ECE 445 Senior Design, Fall 2018

Team 18 Final Report

Interactive Proximity Donor Wall Illumination

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Abstract

A donor wall is located on the southwest side of the first floor in Electrical and Computer Engineering Building at University of Illinois at Urbana–Champaign. The donor wall celebrates and appreciates everyone who has helped and donated for the building. However, due to poor lighting, the donor names are rarely noticed. Team 18's solution to this problem is to design and implement an interactive, highly responsive, and maintenance-free illumination system that would integrate into the current donor wall. Such system has been successfully built by adding LED lightings for visual engagement and by using Infrared (IR) sensors for distance-dependent interaction with the donor wall.

Contents

1 Introduction

A donor wall is located on the southwest side of the first floor in Electrical and Computer Engineering Building (ECEB) at University of Illinois at Urbana–Champaign (UIUC). The donor wall celebrates and appreciates everyone who has helped and donated for the building. However, the donor wall is, if at all, rarely noticed by the people who pass the hallway. We believe that the current donor wall has two main problems - poor lighting and lack of social interaction opportunities. Ultimately, the hallway with the current donor wall became a “highway” to walk through.

Our solution to these problems is an interactive, highly responsive, and maintenance-free illumination system for the donor wall. Our solution will bring more attention to the donor names and ultimately, liven up the hallway with more possible social interactions. In our design, each panel of the donor wall is equipped with an Infrared (IR) sensor. The IR sensor determines the position and the proximity of a person to the donor wall. According to the signals received from the sensors, a microcontroller (MCU) controls LED strips to animate propagation of “electricity” pulses through the translucent gaps in the “circuit board.” Three distinct illumination modes are implemented to differentiate between different positions and proximity of a person to the donor wall – Default Mode, Human-Following Mode, and Override Mode.

Such system has been successfully implemented and this report describes all necessary details of our success. As can be seen in Figure 2, our project has five main components – physical model for demonstration, LED illumination software, microcontroller, IR sensor, and power. The microcontroller and the IR sensors are supplied with power. Depending on the IR sensors' readings, the microcontroller is programmed with LED illumination software to have ”pulse” propagate throughout the physical model of the donor wall. Each components are discussed in more detail in Chapter 2 in each of their respective sections. In Chapter 3, how each parts are verified to work is discussed with respect to the Table of Requirements and Verifications in Appendix A. In Chapter 4, the overall cost of our project is discussed in detail.

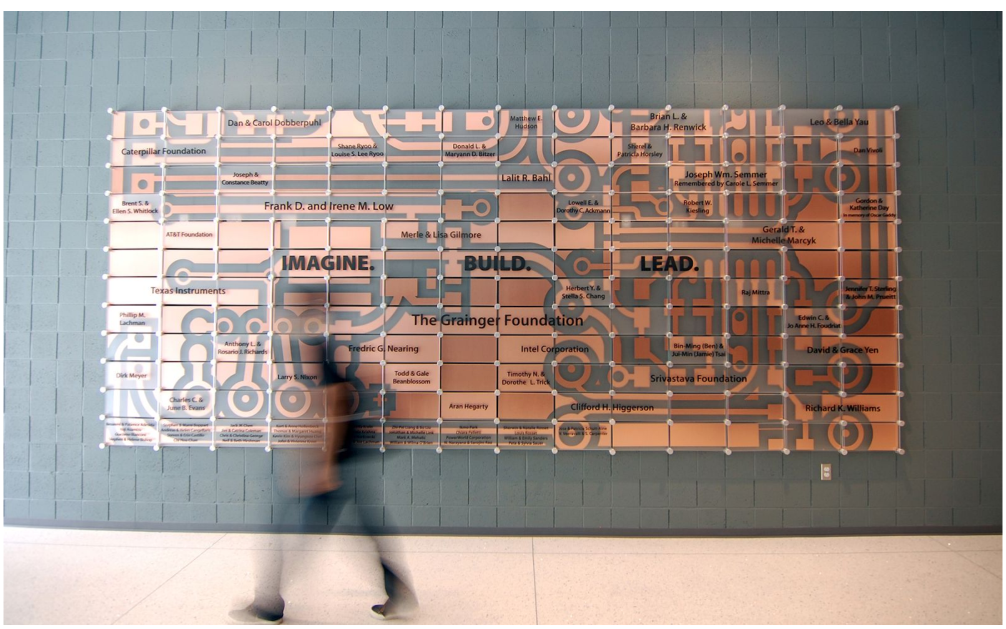


Figure 1: Image of donor wall (touched up by Kurt Bielema) [1]

2 Design

Our interactive proximity donor wall illumination system is mainly divided up as physical model for demonstration, hardware components, and software components. Hardware components include IR sensors, microcontroller, LED strips, and power. Software components include processing IR sensor data and controlling LED strips to implement the pulse animation.

The technical work has been divided up between Anita for power and physical model, Sungmin for hardware and software implementation of IR sensor, and Zheng for hardware and software implementation of MCU and LED strips. The general functionality is as follows with respect to the block diagram in Figure 2. Two separate power adapters are used to supply power – one for IR sensors and microcontroller and the other for LED strips. The power component of the system is discussed in detail in Section 2.5. The IR sensor reads the position and the proximity of an object or a person near the donor wall. More details on IR sensors' software and hardware implementations are discussed in Section 2.4. Then, the analog signals from IR sensors are sent to the microcontroller which then controls the LED strips attached on the physical model. Software implementation of controlling LED strips are discussed in Section 2.2 and hardware implementation of microcontroller is discussed in more detail in Section 2.3. Additional details on hardware implementation of the LED strips can be found in Section 2.1. Each respective technical design components are proven to function in Chapter 3, if applicable, with respect to the Table of Requirements and Verification in Appendix A.

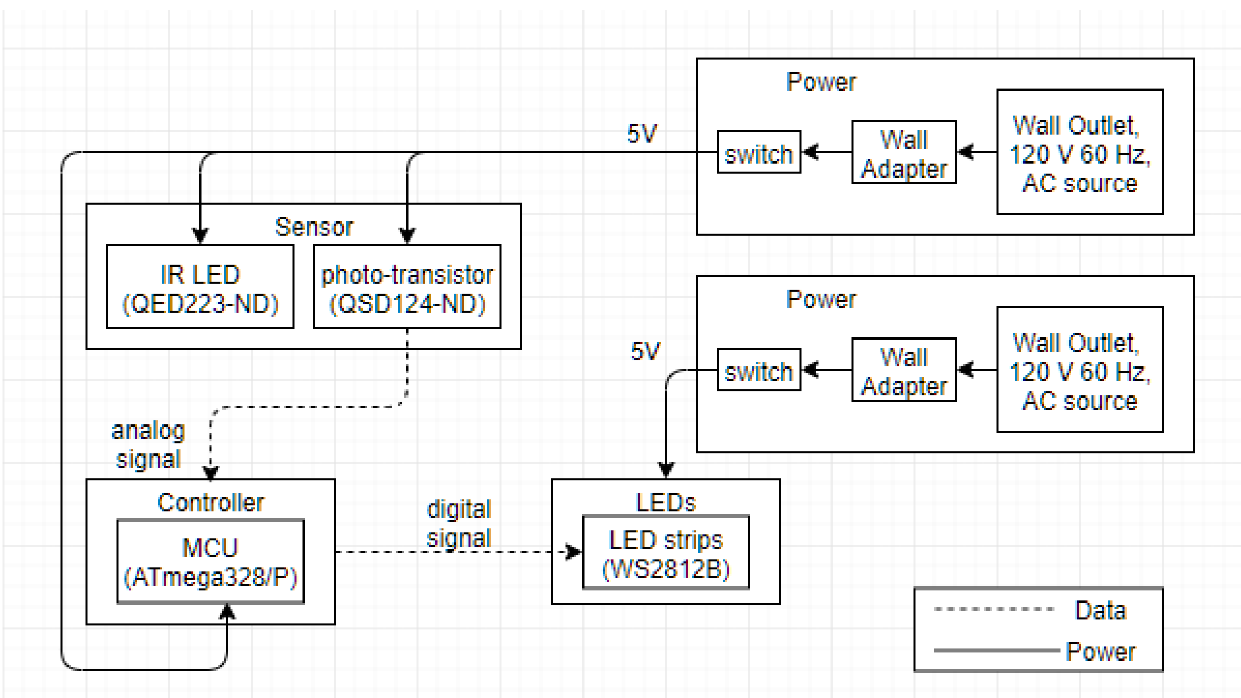


Figure 2: Block Diagram

2.1 Physical Model

The physical model is desired to be as similar to the real donor wall as much as possible without going overboard with our budget. As the material cost of the donor wall is high, the physical model is simplified while still taking into consideration the technical needs and the artistic effects of the model. This simplification is the reduction of three layers of acrylic glass to two layers and using thinner acrylic glass compared to the actual donor wall. The copper circuit background design is completed using copper color spray paint and tape to reduce the transparency, and cut-out cardboard shapes are used to attach the LED strips to the panels. The LEDs are taped around the circumference of the cardboard shapes and connected to other LED strips by wires. The cardboards are cut exactly 1cm smaller than the copper circuit background design to reduce the visibility of individual LEDs on the strips. There are three sets of wires for each LED strips, one wire for each power, ground and data lines. The wires are soldered by hand and enclosed in glue using hot glue gun to have no exposed conducting surfaces. The visible wires and the backboard, used as a fake wall, are all painted by hand using liquid paint similar to the color of the Electrical Engineering Building wall. A picture of the finished illumination system is seen in Figure 3. Our physical model is a small portion of the actual donor wall: three panels in width and two panels in height, small yet large enough to demonstrate all the designed light animations.

Figure 3: Finished Illumination System

2.2 LED Software

The Default Mode is triggered when no one is in front of the donor wall. Each pulse starts randomly from the left, up or right edge of the donor wall with static lighting on each name blocks. In Human-Following Mode, when someone is in front of one of the columns of panels of the donor wall, each pulse spreads out from the middle of that column with static lighting on each name block. The Override mode means that when someone gets close to a name block, the pulse starts from the name block and the background static light of the engaged name block intensifies and dies down. As the pulse propagates and passes through another name block, the lighting on the name block also intensifies and dies down.

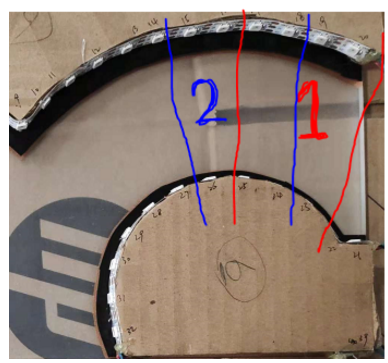
The software implementation must be designed to control WS2812B LED strips to display smooth and satisfying visual effects. Also, the animation speed must be designed to be uniform and consistent without any significant jittering. With a limited global memory space of 2 kB and program space of 32 kB in the microcontroller, the code must be space efficient to fit into the limited global memory and program space.

In our initial design, there were more than 20 short LED strips which were connected to two 4-to-16 line decoders. The select bits of the decoders were connected to output pins of the microcontroller. Then in the software, the selecting bits were changed to send data to different LED strips in some order. This idea is rejected because with this implementation, only two strips can be controlled at the same time. However, to achieve satisfying animation in each mode, different LEDs from multiple LED strips must be turned on and off at the same time.

In our final design, only three separate LED strips are controlled by the microcontroller. The Arduino Integrated Development Environment (IDE) and its FastLED library are used to program the microcontroller to control the LED strips. The FastLED library treats an LED strip as an array of numbers. In other words, Every LED can be accessed with an index of an array and can be controlled by manipulating the array. With control over every LEDs, the basic idea of the implemented code turns on some LEDs at a time interval of 15 μs. After turning them off, next group of LEDs is turned on and off. These two steps are quickly repeated such that human eyes visually see the propagation of "light" or pulse. The 15 μs is chosen based on many visual tests with other tested time intervals of 50 μs, 30 μs, 20 μs, and 10 μs. Based on the pattern and path of pulse in the physical model, the specific times to turn on and off each LEDs is manually determined.

