Atwater Kent Power Panel

A Major Qualifying Project
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Abstract

The Atwater Kent Power Panel is designed to bring an interactive, creative display to the Atwater Kent Pumpkin Lounge. This Panel, comprised of a large LED matrix display and capacitive user controls, will provide statistics on solar power generation and building power consumption. Interactive components and relevant campus information will keep students engaged on a day-to-day basis. The Power Panel's intuitive GUI combined with various external peripherals is an opportunity to convey efforts in energy awareness to Atwater Kent visitors.

Acknowledgements

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1 Introduction

The objective of this project is to create a "21st Century Power Panel" to display in the Atwater Kent (AK) Laboratory's Pumpkin Lounge. The Pumpkin Lounge is a student lounge located on the first floor of the building and is often frequented by students and visitors. The Electrical and Computer Engineering (ECE) Department of Worcester Polytechnic Institute (WPI) has provided numerous resources and technologies to encourage students to explore projects related to renewable energy. The purpose of the Power Panel is to increase awareness related to energy usage through creative and visually appealing methods. The Panel serves as a display of interest to students in AK by providing information including but not limited to upcoming campus events, historical energy consumption information, and interactive games. Various functions of the Panel have been explored through the course of this project. The conclusions reached will allow for student usage and further expansion by future project groups.

In this report, Section 2 outlines the background necessary to begin the project. The team focused on related projects by WPI students in addition to display options and creative aspects of design. Each of the related projects and decisions on display formats contributes to the final design which is addressed in Section 3. This outlines the features and design requirements of the Power Panel. Section 4 discusses the various components researched for the project. This section also includes decisions related to microcontrollers, power and wiring, software, and system integration. Section 5 describes the design parameters and work to develop the capacitive touch controls, specifications for power and wiring of the system, frame design, and standards met by each component used in the Power Panel. Following this section, work for future project teams is included before concluding with overall impressions of the finalized product.

2 Preliminary Project Decisions

The initial intention of this project was to provide a platform to display energy related statistics. The Panel serves as a tool to add character to the lounge and display information gathered from this project and past projects. In making preliminary project decisions, it was necessary to first research projects completed by WPI students related to energy as well as LED display options. Different versions of LED display were considered during this phase of the project before comparing feasible options for the Pumpkin Lounge setup. Each of these systems is explored further through this section and options are weighed to reach the preliminary project design, which provides a basis for the final project decisions.

2.1 Related Projects

Due to the ECE department's high interest in renewable energy in addition to display technologies through previous MQPs, there are many projects applicable to the development of the Power Panel. The multiple topics explored through this project are summarized below.

Project Title	Year Completed	Project Type
Instrumentation of the Atwater Kent Wind Turbine	2008	MQP
Renewable Energy Applications	2012	MQP
Monitoring Energy Consumption on WPI Campus	2007	IQP
Grid Independent Solar Charging Display	2012	MQP
Color Dot Matrix Proof of Concept	2012	MQP

Table 1: Related Projects

2.1.1 Instrumentation of the Atwater Kent Wind Turbine

In 2008, a SWIFT wind turbine was donated by National Grid to the ECE department at WPI. This turbine has been the subject of multiple projects since its installation. Before the 2008 "Instrumentation of the Atwater Kent Wind Turbine" project, the turbine fed energy back into the grid and was not used directly by the ECE department. An image of the SWIFT wind turbine is shown in Figure 1.

Figure 1: SWIFT Wind Turbine on Roof of AK

This project aimed to build a system to measure current and voltage output of the turbine. The MQP team created an online portal to display real time measurements, in addition to a circuit which charged a battery (2). Based on power generation computed by this previous project and discussions with professors in the ECE department, it is noted that the wind turbine does not produce as much power as was initially thought. The wind turbine is not in a location of maximum wind velocity on the WPI campus. Based on investigations through the study of this past project, the wind turbine does not provide enough power input for the Power Panel at this time, however would be available if resources proved efficient.

2.1.2 Renewable Energy Applications

In 2012, an MQP team worked on a previous iteration of the Power Panel project. This team evaluated the extent to which using power obtained from the wind turbine was feasible. After determining that the wind turbine did not create enough power to use for their Power Panel, they created a "solar energy harvesting board" (3). This board served to store energy in batteries for use within the ECE department.

