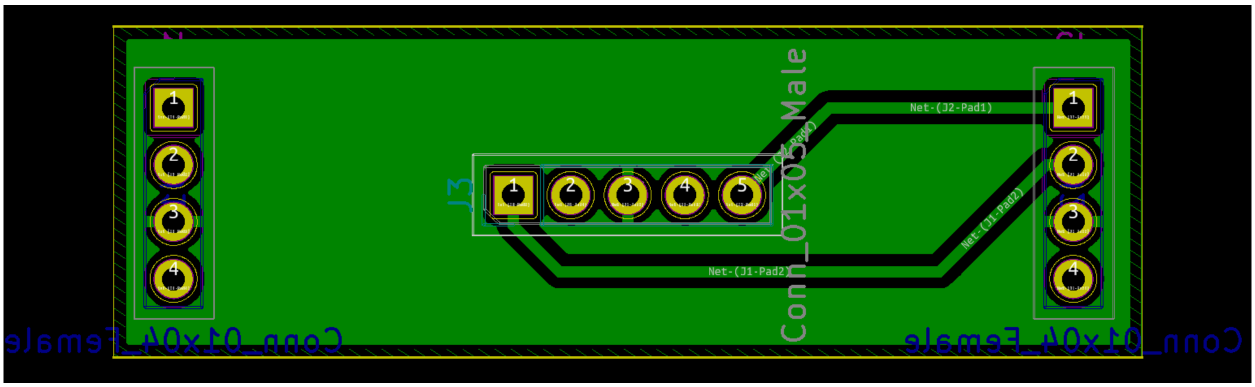
Photodiode Transimpedance Amplifier (Bottom Metal View)



Photodiode Transimpedance Amplifier Connector (Top Metal View)



Photodiode Transimpedance Amplifier Connector (Bottom Metal View)



Appendix C

Task Assignments and Difficulty/Technical Risk

Task Description	Task Assignment	Difficulty	Risk Level
Design Review and Confirmation	All	Medium	Medium
Material Procurement	All	Low	High
Actuation Module Build	Ben Brown Justin Koudonou	High	High
Building Actuation Hardware	Justin Koudonou	High	High
Develop Actuator Control Software	Ben Brown	Medium	Medium
Dimmer Array Build	Justin Koudonou	High	Medium
Build Enclosure for Actuation Module	Justin Koudonou	High	Medium
Develop Limit Switch Control Software	Ben Brown	Medium	Low
Sensing Module Build	Geon Woo Kang Justin Koudonou	High	High
Photo-sensor Design and Build	Geon Woo Kang	High	High
Develop Software for Sensing (Mbed/Pi)	Geon Woo Kang	Medium	High
LED Array Build	Justin Koudonou	Medium	Medium
Build Enclosure for Sensing Module	Justin Koudonou	Medium	High
Develop Control Module Mainboard	Geon Woo Kang	High	Medium
Assemble Modules to Complete Prototype	All	Medium	High
Develop Algorithms for Key Measurements	Soo Kwon Ha	High	High
Develop Data Export Function	Soo Kwon Ha	Medium	High
Develop ALDCT Software	Ben Brown Soo Kwon Ha	High	High
Presentation and Documentation	All	High	High
Expo	All	Medium	Medium