As shown in Figure 4a, the physical model is separated to six parts. Figure 4b shows how four LEDs are grouped to always turned on and off together. Two groups of the four LEDs are overlapped with two middle LEDs. This way, multiple groups of four LEDs can be combined together by turning them on at the same time. This is an efficient way to reduce the occupied program space because each part of the model and each group can be called repeatedly in multiple illumination modes. With this method, the occupied program space is small enough to be uploaded to the microcontroller. The implemented code for the LEDs takes up 87% of the total available space. Also, with this method, any jittering illumination is completely eliminated. Figure 5 shows the state diagram of the final software implementation. The sensor software implementation is discussed in Section 2.4.2.

(a) Column Separation of the Panels



(b) Groups in one part

Figure 4: Physical View of Software Design

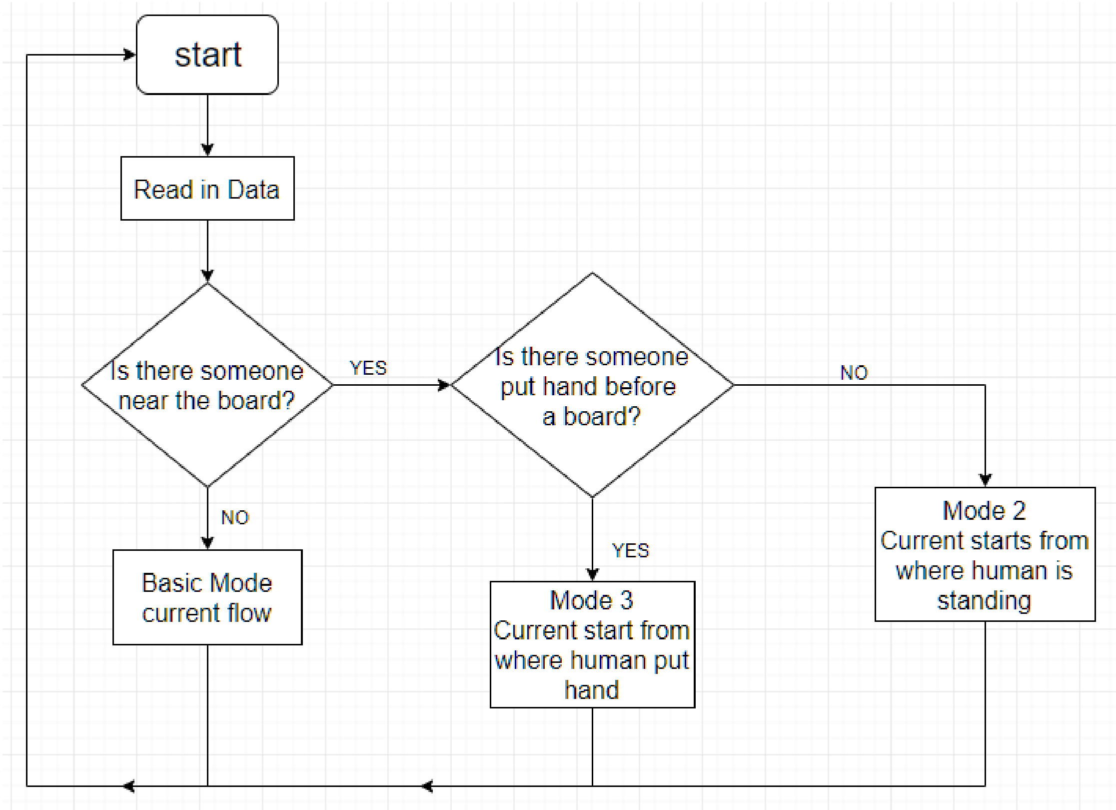


Figure 5: Software State Diagram

2.3 Microcontroller

An ATMega328P microcontroller chip is used to perform and control the illumination modes based on the input sensor data. The circuit to correctly operate the microcontroller chip is redesigned from the official document of the Arduino Uno board [2]. Instead of ATmega328P, other microcontroller chips could have been used. For example, ATMega2560 is a more powerful chip than the used ATmega328P chip. The ATMega2560 chip has larger memory and program space with more Input and Output (IO) pins. However, the ATMega328P chip is used because the ATMega2560 chip is much more expansive than the ATMega328P chip. Also, the ATMega328P chip is determined to be good enough for our applications. Figure 9 and 10 in Appendix B shows the final circuit schematic for our final PCB. Figure 11 in Appendix B shows the relevant circuit schematic for the microcontroller's operation.

As observed in Figure 11, the microcontroller cicuit includes a reset button. The reset button is indicated as "TS42 "in Figure 11. Using the reset button efficiently restarts the program in the microcontroller without the need of re-powering the whole circuit. Between pin 9 and pin 10 on the left side in Figure 11, there is a 16 MHz crystal oscillator operating as an external clock for the ATMega328P chip. The crystal oscillator is placed parallel to a 1 MΩ resistor with two 22 pF capacitors connected to each side of the crystal oscillator. Notice that a 0.1 μF decoupling capacitor is placed between pin 7 and pin 8 to get rid of any noise from the power supply. On the right side of Figure 11, pins are connected to sensor circuit for receiving the input data and to LED strips for displaying illumination animations.

2.4 Sensor

One IR sensor is placed on each of the six panels of the donor wall and all the sensors are collectively used to detect the position and the proximity of a person with respect to the donor wall. This data is used by the microcontroller to control which LED illumination animation to display. IR sensor implementation is composed of hardware and software components. With the hardware component, each IR sensor circuit must filter undesired noise to output stable signals for the microcontroller and be optimized for maximum working distance and sensitivity. With the software component, the microcontroller must correctly filter out any undesired noise and reliably and consistently detect the presence of a person at 100cm and at 30cm from the donor wall. Our team determined these distances from the donor wall to be appropriate working distances if our system were to be built on the actual donor wall. Each successful hardware and software components of IR sensor are discussed in Sections 2.4.1 and 2.4.2, respectively.

Other possible sensors has been researched such as Passive Infrared (PIR) sensor and ultrasonic sensor. The PIR sensor is ruled out because PIR sensor detects the change in the radiated IR light, not absolute measure of the amount of IR light present. As a result, PIR sensor is determined to be applicable for detecting the presence of a person, not for the proximity of a person. Ultrasonic sensor is also excluded because of large receivers and transmitters. The sensor must be hidden throughout the donor wall in between cracks of 1cm without hindered performance. Perhaps, there are small ultrasonic sensors but no cheap and small ultrasonic sensors have been found. As a result, IR LED and phototransistor is used. Furthermore, these components are readily available from leftover parts from Sungmin's previous semesters' projects.

2.4.1 IR Sensor - Hardware

The main hardware components in each sensor include IR LED (QED223-ND) with peak emission wavelength of 890nm [3] and phototransistor (QSD124-ND) with peak sensitivity wavelength to be 880nm [4]. The input voltage of IR LED and phototransistor are chosen to be $5V$ because it's also the same working voltage as the microcontroller block. With $5V$ as the input voltage, the IR sensor works by having the IR LED on and by increasing the output (emitter) voltage of the phototransistor as the IR light emitted by the IR LED is reflected back to the phototransistor. The final circuit schematic for an IR sensor is shown in Figure 6. In this schematic configuration, the more IR light from IR LED is reflected back to the phototransistor, the greater the output voltage. Note that the output voltage has exponential dependence on the distance. In other words, the change in the output voltage with respect to the distance from the donor wall is greater at 30cm than at 100cm. This exponential dependence on distance proved to be the main problem in the hardware component of IR sensors. With respect to this problem, in written order, there are three main sub-components of the IR sensor hardware component: determination of IR LED's current-limiting resistor, implementation of a Low-pass Filter (LPF), and determination of phototransistor's pull-down resistor.

2.4.1.1 IR LED Current-Limiting Resistor

For maximum IR sensor's sensitivity, the current-limiting resistor for the IR LED is carefully chosen to be 40Ω such that the IR LED is on at maximum brightness. Table 1 shows the IR LEDs working voltage and current from the datasheet [3] from the manufacturer. Note that the temperatures are arbitrarily chosen to be the approximate temperatures inside ECEB with the facilities heating and air circulation system. The temperature of 60 °C is also chosen arbitrarily to be the maximum working temperature due to heating from prolonged hours of operation.

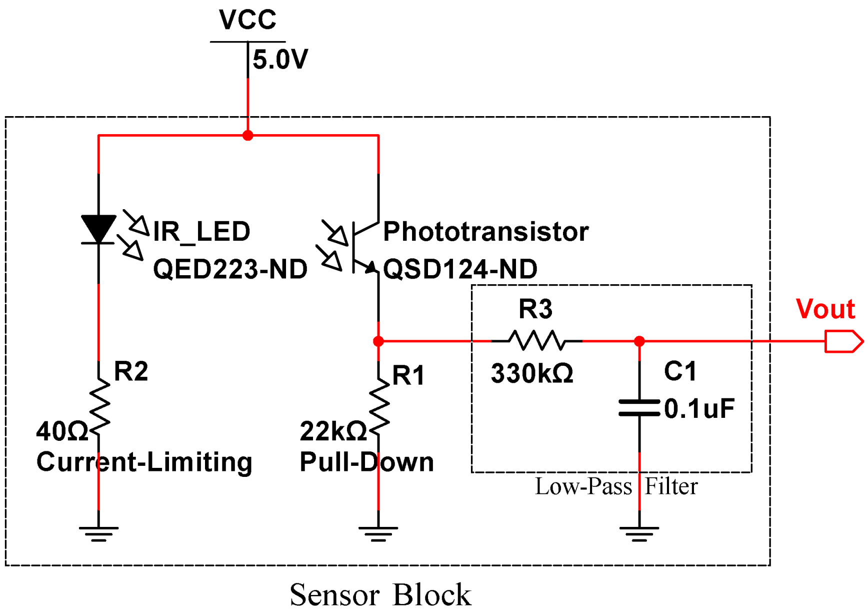


Figure 6: Circuit Schematic of Each IR Sensor

With the knowledge of V_f from Table 1, the voltage across the current-limiting resistor can be calculated by $V_R = V_{cc} - V_f$ where V_{cc} is $5V$ and V_f is shown in Table 1 for various temperatures. With the knowledge of I_f from Table 1, the current through the current-limiting resistor I_R must be the same as I_f because the IR LED and the current-limiting resistor are in series. Table 2 shows the resistor value and minimum power rating calculations for various ambient temperatures.

From Table 1 and Table 2, the current-limiting resistor value is calculated and chosen to be 40Ω with minimum power rating of $327.54mW$. The resistance value of 40Ω is chosen to be higher than 37.6Ω to leave space for potential power source issues and for the ease of buying the resistor. The minimum power rating was chosen to be $327.54mW$ because that value is the highest minimum power rating for various temperatures and because the resistor can efficiently dissipate more heat away from the sensors.

Table 1: IR LED Performance's Dependence on Ambient Temperature

T_A, Ambient Temperature [°C]	I_e, Normalized Radiant Intensity [1]	I_f, Forward Current [mA]	V_f, Forward Voltage [V]
15 (Min. Weather)	1.3	103	1.82
22.5 (Avg. Weather)	1.1	101	1.78
30 (Max. Weather)	0.99	95	1.75
60 (Max. Heat Temp.)	0.9	90	1.62

Table 2: IR LED's Current-Limiting Resistor Calculation

T_A, Ambient Temperature [°C]	R, Resistance [Ω], $R = \frac{V_R}{I_R}$	P, Power [mW], $P_R = V_R I_R$
15 (Min. Weather)	30.8738	327.54
22.5 (Avg. Weather)	31.88	325.22
30 (Max. Weather)	34.2105	308.75
60 (Max. Heat Temp.)	37.6	304.2

2.4.1.2 Low-Pass Filter

Low-Pass filter can be implemented independent of the current-limiting resistor discussed in Section 2.4.1.1 and the pull-down resistor discussed in 2.4.1.3. The current-limiting resistor of 40Ω, as calculated in Section 2.4.1.1, and the pull-down resistor of $9k\Omega$ is used to implement the LPF. With respect to Figure 6, the circuit with $R2$ of 40Ω and $R1$ of $9k\Omega$ is used. In Section 2.4.2, why the pull-down resistor of $9k\Omega$ was initially chosen is discussed. In Section 2.4.2.1, why the resistance value is changed to $22k\Omega$ is discussed in more detail.