Initially, this team had three sections of renewable energy applications which they focused on. With interest in developing a solar panel system, wind system, and site monitoring system, it was determined that in order to stay on schedule, only the solar panel system would be explored. The roof of AK was surveyed and the most optimal location for the solar panels was determined. The team installed two out of the six panels that were donated to the NECAMSID Lab. The remaining four have not yet been installed and are still located in the Lab. The solar panels located on the roof are still functional and will be utilized by this Power Panel project for the Atwater Pumpkin Lounge. An image of the set-up on the roof of AK can be seen in Figure 2 with the solar panel installation circled in red.

Figure 2: Location of Solar Panels of Roof of AK

The 2012 team proposed to install a panel display similar to the intentions of this Power Panel. The past team focused the majority of available time on establishing an effective method to collect energy from the panels and therefore was not able to develop a means for display. The project concentrated on developing a system to measure the output voltage and current accurately. This has been used to collect and make assessments of the output energy from the solar panel array.

2.1.3 Monitoring Energy Consumption on WPI Campus

In 2007, a group of IQP (Interactive Qualifying Project) students worked to increase awareness of energy consumption on the WPI campus (4). This team compiled information from energy monitors across the campus, which included gathering and analyzing the data. The team collected a significant amount of information which this Power Panel team will use to begin gathering data for display.

This team collected data from the meters by meeting with a member of the WPI staff from Plant Services. Reading of data from the meters occurred over 4 months and during this time frame, data from sixteen buildings was collected (4). The team also obtained the electric bills from WPI in order to understand electricity consumption for the campus. They analyzed this data and created a chart shown in Figure 3.

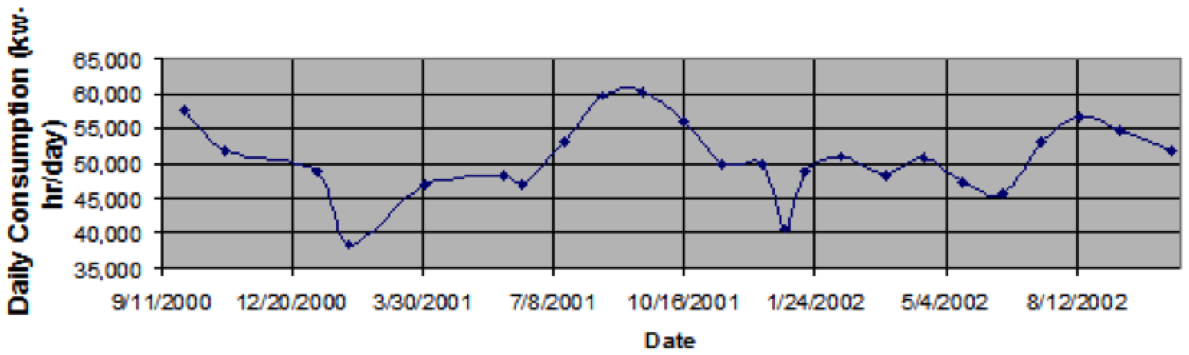


Figure 3: WPI Energy Consumption from September 2000 to September 2002 (4)

This team gathered information and measurements on the monitoring systems of each building and created a map of this information. On this map, shown in Figure 4, red buildings indicate meters which aren't working and green indicates meters which do. Meters shown in yellow are analog, blue meters are digital, and orange are both digital and analog.