To determine the cut-off frequency of the LPF, a hand is waved in front of the IR sensor as fast as possible. With Teledyne LeCroys HDO 4054-MS oscilloscope, the V_{out} reading of such event is shown in Figure 16 from Appendix B. The cut-off frequency is calculated to be $4.75397Hz$ using Equation 1. To determine an accurate cut-off frequency, the time for nine periods of 1.893152 s is measured, averaged, and used as T in Equation 1. Then, the R and C values are determined and calculated using Equation 2. The capacitor value, C is chosen to be $0.1\mu F$ because $0.1\mu F$ capacitors are cheap and common ceramic capacitors. Additionally, ceramic capacitors generally last longer than electrolytic capacitors and are generally better suited for filtering high frequencies. So, with C of $0.1\mu F$ and $f_{cut-off}$ of $4.75397Hz$ in Equation 2, the R value is calculated to be 334 783Ω. This R value is rounded off to be $330k\Omega$ for the ease of buying the resistor cheap. In short, the LPF is composed of R of $330k\Omega$ and C of $0.1\mu F$ and the reliability of the implemented LPF is discussed in Section 3.3.

$$f_{cut-off} = \frac{1}{T} \tag{1}$$

$$f_{cut-off} = \frac{1}{2\pi RC} \tag{2}$$

2.4.1.3 Phototransistor Pull-Down Resistor

The pull-down resistor on the phototransistor determines the IR sensor's output voltage range and thus, the detectable range of a person from the sensor. However, many tests with many different values of the pull-down resistor have shown that the output voltage range also depends on the distance between IR LED and phototransistor. Because of this interdependent relationship between multiple factors, choosing the phototransistor's pull-down resistor proved to be difficult. For the sake of brevity in the following discussions, the distance between the IR LED and the phototransistor, distance between a person and the IR sensor, the pull-down resistor, and the output voltage are referred to as $d_{IR-Photo}$, $d_{Person-Sensor}$, $R_{Pull-Down}$, and V_{out} respectively.

Initially, the V_{out} dependence on $d_{IR-Photo}$ went unnoticed. Upon many test failures and inconsistent data, this connection was found. Such dependence is speculatively determined to be caused by either defective components' lateral IR emission by the IR LED and lateral IR detection by the phototransistor or the reflection and refraction of IR light through the components' package materials. Even though the datasheet of IR LED and phototransistor respectively indicate medium wide emission angle of 30°[3] and narrow reception angle of 24°[4], the IR light somehow seems to laterally travel into the phototransistor. No optical tests have been performed to determine exactly how such lateral emission and detection occurs. However, since this behavior of the IR LED and the phototransistor is not crucial to the functionality of the IR sensor, this issue has not been examined further.

To determine how $d_{IR-Photo}$ affects the V_{out} range, the sensor circuit shown in Figure 6 was tested by the testing various $d_{IR-Photo}$. For each $d_{IR-Photo}$, $R_{Pull-Down}$ was varied. For each $R_{Pull-Down}$, $d_{Person-Sensor}$ was varied in increments of 10cm. Portions of these tests can be found in Figure 12 and 13 from Appendix B. When nobody is present within 2m in front of the sensor, the key effect that $d_{IR-Photo}$ has on the output voltage became clear after many tests. The smaller the $d_{IR-Photo}$ is, the greater the measured V_{out} is. Table 3 shows the minimum measured V_{out} with nobody present within 2m in front of the sensor with varying $d_{IR-Photo}$. Note that $R_{Pull-Down}$ of $22k\Omega$ is used for the data in Table 3 because $R_{Pull-Down}$ of $22k\Omega$ is the only common $R_{Pull-Down}$ throughout many tests with different $d_{IR-Photo}$.

From Table 3, the minimum V_{out} is observed to dramatically decrease from $d_{IR-Photo}$ of 1.8cm to 3.0cm. The change of minimum V_{out} is observed to be less dramatic between other $d_{IR-Photo}$. In other words, choosing $d_{IR-Photo}$ is a trade-off between the IR sensor's V_{out} range and the aesthetics. The larger the $d_{IR-Photo}$ is, the longer the sensors' Printed Circuit Board (PCB) becomes and thus, less aesthetically pleasing sensors become. Also, Figure 12 from Appendix B shows V_{out} dependence on $d_{IR-Photo}$. Note that V_{out} at ∞ represents V_{out} when there's nobody 2m around the sensor except for ambient light.

Table 3: Minimum V_{out} of IR Sensor (Nothing in 2m from the IR sensor) with $R_{Pull-Down} = 22k\Omega$

$d_{IR-Photo}$ [cm]	V_{out} [mV]
1.8	220
3.0	98
4.3	82
5.6	65
6.9	61

Through initial difficulties from the unexpected IR sensor's behavior, $d_{IR-Photo}$ of 4.3cm is chosen because the distance is large enough that the lateral emission and reflection issue is not significant. Additionally, as discussed in Section 2.4.2, the absolute working voltage range of the microcontroller is chosen to be from 0V to $AREF = 1.1V$. This means that even in worst operating conditions, less than $100mV$ or 10% of the total voltage range will be "wasted." Lastly, the distance is small enough to not be visually obvious. Choosing the appropriate $d_{IR-Photo}$ proved to be simple and seemingly obvious but difficult. Without the initial knowledge of $d_{IR-Photo}$ being one of the main factors that determine the V_{out} range, the IR sensor initially seemed unreliable and inconsistent. Ultimately, such inconsistency came from inconsistent $d_{IR-Photo}$.

How $R_{Pull-Down}$ affects the V_{out} range can be determined using previous test data from determination of $d_{IR-Photo}$. Figure 13 from Appendix B shows the output voltage's dependence on $R_{Pull-Down}$. As discussed in Section 2.4.2, the maximum reference voltage (AREF) is chosen to be $1.1V$. Since the relevant distances of a person to the sensor are from 30cm to 100cm, $R_{Pull-Down}$ of $22k\Omega$ is observed to be suitable for the IR sensor with a bit of room for error. Furthermore, as seen in Table 4, $\Delta V_{\ d=100cm-d=\infty}$ is found to be independent of $d_{IR-Photo}$. Thus, choosing $R_{Pull-Down}$ to be $22k\Omega$ means that $\Delta V_{\ d=100cm-d=\infty}$ is consistently equal to $\sim 60mV\ or\ 70mV$. Such consistent difference in voltage is more than enough to detect a person at 100cm with the LPF filter and the averaging filter, as discussed in Section 2.4.1.2 and in Section 2.4.2, respectively. This also means that it is even easier to detect a person at 30cm. If about 1 digital unit were to be used as the difference in output voltage in working distance instead of roughly 60 or 70 digital units, the maximum theoretical working distance of IR sensor is greater than $2.5m$.

Table 4: Measured $\boldsymbol{\Delta V_{\ d=100cm-d=\infty}}$ For Various $\boldsymbol{R_{Pull-Down}}$

$R_{Pull-Down}[k\Omega]$	$\Delta V_{\ d=100cm-d=\infty}[mV]$
10	~ 30
22	$\sim 60\ or\ 70$
33	$\sim 100\ or\ 110$
47	~ 138

In short, The finalized values of $R_{Pull-Down}$ and $d_{IR-Photo}$ are chosen to be $22k\Omega$ and $4.3cm$, respectively. The validations of IR sensors with these values are discussed in Section 3.3.

2.4.2 IR Sensor - Software

2.4.2.1 Analogue Reference (AREF) Voltage

The microcontroller chip ATMega328P has a 10-bit Analog to Digital Converter (ADC). In other words, the analog voltage readings are converted to a digital number in the range from $0\ digital\ unit$ to $2^{10} - 1 = 1023\ digital\ unit$. At the time of implementing the LPF, the Analogue Reference (AREF) pin on ATMega328P was found to be able to use an external reference voltage such as $5V$ and $3.3V$ or an internal reference voltage of $1.1V$. The $1.1V$ internal voltage is produced by the ATMega328P chip. The reference voltage is chosen to obtain appropriate analog resolution depending on the required voltage range. External AREF greater than $1.1V$ could be used but the minimum voltage that can be used as the AREF is found to be the chip's internal AREF of $1.1V$ [5]. Table 5 shows corresponding analog resolution for three examples of different reference voltages.

As can be observed in Figure 12 and 13 in Appendix B, the output voltage of the sensor only ranges from some voltage under $100mV$ to about $1.0V$ for distances from $100cm$ to $30cm$, respectively. As a result, the internal AREF voltage of $1.1V$ is chosen for maximum analog resolution in the working distances.

As discussed in Section 2.4.1.2, the initial value of $R_{pull-Down}$ is chosen to be $9k\Omega$. This design choice is appropriate if AREF voltage is $5V$. Figure 14 from Appendix B shows the plot that was used for initial determination of $R_{pull-Down}$ before proper implementation of Low-pass Filter. It can be observed from Figure 14 that using a resistor value in between $8k\Omega$ and $10k\Omega$ has the maximum range of voltage. If AREF of $5V$ is used, this is desirable for maximum sensor's sensitivity. It can also be observed from Figure 14 that maximum measured voltage using higher resistor values than $10k\Omega$ converges at about $4.75V$. As a result, using any higher resistor value than $10k\Omega$ only decreases the voltage range as the maximum voltage is fixed to be $4.75V$ and because the slopes of the curves are increased. As a result, it was initially decided to use a $9k\Omega$ resistor which is in between $8k\Omega$ and $10k\Omega$.

Table 5: Analog Resolution with Different AREF voltage

Analogue Reference Voltage [V]	Analog Resolution
5.0	$\frac{5V}{1024} = 0.00488V/Digital\ Units$
3.3	$\frac{3.3V}{1024} = 0.00322V/Digital\ Units$
1.1	$\frac{1.1V}{1024} = 0.00107V/Digital\ Units$

2.4.2.2 Sensor Coding

With AREF voltage of $1.1V$ and with correct stable sensors' readings with the implemented Low-Pass Filter (LPF), software implementation must correctly filter out any undesired noise and reliably and consistently detect the presence of a person at 100cm and at 30cm from the donor wall. To filter out any extra noise, an average filter is implemented by taking 10 sensor readings and by treating the average value to be "one sensor reading." To reliably detect the presence of a person at the working distances, predetermined digital sensor readings at 100cm and 30cm are used to set a threshold for each illumination mode. Furthermore, the code is written such that it checks the readings of the relevant surrounding sensors to make sure that no sensor is unexpectedly getting false readings.

For consistent detection of a person at 100cm and at 30cm from the sensor, a calibration routine was implemented and is performed upon each reset of the microcontroller. The calibration part of the software is important as IR light is present in normal room lightings. As a result, the IR sensor's readings are different depending on the ambient light. During initial prototyping of the LPF, many different capacitors were tested in parallel to V_{out}. Figure 15 in Appendix B shows the digital readings for various capacitors. During these tests, the IR LED and phototransistor are found to take about two minutes to stabilize. Note that the stabilization time is determined to be two minutes because that time is approximately the time the microcontroller takes to read 2×10^4 samples with a baud rate of 9600. As a result, the code is set to wait for two minutes while constantly taking readings from the sensors. During this calibration time, no object or person should be within two meters around the sensors. To take care of the ambient light, a reference sensor reading is taken right after the calibration time. Then, every other sensor "readings" are calculated by the difference between the new and the reference reading.

2.5 Power

As the Donor wall has three sets of outlets, allowing a total of six wall adapters, unused and hidden behind the acrylic glasses, the 120V AC wall source is chosen to power up our illumination system.

2.5.1 Evolution of the Power Module

As the power requirements and the restrictions changed over the development of the project, it called for several changes to be made for the power module throughout the semester. This section describes the three stages of the power module design in-depth and the reasoning and design decisions made for each of the three stages.

The original power module designed for the illumination system consisted of one wall adapter, an inline switch, and three switching buck converters, or voltage regulators, to meet the voltage required for each of the parts, the sensor circuit, microcontroller circuit, and the LED strips. As seen in Figure 17 from Appendix B, a wall adapter was used to convert the 120V, 60Hz AC source to a lower DC source between 9V to 15V. This DC voltage is then fed into the voltage regulators to meet the power requirements for individual parts of the system.

During the development of the first prototype, a problem surfaced due to high current drawn by the LED strips which could burn out the voltage regulators with typical current rating of 1A or lower. According to the datasheet [6], each of the LEDs on the LED strips could draw 50mA at the highest intensity of light. Thus, a strip of 20 LEDs was enough to burn out the voltage regulators. Our team initially expected to use more than 200 LEDs, which then required at least ten voltage regulators with simple filter circuits on the PCB. A simpler alternative method was made possible when the sensor circuit, the microcontroller circuit, and the LED strips all functioned using a same 5V source. This simplified the power module design as seen in Figure 18 from Appendix B, where the problematic voltage regulators with low current ratings were no longer needed.

The redesigned power module converts the 120V AC source to the 5V DC source directly with a decoupling capacitor at the input to filter the noise from the wall outlet. This design was sufficient until the number of LEDs and their brightness was accurately determined with cardboards and coded accordingly to be used for the physical model. A new problem arose due to heavy variations of current, which introduced significant variation in voltage. This variation of current is the result of LEDs on the strips turning on and off, where more LEDs are turned on at certain area of the physical model and less LEDs on other areas of the physical model. This introduces voltage variations with period of 1s as seen in Figure 19 from Appendix B, which propagated into the sensitive sensor and microcontroller circuits.

This variations disrupted the stable readings acquired by the Sensor Module and did not satisfy the voltage input restriction of 5V with 10% error for the microcontroller. As this variation is not noise that could be filtered using LC filter or other types of simple filters, a final design of the power module was constructed as seen in Figure 7.

The final design consists of two separate power sources: one for the LED strips alone, and the other source for the sensor and the microcontroller circuits. As the LED strips have high input voltage tolerance of 3.5-5.3V, the voltage variations do not impact the functionality of the LED strips as long as enough current is provided by the source. Thus, a wall adapter of 20W with 5V output and current rating of 4A is used for the power source of the LED strips. The other power source chosen for the sensor and the microcontroller circuits is a 12W wall adapter with 5V output and current rating of 2A as the total current for two circuits is well below 2A shown in Equation 3.

$$(6\ Sensor\ Circuits \times 89mA) + 15mA = 549mA \tag{3}$$

89mA is the current drawn by a single sensor circuit, and 15mA is drawn by the microcontroller circuit. Total of six sensors are implemented for our physical model as described in Section 2.4. An inline switch is included for each of the two power lines for the user to conveniently turn the illumination system on and off. Both of the inline switches chosen have current rating of 5A.

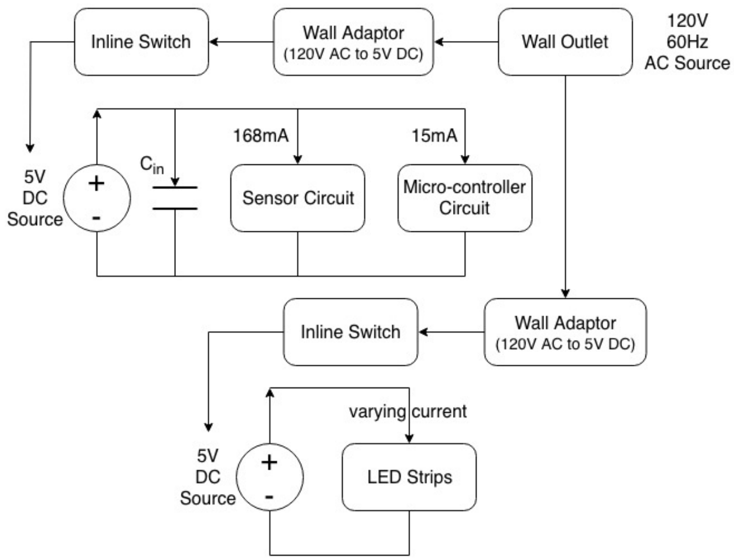


Figure 7: Final Design of Power Module

2.5.2 Power Consumption

A summary of the voltage and current drawn by each part of the illumination system is shown in Table 6. The method used to measure and verify the data in Table 6 is described in Section 3.4. The total maximum power used for the illumination system is shown in Equation 4 and Equation 5. This shows how minimum power, even lower than the power needed to light a cheap light bulb, is sufficient for our designed illumination system.

$$(Power\ for\ LED\ Strips) + (Power\ for\ Sensor\ and\ Microcontroller\ Circuits) = Total\ Power \tag{4}$$

$$(5V \times 1.03A) + (5V \times 0.534A) = 7.82W \tag{5}$$

Table 6: Summary of Power Data

Part(s) of System Powered	Voltage [V]	Current [A]
LED Strips	4.37 - 4.64	0.63 - 1.03
Sensor	4.62 - 4.65	0.534

3 Design Verification

3.1 LED Software

This part is only related to software implementation, instead of the hardware. So, there is no quantatitive verification for software part. Firstly, the software for the final design can work as expected. These evaluation and verification are based on the final visual effect. The reason that the initial design of using the decoder was rejected is discussed in Section 2.2.1.

The time period for finishing each completed pulse on the model is around 1 second, because the starting point of the pulse is different for each mode. In this way, the sensor can get the updated data quickly and the new mode can be triggered in time so that the lag of changing mode is minimal.

3.2 Microcontroller

The circuit was redesigned base on the official document of Arduino Uno board and it can work correctly as required. Initially, the prototype of our microcontroller circuit was built on a bread board. And the chip was uploaded with the simple LED blinking program. After supplied with 5V voltage, the desired effect was displayed. So this proved that the connection and required components were completed.

Next step is to test the circuit on the PCB. After soldering every necessary component and uploading the chip with test program, the same desired effect was on the LED. This proved that the PCB was working correctly, and nothing was burnt.

3.3 Sensor

Figure 20 from Appendix B shows the physical view of the implemented IR sensors. To use less wires, each sensor PCB attached to each acrylic panel is designed to only have the IR LED and phototransistor. Figure 20a shows how the IR sensor PCB are attached in between the acrylic panels of the physical model. As shown in Figure 20b, all other necessary sensor circuitry can be found on the main PCB.

As specified in Table 7, IR sensors were extensively tested. The voltage across the IR LED is found to not go under 1.62V for a testing time period of one hour. The implemented Low-Pass Filter in the sensor's hardware part and averaging filter in the sensor's software part successfully works together to result in very rare ± 1 digital fluctuations. Also, the IR sensors have been extensively tested with a meter stick to reliably and consistently work at the designed working distances of 100cm and 30cm. Even with different reflective materials and colors of worn clothes, the working distances are well within ± 10cm from the working distances. A demo video is available to show that the sensor block works as intended. Each sensors were also visually tested in conjunction with the LED software.

Figure 8: IR Light Visible Through Old Phone's Camera (Moto E 2nd Gen.)

3.4 Power

As mentioned in Section 2.5.1, a 20W wall adapter with 5V output and current rating of 4A powers the LED strips. To meet the specifications of the LED strips, the input voltage is required to be within the range of 3.5V - 5.3V and be able to supply sufficient current to light up the individual LEDs on the strips as long as the strips were under 5m long. To ensure that the input voltage variations are within the acceptable range, a DMM was used to probe at the input of the power on the PCB. The resulting DMM reading varied between 4.37V and 4.64V, which is well within the required 3.5V - 5.3V. A single LED on the LED strip can draw up to 50mA at its brightest light, and a total of 382 LEDs are used for the illumination system. The LEDs in the illumination system for our physical model is programmed close to its brightest light, and the total current drawn by the LED strips of our design was measured to be within the ranges of 0.63A - 1.03A. The current was also measured using a DMM probing at the input of the PCB, and it proves the current to be well below 10A current rating of the wall adapter.

A 12W wall adapter with 5V output and current rating of 2A powers the six sensor circuits and the microcontroller circuits. The current drawn by the circuits are low as shown in Equation 3 in Section 2.5.1. Instead of the current, the challenge was to supply steady voltage of 5V with ripple of 500mV (10%) or lower as specified in the Table 7 in Appendix A due to the input requirement of the microcontroller chip. This specification is verified by probing the wall adapter using an oscilloscope as shown in Figure 22 from Appendix B, and adding decoupling capacitors to filter out the noise from the source. Figure 23 from Appendix B shows how a single decoupling capacitor of .47uF filters the noise and drops the voltage ripple from 528mV to 140mV.

A standard method used to filter power adapters is to use a 100uF electrolytic capacitor and a 100nF ceramic capacitor [7]. Thus, the electrolytic capacitor of 100uF is implemented at the input power for the sensor circuits and the microcontroller circuit. The ceramic capacitor is used to filter out high frequency noise compared to the electrolytic capacitors used to filter lower frequency noise. As the high frequency noise is filtered within the sensor circuit as shown in Section 2.4.1.2 and a decoupling capacitor is included in the voltage sensitive microcontroller circuit, another ceramic capacitor is not required at the input power. With the single electrolytic capacitor at input power, the voltage requirement of 5V with maximum of 500mV ripple is satisfied.

4 Cost

The table of cost can be found in Table 8 in Appendix B. We estimate our labor cost to be \$35/hour and working about fifteen hours a week for each person. Our project was completed in ten weeks. Thus, our labor cost come out to be \$39,375.

$$\$35/hour \times 15\ hours/week \times 10\ weeks \times 3\ people \times 2.5 = \$39,375.00 \tag{6}$$

To make our model of the donor wall, we acquired the help of the Machine Shop located in ECEB. According to the Machine Shop, it took a full day to saw the acrylic panels into its correct sizes and to make the custom aluminum knobs. The labor cost is \$400/day according to the representative from the Machine Shop.

$$1\ day \times \$400/day = \$400 \tag{7}$$

Thus, the grand total cost including our labor cost, the labor cost of the Machine Shop, and the material cost is estimated to be \$40,192.43.

5 Conclusion

5.1 Accomplishments

Our project is a success with every component working as designed. The IR sensors consistently and reliably provide extremely stable input data to the microcontroller to change between the illumination modes. The software accurately handles the calibration and the working distances of the sensors. Our redesigned microcontroller circuit guarantees that the chip can work as on the original Arduino Uno board. With a powerful enough microcontroller chip, visually satisfying illumination animations are successfully displayed based on the detected distance of a person from the donor wall. All of the components are supplied with power without hindered performance. With the two separated power supplies, the noisy current changes in the LED strips does not affect the sensors' and microcontrollers' functionality. Needed current is also supplied to the LED strips without any problems. Lastly, the most successful accomplishment of our project is that everyone who took part in our demonstration session seems to really enjoy our design with bright smiles on their faces.

5.2 Ethical Considerations

5.2.1 Safety

With any project, there are safety concerns. Though the programming of the LEDs prevent all of the LEDs on the strips to light up at once, our team implemented an inline fuse to prevent excessive current. Theoretically, if the LEDs all turned on at once at full brightness, the current drawn from an ideal power source can reach up to 20A. As our programmed LED strips do not draw more than 1.03 A, an inline fuse with current rating of 3A is chosen, as the wires used for the illumination system would be the first to melt with increases in current. Wires typically have current ratings of 7A, with lower current ratings depending on the environment and the project [8]. 3A is well under 7A current rating and was also high enough to ensure the desired light animations of the illumination system. Thus, an easily replaceable inline fuse is used as a safety measure.