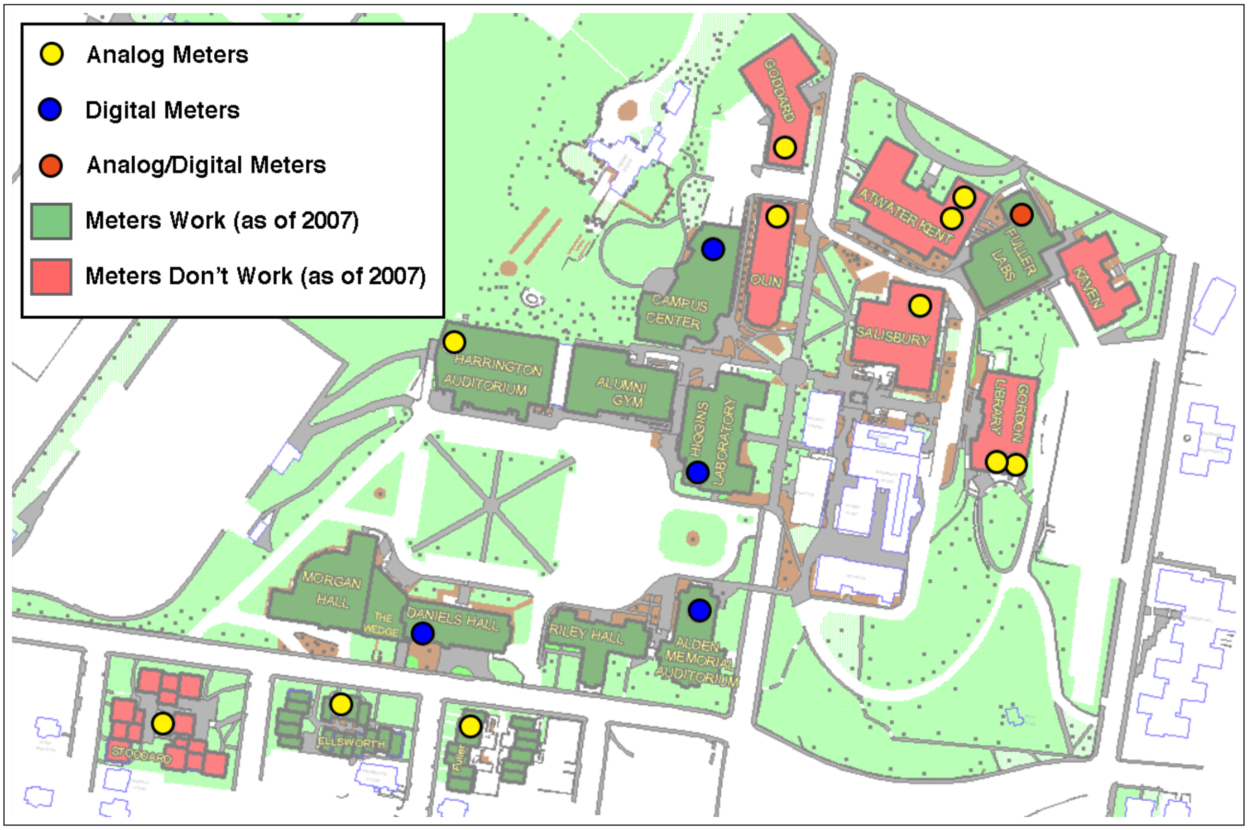


Figure 4: WPI Building Meters (4)

2.1.4 Grid Independent Solar Charging Display

In 2012, an MQP called the "Grid-Independent Charging Display" was developed to display the power flow of the AK solar panels into a wall mounted charging station (5). The primary goal of this project was to promote the use of green energy while also providing a useful device to the visitors of Atwater Kent. Figure 5 shows an image of their final design.