5.2.2 Ethics

1. **to hold paramount the safety, health, and welfare of the public, to strive to comply with ethical design and sustainable development practices, and to disclose promptly factors that might endanger the public or the environment:**
   According to the IEEE Code of Ethics[9], the first code explicitly asks us to warn the user that do not touch the circuit and only interacting with the model in appropriate ways. And because our project relates to handle a large number of IOs, we need to carefully and seriously test the input data. We also need to assess our project based on these accurately measured data because of the third statement in the Code of Ethics.

2. **to seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others:**
   On the other hand, we will consider and evaluate the valuable and honest suggestions and advice from our TAs, professors and our sponsor. We need to correct ourselves actively when we encounter some unexpected errors in the progress, as specified in the seventh statement of Code of Ethics.

3. **to treat fairly all persons and to not engage in acts of discrimination based on race, religion, gender, disability, age, national origin, sexual orientation, gender identity, or gender expression:**
   In the end, our project is aimed to let users enjoy art with no discrimination with our interactive design. We hope that our project can bring more fun to everyone.

5.3 Uncertainties

Each component of our project has been tested to reliably and consistently work as designed. With all components working well together and with the project's success, there is barely any uncertainties around our project. After being turned on for a long time, the whole system is tested to be functional with the operation temperature as normal. And during the demonstration session, the system did not show any uncertain phenomenons.

5.4 Future Work

If our idea is approved by the department, then our idea must be scaled up from the implemented small model to the huge real donor wall. First solution is to use a more advanced microcontroller chip, for example, ATmega2560, with more IO pins and more memory. Second solution is to build a hierarchy level between microcontrollers. The donor wall can be logically separated to many small parts where each part can be controlled by an ATMega328P chip. Then, another microcontroller chip can be used to control each ATMega328 chips. Another interesting problem is that programming the LEDs is time consuming because what LEDs should be in the same group and when each group should be turned on has to be manually determined. A solution for this problem can be developing a more advanced LED programming library such that the animation can be done more easily.

5.5 Schedule

Our weekly schedule can be found in Table 9 in Appendix C.

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Appendix A Requirement and Verification Table

Table 7: System Requirements and Verifications

Requirement	Verification	Working?
1. **IR LED:** When supplied with 5V from a bench power supply, IR LED turns on and the voltage drop across the LED does not go under 1.62V for 1 hours in room temperature 2. **Phototransistor 100cm:** When supplied with 5V from a bench power supply, the phototransistor works with IR LED, Arduino Development board to correctly detect the three different modes. The transitions between each modes should be when the distance of the person is 100cm ±10cm from the phototransistor consistently for 1 hour in room temperature. NOTE: The voltage measured cannot be specified because the range of the measured voltage varies largely depending on the amount of Infrared light present in the environment. NOTE: The development board is used for requirement because of limited ADC resolution of the microcontroller. 3. **Phototransistor 30cm:** The same as #2 except the working distance is at 30cm ±10cm.	1. **IR LED:** (a) Supply the IR LED supplied with 5V from a power supply. (b) Set up a multimeter to read the voltage across the IR LED. (c) At an interval of 15 minutes, measure the voltage across the IR LED. 2. **Phototransistor 100cm:** (a) Given that the requirement #1 is fulfilled, setup the IR LED circuit. (b) Check whether the IR LED is on using a phone camera capable of seeing Infrared light. (c) Setup the phototransistor circuit. (d) Connect the sensor circuit to microcontroller and load the program. (e) At a regular interval of 15 minutes, walk in front of the sensor to check whether the modes change at 100cm ±10cm. 3. **Phototransistor 30cm:** (a) The same as #2 except the working distance is at 30cm ±10cm.	1. Yes 2. Yes 3. Yes
4. **Power:** Ensure that the wall adaptor outputs 5V within 10% voltage ripple for normal operation.	4. **Power:** (a) Plug power adapter and connect it to the breadboard. (b) Probe the output of the adapter using oscilloscope. (c) Check that the voltage ripple is 500 mV or lower. (d) If it is not lower, add decoupling capacitor to lower the voltage ripple. Go back to 3. and check voltage ripple.	4. Yes

Continued on next page

Table 7 – continued from previous page

Requirement	Verification	Working?
5. **Sensor Software:** Correctly compare the input data and switch to correct mode	5. **Sensor Software:** (a) Start from handling the case that has only 3 boards, putting them in a row, initially. Each board has a sensor circuit on it. So we have 3 inputs now and these 3 inputs are sent to microcontroller. (b) Then we put three LEDs on the breadboard to represent three mode. LEDs are connected to three output pins of microcontroller. (c) Then we walk through the boards, or put hand in front of one board or leave the board empty. This is the simulation of 3 different situations. (d) Then in the software, we compare these 3 inputs by threshold conditions. Then determine which mode is triggered. Then the LED representing that mode should be turned on. (e) In the end, we apply this algorithm and expand these conditions for 6-input case.	5. Yes
6. **LED Software:** Send data to the LED strips.	6. **LED Software:** (a) We are coding the led strips directly, so all of the points are for the software.	1. Yes

Appendix B Figures and Tables

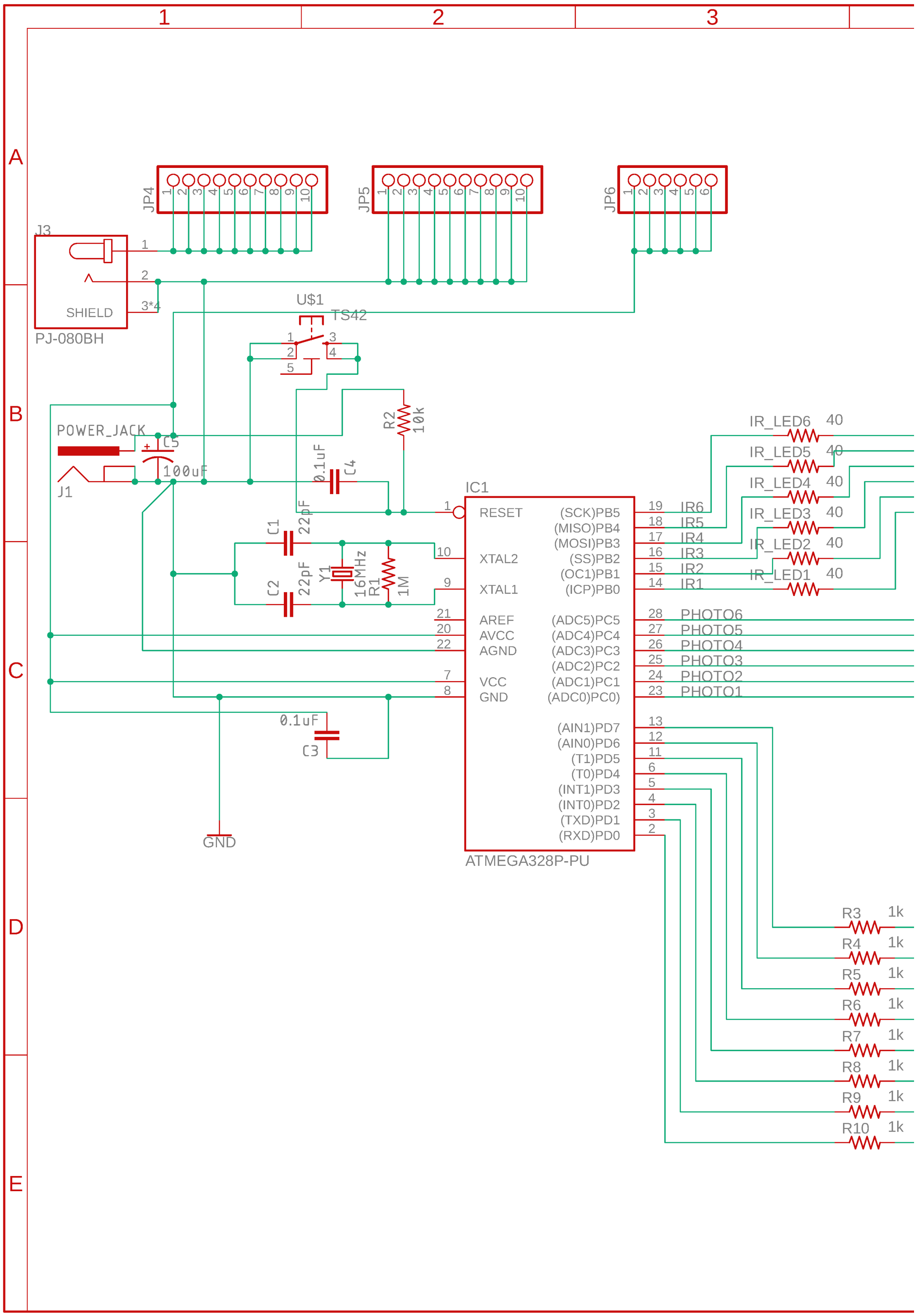


Figure 9: Main PCB Schematic Left Side

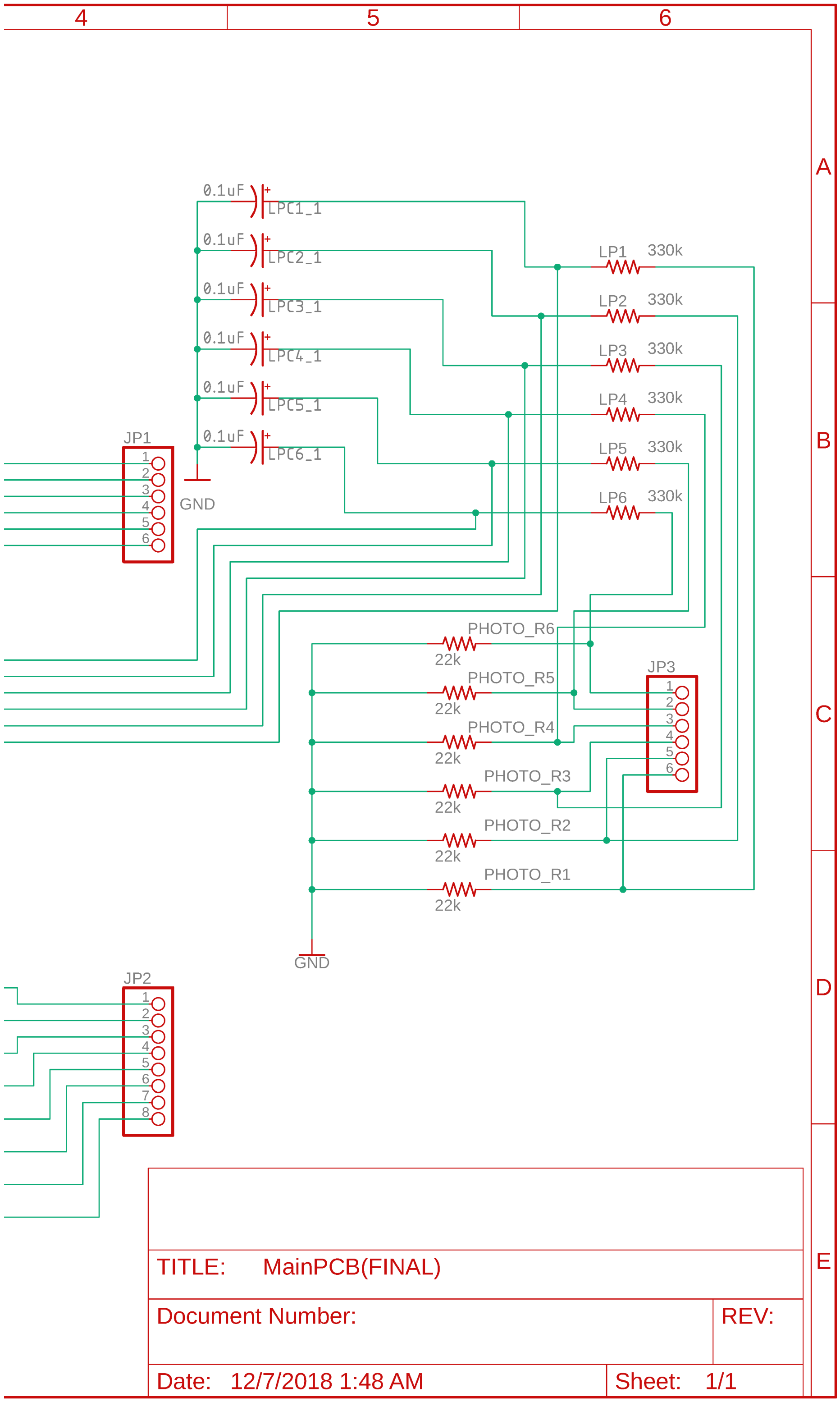


Figure 10: Main PCB Schematic Right Side

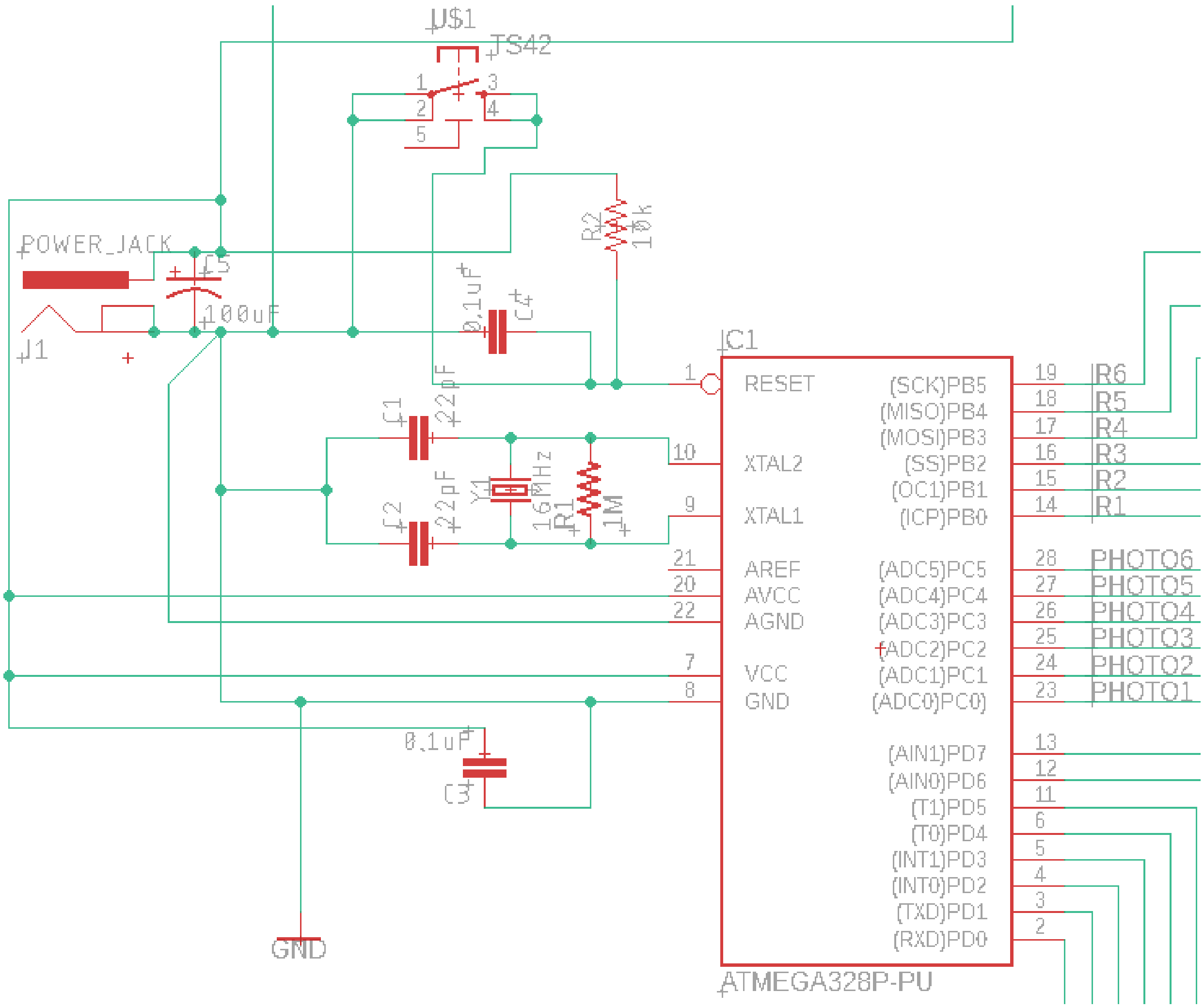


Figure 11: Microcontroller Circuit Diagram

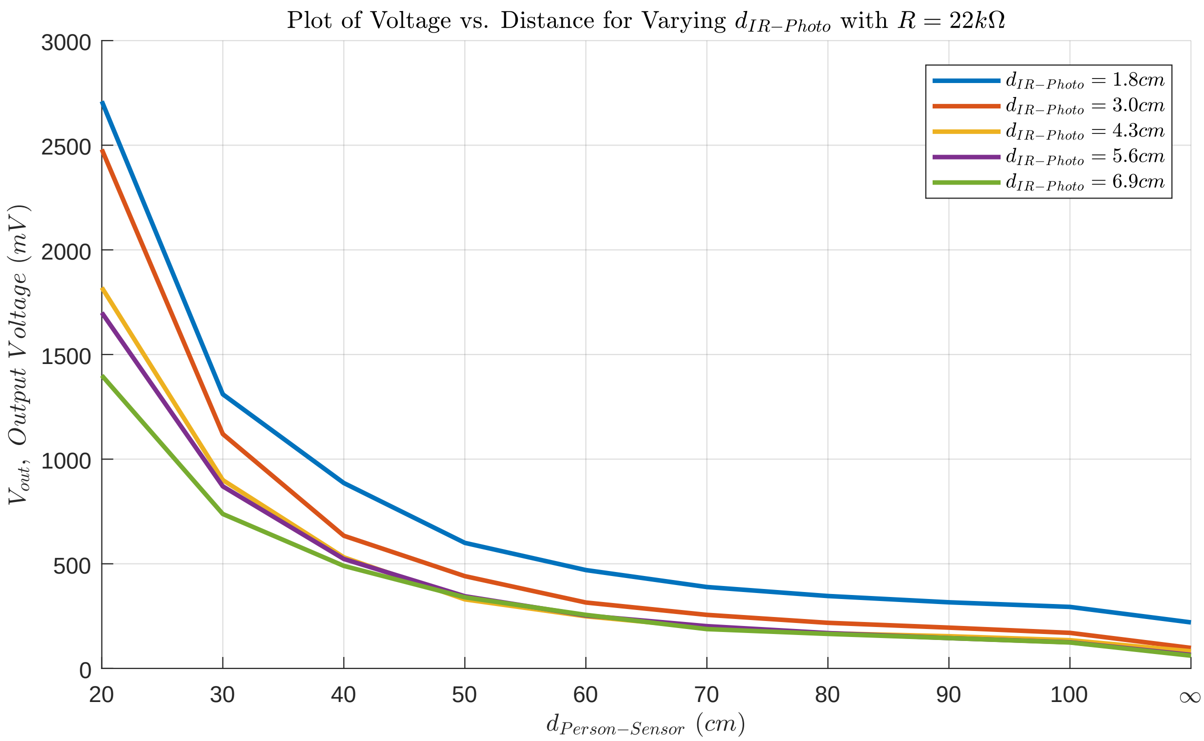


Figure 12: Output Voltage Dependence on $d_{IR-Photo}$

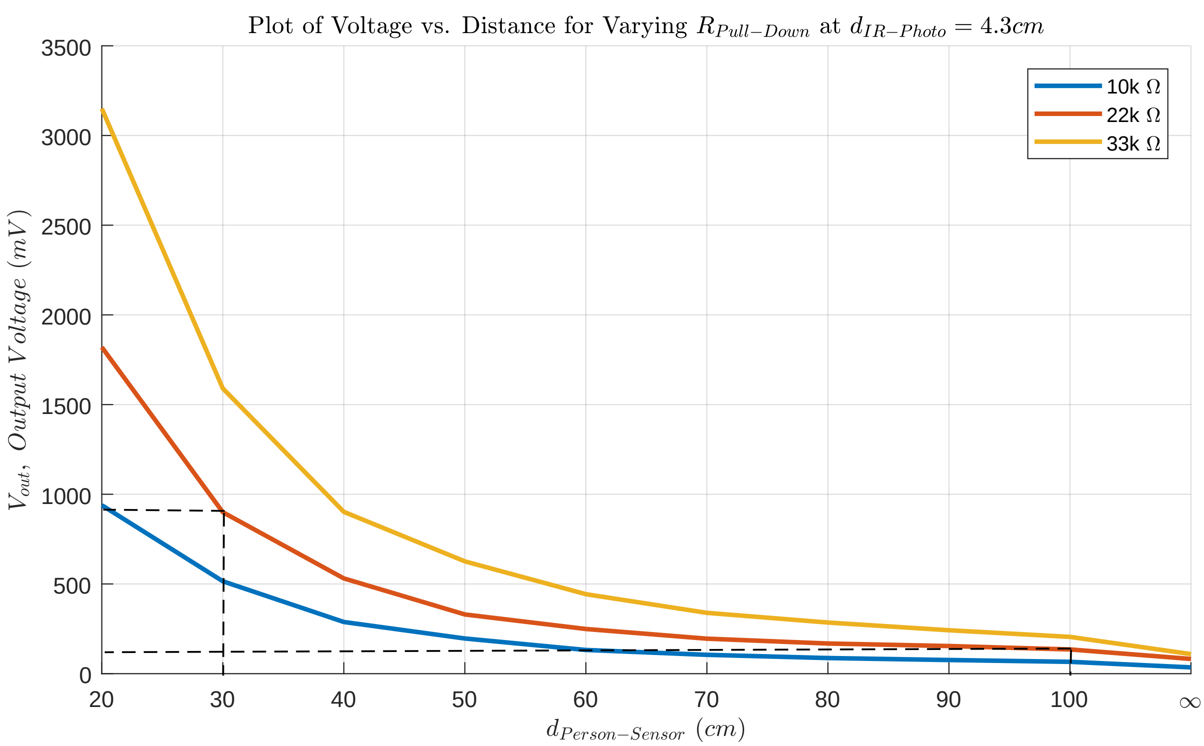


Figure 13: Output Voltage Dependence on $R_{Pull-Down}$

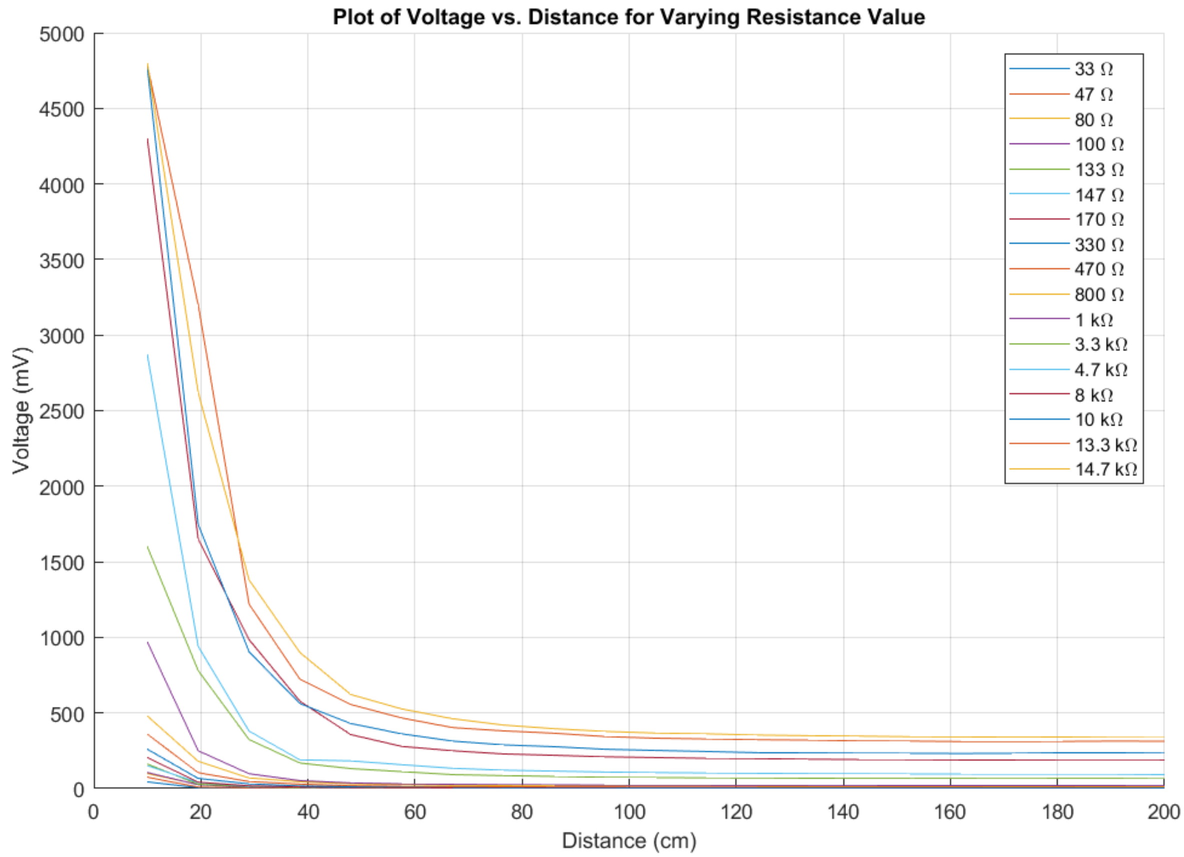


Figure 14: Output Voltage Dependence on $R_{Pull-Down}$ Without Low-Pass Filter