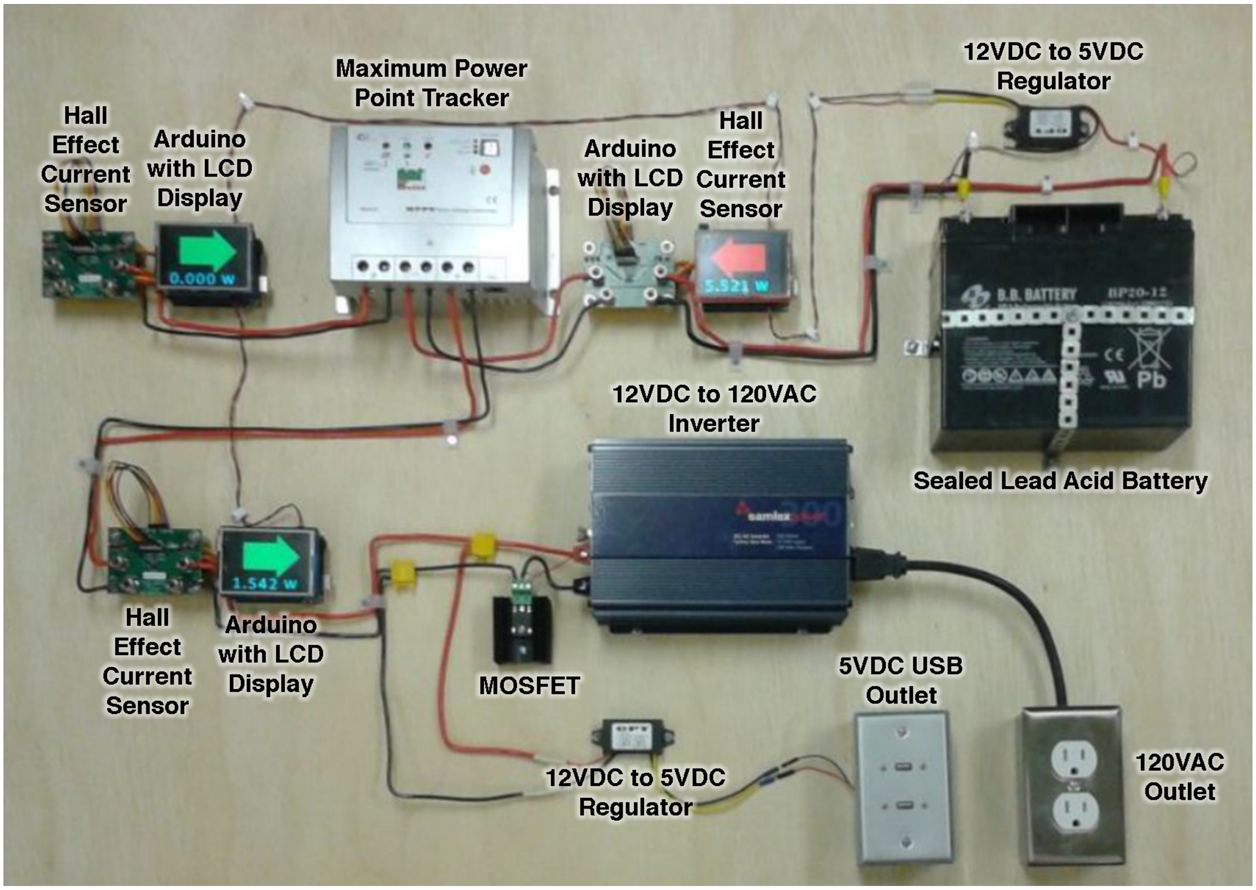


Figure 5: Grid Independent Solar Charging Display (5)

The project displays the power flow at three different points: the solar panel output, battery charging circuit input, and the load output. This was meant to give the user a logical understanding of how power flows from generation to consumption. By continuously displaying data through LCD screen modules, the team expected users to become more conscious about their energy usage and needs.

Instead of being installed in the Pumpkin Lounge, the project remained in the NECAMSID lab where it was occasionally used. It remained there for a number of years until an issue with one of its LCD displays arose and could not be easily fixed. Additionally, the previous MQP team came up with some improvements that they felt could be easily implemented into a future redesign. The team felt that one of the major concerns with the design was the limited amount of space for displaying text and images on the 2.8 inch LCD touch screens (5). Initially, they wanted to display the energy saved in terms of equivalencies such as kilowatt-hours saved, joules of energy from the sun, or amount of money saved. They recommended incorporating larger display screens at each point or relaying the information from the Arduinos via Ethernet to a TV panel in order to display more visually appealing images and text.

2.1.5 Color Dot Matrix Proof of Concept

One previous MQP that shared a similar project description was the "Color Dot Matrix Proof of Concept." A photo of their final product is shown in Figure 6.

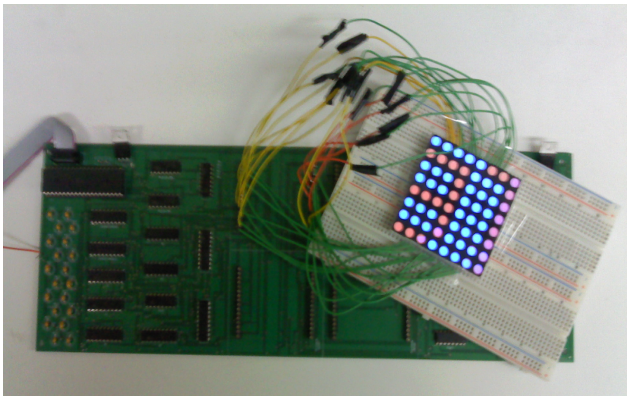


Figure 6: Dot Matrix Concept MQP Final Product (6)

The group's four major goals are quoted below:

1. Develop a functional display that will entertain and inform.
2. Allow for modularity and expansion.
3. Provide a means of reprogramming the display with updated information.
4. Keep power consumption within reasonable constraints. (6)

The Power Panel project goals are similar to the above four, making the thought process and final results of this previous MQP quite relevant. After considering two pre-built options, "Peggy 2" a prebuilt LED matrix with integrated display controller (7) and an interactive LED matrix that responds to hand movements (8), the group settled on modular design based around an eight LED wide by eight LED high matrix. Both pre-built options suffered from either limited expansion options or a low resolution. The standalone LED matrix option met higher resolution and expandability requirements, but needed a separate circuit to interpret text and display it on the matrix.

The group focused on the design of a circuit to drive the sixty-four-pixel display, as well as the software to output scrolling messages. Due to the complexity of this task, the final product was a single 2.37 square inch display that was able to scroll text messages across. Realizing the amount of time required to design and build a relatively small display from the component level, the Power Panel display will be built of pre-made components.

2.2 Prior Art

In addition to exploring past projects, research on LED art forms was also conducted. This section outlines all relevant research material used to better understand the design options presented. Overall, the research material provided inspiration for features and system design.

2.2.1 LED Panel Pixel Art

PIXEL develops hardware and software for 32x32 LED Matrix panels that focus on displaying pixelated artwork from pixel artists (9). They have developed numerous apps for Android, PCs, and Raspberry Pi's in an effort to inspire people to create and upload artwork for seamless display. The applications support images, GIFs (Graphics Interchange Format, commonly used to store a collection of video frames), memes (media that gains popularity through the internet), and short video clips. In addition to the LED Matrix Panels, PIXEL developed its own IOIO board that serves as an interface between the LED Panels, the microcontroller, and numerous sensors (9). This board features a slot for a microSD card, proximity sensors, a PIC Microcontroller, a Bluetooth dongle, and several general purpose input output (GPIO) ports for external interfaces. Figure 7 below shows examples of the artwork displayed through PIXEL's LED Matrix Panels.

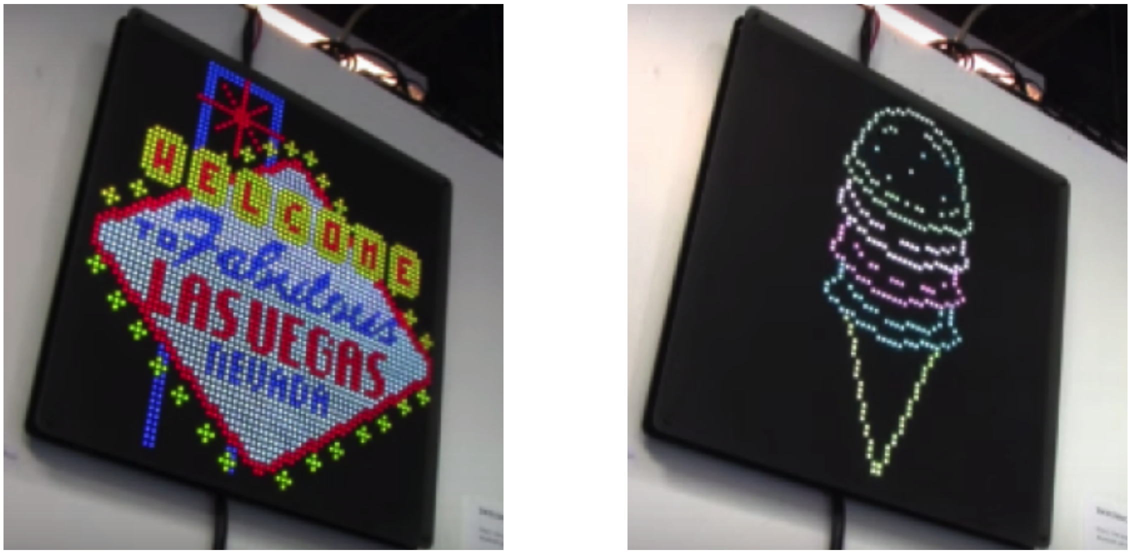


Figure 7: PIXEL Display Examples (9)