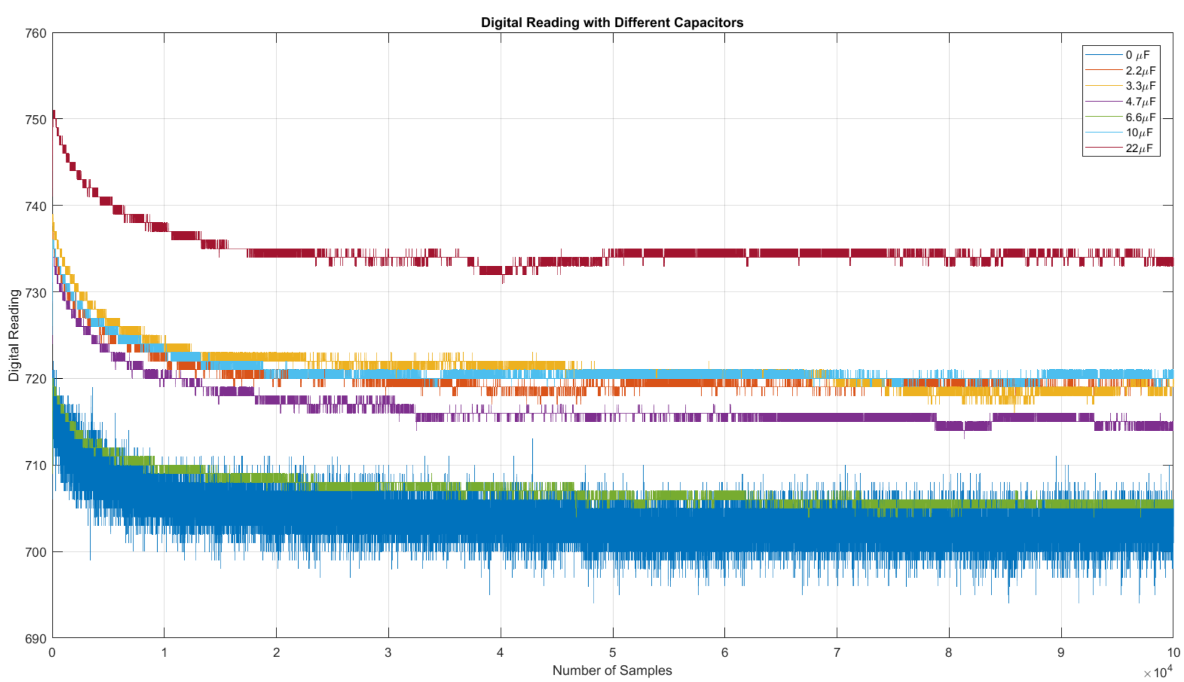


Figure 15: Digital Readings of IR Sensors with Varying Capacitors (placed parallel to V_{out} as Low-Pass Filter)

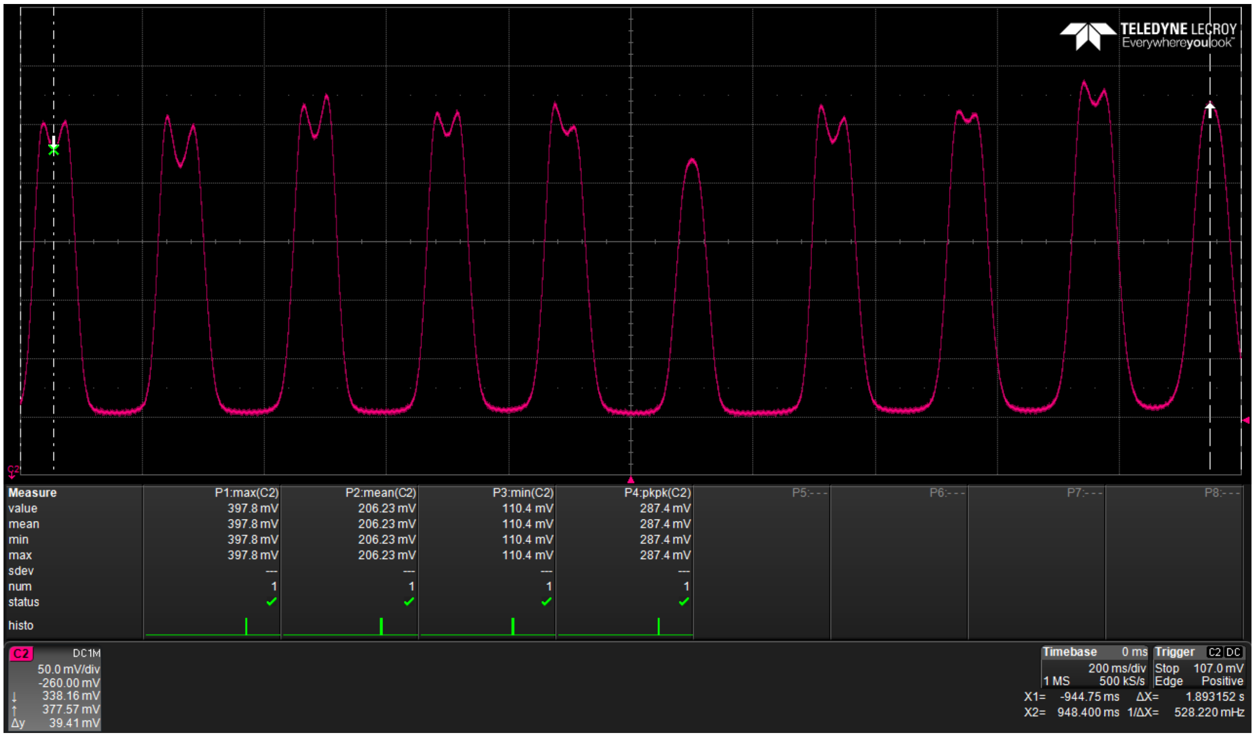


Figure 16: Oscilloscope's reading of waving one's hand as fast as possible in front of the sensor

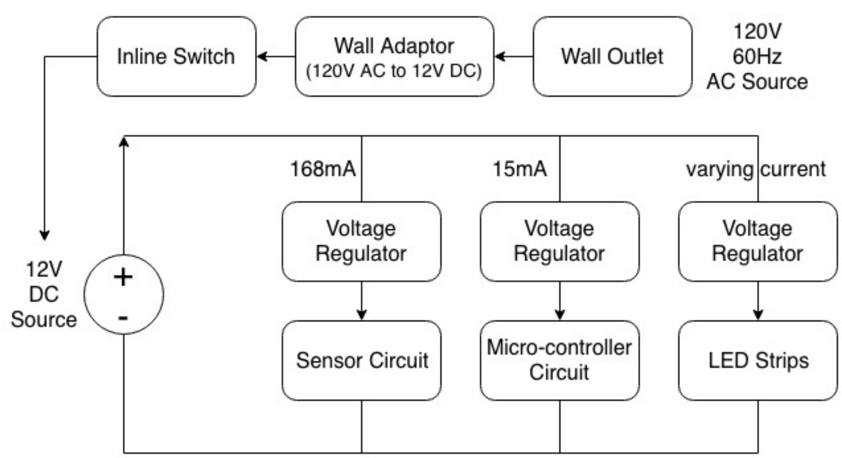


Figure 17: Original Power Module Design

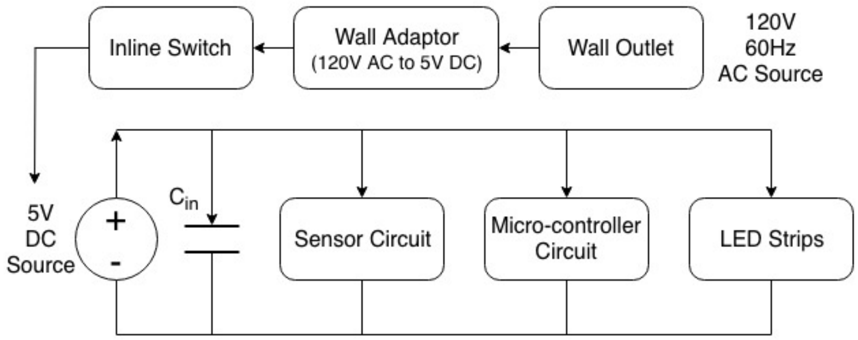


Figure 18: Redesigned Power Module

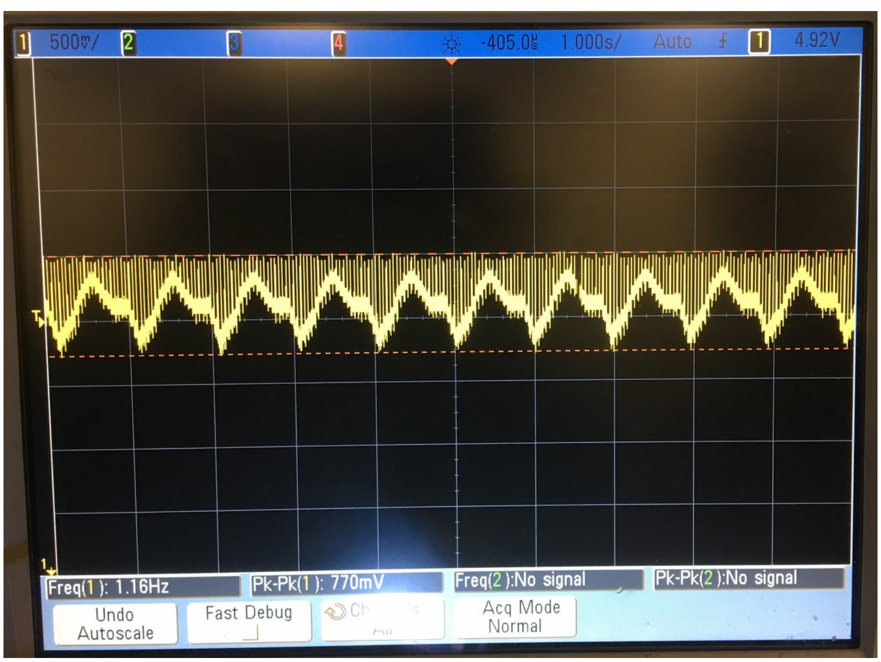
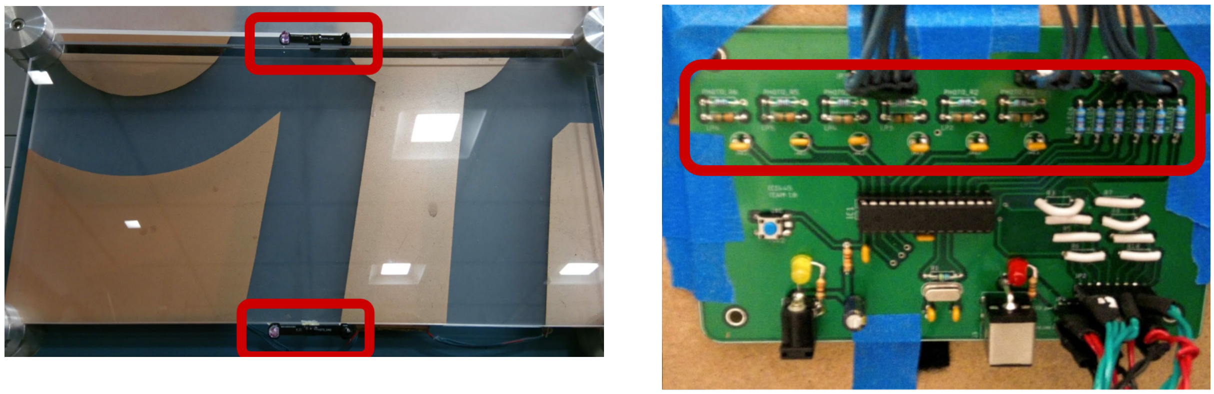