In addition to displaying artwork, the LED Panel can be programmed to respond to sensors and display texts, time, weather updates, and events. Currently, PIXEL only produces two sizes of their LED Matrix panels, an 8.5 inch by 8.5 inch version with 32x32 LEDS and a 16.5 inch by 16.5 inch version with 64x64 LEDS (9).

2.2.2 LED Cube

LED Matrix cubes have become a popular choice among hobbyists and designers in order to portray three dimensional images. The example shown in Figure 9 by Allen Productions is a 16x16x16 LED matrix cube that displays letters, images and patterns in a variety of colors. The LED Matrix cube shown in Figure 9 uses 4,096 LEDs. Allen Productions went on to expand this project by developing a much larger LED Matrix cube that uses 13,824 RGB LEDs (10). Some LED cubes are integrated with phone and computer applications for easy user interaction.

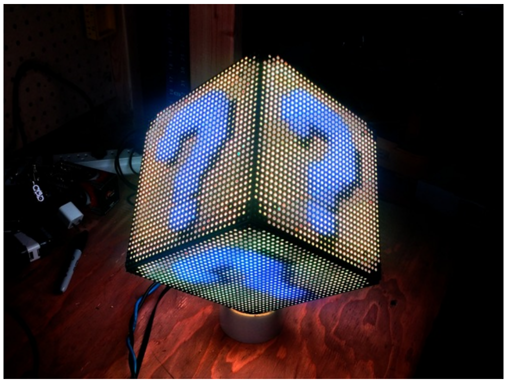


Figure 8: Adafruit: LED Panel Cube Example (11)

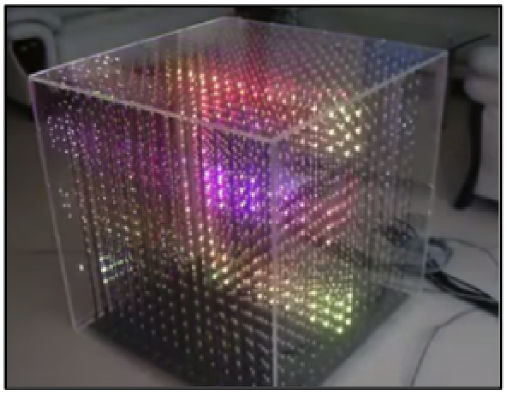


Figure 9: Allen Productions Cube Display (12)

In addition to LED Matrix cubes, Adafruit, an online distributor of electronics and breakout boards, developed an example project orienting six 32x32 RGB LED panels into a cube formation (11). The cube structure was not only used to display images such as the one shown in Figure 8 but also messages that could be viewed from any direction.

In order to drive these LED Panels, Adafruit incorporated LED Video Wall Controllers – explained in more detail in Section 4.2.2 – in order to mirror images and texts shown on a computer screen. This shows how LED Matrix Panels can be reoriented in order to achieve differently shaped and sized structures. Based on these examples, both groups took different approaches towards creating cube shaped LED projects. Allen Productions focused on creating a matrix display that allows for easy display of three-dimensional images, patterns, and text. This led to an interesting display characteristic, but depending on the spacing of the LEDs it became difficult to identify letters, shapes and texts displayed. Adafruit on the other hand, focused on reorienting the LED Matrix panels into a cube shape. By using the LED panels, Adafruit was able to display sharp images and text as a result of the higher pixel density.

2.2.3 LED Strings

Another way to achieve three-dimensional LED lighting effects is through LED strings. Makoto Tojiki uses this method in order to create three-dimensional LED sculptures such as the one shown in Figure 10.

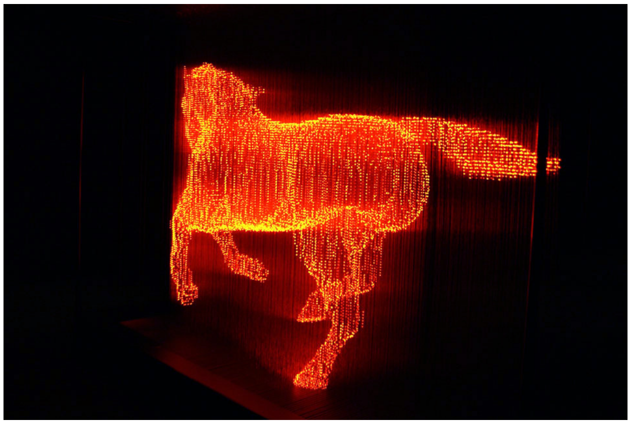


Figure 10: Makoto Tojiki LED Strings (13)

Unlike the Adafruit LED Cube, which focuses on reorienting the panels to achieve interesting forms, these LED String sculptures are made by carefully programming each LED to ensure accurate position, color, and brightness. Makoto Tojiki's portfolio shows that he primarily focuses on creating life-sized sculptures rather than animating messages or images.

2.2.4 Floor LED Matrix Panels

Scott Brusaw created a LED Solar Floor Panel (14) which embeds LED Matrices into solar panels to display information to users on the road. The information includes speed limits, upcoming road hazards, traffic updates, and can even rearrange sidewalks and roads according to the situations at hand. Figure 11 shows an image of Scott's Solar LED Panels.

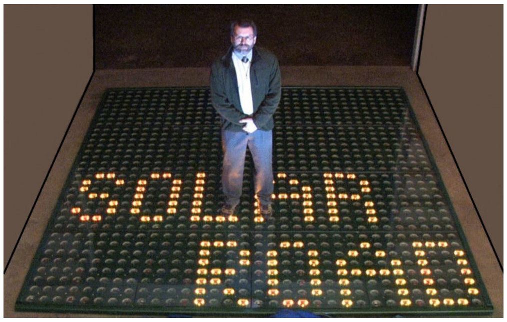


Figure 11: Solar Road (14)

Figure 12: Dance Floor LED Surface (15)

Another example of an interactive floor panel is a product produced by Mediatec. They develop large floor panels that display graphics, patterns, or images that react accordingly with weight sensors (15). These panels are 1.57 feet by 1.5 feet with 48x48 LEDs. Some of the highlighted features are high resolution, easy installation, scratch resistance surface, 120-degree viewing angles, and an automated address system. The company advertises its product as a dance floor for nightclubs, exhibitions, hotels, bars and operas. Figure 12 shows two panels side by side.

2.2.5 Water Light Graffiti

Another interesting example of an LED Matrix project is the Water Light Graffiti LED Panel, developed by Antonin Fourneau from Digitalarti Artlab (16). This panel is made up of a large matrix of LEDs which lights up when contacted with water. Users can throw or squirt water at the panel in order to make splash or graffiti art. Figure 13 shows an image of the panel.

Figure 13: Water Light Graffiti Panel (16)

Based on images and videos, the panel is approximately 4 feet by 10 feet and displays various degrees of white light. It must also have been designed with a touch or water-sensing panel atop the LEDs. There is no function towards displaying images or messages to the screen via texting, or Bluetooth as in some of the other prior art reviewed.

2.3 Design Options

While considering implementing a display in the Atwater Kent Pumpkin Lounge, much consideration was given to building a practical, multifunctional system. This section explores each design option, including multiple LED panel systems, LCD displays, LED artwork, and other options. A value analysis was conducted to determine the best system for product development and is included below, although explained further in Section 2.3.5.

Idea	LED Wall Panels with Sensor on Wall	LED Wall Panels with Sensor on Floor	LCD Screen	Mock Wind Turbine	LED Strings	LED Matrix Cube with Sensors	LCD Projector	LED Floor Panels with Sensors on Floor	LED Sculpture
Visibility (5)	3	3	3	2	2	1	1	2	1
Feasibility (4)	3	2	3	3	2	2	3	0	1
Interactivity (3)	3	3	1	1	2	3	1	3	2
Cost (2)	1	1	2	3	2	2	2	0	0
Creativity (1)	2	2	0	2	2	3	0	3	3
TOTAL	40 90%	36 80%	34 76%	33 73%	30 67%	29 64%	24 53%	22 49%	18 40%

Table 2: Design Ideas Value Analysis

2.3.1 LED Panels

Adding LED panels to the AK Pumpkin Lounge brings up multiple possible design options. In order for the design to be interactive, multiple systems have been explored. LED panels could be displayed on the wall with controls on the wall. Another option explored with regard to LED panels contains both the sensors and the panels on the floor. The final option includes having LED panels on the wall with interactive sensors on the floor.