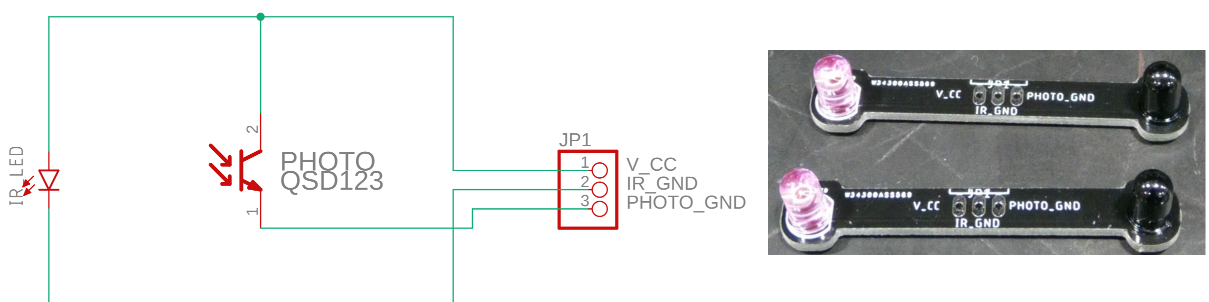
Figure 19: Voltage Variations at the Power Input



(a) Two IR Sensors Attached to Each Panels

(b) Sensor Components on Main PCB

Figure 20: Physical View of Implemented Sensors



(b) Physical Sensor PCB

(a) Sensor PCB Schematic

Figure 21: Close-up View of Each IR Sensors

Figure 22: Noise Detected at Wall Adapter Output

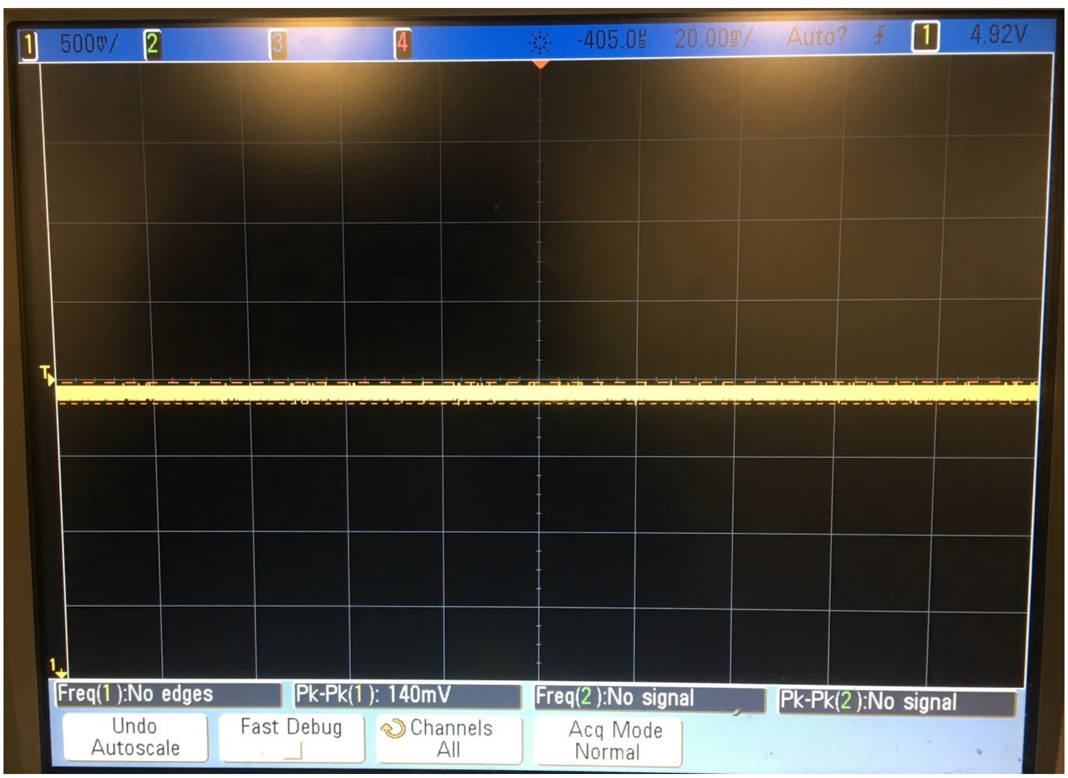


Figure 23: Noise Filtered by Decoupling Capacitor

Table 8: **Parts Costs**

Component	Manufacturer	Quantity	Unit Cost ($)	Actual Cost ($)
Acrylic glass	Machine Shop	12	N/A	200.00
Copper Spray Paint	Home Depot	3	6.76	22.31
Knobs (Aluminum)	Machine Shop	12	N/A	50.00
Backdrop (Medium-Density-Fiberwood)	Machine Shop	1	N/A	20.00
Multi Voltage Switching Replacement Power AC Adapter	ZOZO	1	9.98	9.98
4-pack Black Male to Female DC Power Inline Cable with On Off Switch	ANVISION	1	9.98	9.98
DC-DC Voltage Regulator (12V to 5V) TS30013-M050QFNR	Semtech Corporation	1	1.37	1.37
IR LED (QED223-ND)	ON Semiconductor	6	N/A	0.00
Phototransistor (QSD124-ND)	ON Semiconductor	6	N/A	0.00
ATmega328P	Arduino	4	1.66	4.67
WS2812B LED strip	Alitove	2	32.50	65.00
CAP CER 22pF 50V C0G/NP0 RADIAL (BC1005CT-ND)	Vishay BC Components	10	0.17	1.74
RES 40.2Ω 0.6W 1% AXIAL (BC4157CT-ND)	Vishay BC Components	30	0.17	5.28
SWITCH TACTILE SPST-NO 0.05A 12V (CKN9112CT-ND)	C&K	5	0.17	0.85
CONN PWR JACK 2X5.5MM KINKED PIN (CP-202A-ND)	CUI Inc.	3	0.64	1.92
CAP ALUM 100μF 20% 25V RADIAL (P10269-ND)	Panasonic Electronic	5	0.31	1.55
CONN PWR JACK 2.5X5.5MM SOLDER (CP-080BHCT-ND)	CUI Inc.	3	2.54	7.62
RES MF HV .25W 330$k\Omega$ 1% AXIAL (RNV14FAL330KCT-ND)	Stackpole Electronics Inc.	30	0.16	4.75
RES 1$M\Omega$ 1/4W 1% AXIAL (S1MCACT-ND)	Stackpole Electronics Inc.	5	0.10	0.50
RES 22$K\Omega$ 1/4W 1% AXIAL (S22KCACT-ND)	Stackpole Electronics Inc.	30	0.05	1.58
CRYSTAL 16.0000MHZ 20pF T/H (X1103-ND)	ECS Inc.	5	0.69	3.45
5.5mm x 2.1mm Female to Male DC AC Power Plug Jack Connector	VizGiz	1	4.88	4.88
Total				**$417.43**

Appendix C Weekly Schedule

Table 9: Weekly Schedule

Date	Anita	Sungmin	Zheng
Week of 10/01	1. Determine how many LEDs are being used and how they illuminate the panel. 2. Should have at least one frosted acrylic glass that allows us to test LEDs.	1. Have a decent reliable sensor block to output voltage into the MCU.	1. Have a detailed MCU circuit diagram that will interface with sensors and LEDs. 2. Fix/adjust the block diagram to include all details.
Week of 10/08	By the end of this week, all details to get the actual model of Donor Wall is all requested, processed, and well under way to finished construction from Machine Shop or an necessary physical tasks to be done on the acrylic glass.	If any, troubleshoot the sensors with acrylic glass. If time allows, look into LED strips and LED illumination of donor name blocks. By the end of this week, sensor should be able to correctly interface with microcontroller.	Work with microcontroller to figure out how to control LED strips.
Week of 10/15	1. Order sensors, adapters or other chips needed for the project. 2. Prepare the PCB file. 3. Finish up design the power block circuit.	1. Order sensors, adapters or other chips needed for the project. 2. Prepare the PCB file. 3. Finish up design the sensor block circuit.	1. Order sensors, adapters or other chips needed for the project. 2. Prepare the PCB file. 3. Finish up design the control block circuit. 4. Use the Arduino Board to control LED to mimic current flow in default mode.
Week of 10/22	1. Submit the PCB file. 2. Place the LED strips in designed shape.	1. Submit the PCB file. 2. Place the sensors and the circuit in required places.	1. Submit the PCB file. 2. Use Arduino board to communicate between sensors and microcontroller. Control LED to mimic current flow in Third Mode.

Continued on next page

Table 9 – continued from previous page

Date	Anita	Sungmin	Zheng
Week of 10/29	1. Build up the PCB, finish up the soldering work to test if there is something wrong in the PCB. 2. Implement the Second Mode with Arduino Board.	1. Build up the PCB, finish up the soldering work to test if there is something wrong in the PCB. 2. Implement the Second Mode with Arduino Board.	1. Build up the PCB, finish up the soldering work to test if there is something wrong in the PCB. 2. Implement the Second Mode with Arduino Board.
Week of 11/05	1. If the PCB is not working correctly, make sure it can be fix by Thursday and submit final design circuit. 2. If the physical model needs to be changed, make sure it can be done by Friday.	1. If the PCB is not working correctly, make sure it can be fix by Thursday and submit final design circuit. 2. If the physical model needs to be changed, make sure it can be done by Friday.	1. If the PCB is not working correctly, make sure it can be fix by Thursday and submit final design circuit. 2. If the physical model needs to be changed, make sure it can be done by Friday.
Week of 11/12	Debug the program. Or if there are add-on features, program as required.	Debug the program. Or if there are add-on features, program as required.	Debug the program. Or if there are add-on features, program as required.
Week of 11/19	Prepares for the Mock Presentation and starts working on the final paper and organize the notebook to get important part clear.	Prepares for the Mock Presentation and starts working on the final paper and organize the notebook to get important part clear.	Prepares for the Mock Presentation and starts working on the final paper and organize the notebook to get important part clear.
Week of 11/26	Everyone double checks the detailed requirement for the presentation. Work on the final paper.	Everyone double checks the detailed requirement for the presentation. Work on the final paper.	Everyone double checks the detailed requirement for the presentation. Work on the final paper.
Week of 12/03	Prepare for the presentation and finish the final report by the end of the week.	Prepare for the presentation and finish the final report by the end of the week.	Prepare for the presentation and finish the final report by the end of the week.
Week of 12/10	Presentation, and fix some minor details in the final report, then submit.	Presentation, and fix some minor details in the final report, then submit.	Presentation, and fix some minor details in the final report, then submit.