The first option, both LED panels and sensors on the wall, would provide for easy set-up and a low chance of damage. Panels will have a long life with less abrasive interaction than other options may provide. With panels mounted on the wall, they will often be easily visible and not obstructed by foot traffic. This would provide a great location for displaying important messages even while many people are passing by the panels. With less protection issues than other design idea options, the panels would be less costly. Although the wall panels have many advantages, there are disadvantageous points as well. Wall mounted displays aren't as unique as some other options. The panels could be easier to walk by without noticing, depending on what they're displaying. There are some implementation issues that arise with panels on the wall. The panels would have to be located in a place where they can be easily seen, but also a location where they will not obstruct traffic. The wall mounting itself would be important, as there would need to be access to the internal components if any necessary hardware modifications need to be made.

The second LED panel design option includes having both the sensors and display mounted to the floor. This adds much potential for interaction with the display as the user could directly step on the display rather than relating their position on the floor to a display on the wall. This full floor integration is also more novel and eye-catching than other options. Although the installation could potentially draw more attention than a wall mounted display, there are many implementation issues with this idea. Making the display flush with the floor would require significant renovation to the building structure. Such a change would probably be permanent, thereby making access to the display difficult. A floor-mounted option would also need to be incredibly durable to withstand the wear of people and equipment traveling over the surface daily. In winter months, pedestrians track in snow from outside which would then be deposited on the surface of the panels, making waterproofing an important factor in the longevity of such a display. In addition to these concerns, the placement of a display on the floor can easily be obscured by foot traffic as well, causing anyone using the display to obstruct traffic depending on the location of the display.

The final option includes LED panels on the wall with touch sensors for interaction on the floor. This overall system would be simpler to design and to maintain than one with the entire system on the floor. Though there are many advantages of having touch sensors on the floor, disadvantages still arise. This design is invasive to the floor and would need to meet many requirements similar to having both the panels and sensors on the floor. Although only the sensors would need to withstand high forces and have waterproof properties, this still limits design options. The sensors, once integrated into the floor, would be difficult to access for updates and repairs. It would also be necessary to find an appropriate location including wall mounting for the LED display.

2.3.2 LCD Display

Some alternative forms of wall-based displays are LCD screens or LCD projectors. Due to the physical similarities between LED matrix panels and LCD screens, it is expected that they share the same implementation pros and cons. An LCD display would be a lot simpler as it is a self-contained unit that uses standard video-in formats. On the other hand, a large LED Matrix display may require numerous panels, an external video controller, a power supply, and other components. Despite the ease of integrating and outputting video to a premade LCD screen, this method of displaying information on a wall is the most common, and therefore would be much less interesting to the passerby. Another form of LCD technology, LCD projection, could be used as well. The LCD projector would share many of the benefits of an LCD screen, such as standard video input and as a self-contained system. It would also be simple to scale the size of the display to the space, as well as reposition the display by rotating or moving the projector. However, there are some inherent downsides to projected displays. In order to be visible in a well-lit environment, the projector would have to be especially bright, adding to the cost of the unit. Also, the display could easily be obstructed by people walking by, depending on the location of the projector and the image being displayed. This would provide limited interaction and visibility during high traffic times, resulting in hindered use of the system.

2.3.3 LED Artwork

Aside from using flat panels in order to display information, the team explored a variety of other unconventional ideas that could be implemented for this project. One idea was to reorient and reshape numerous LED panels, which would then be pieced together in order to form an LED panel sculpture. This could be used to display images, optical illusions, messages, or lighting patterns associated with power from the solar panels. Figure 14 below shows a preliminary concept sketch that the team developed while brainstorming.

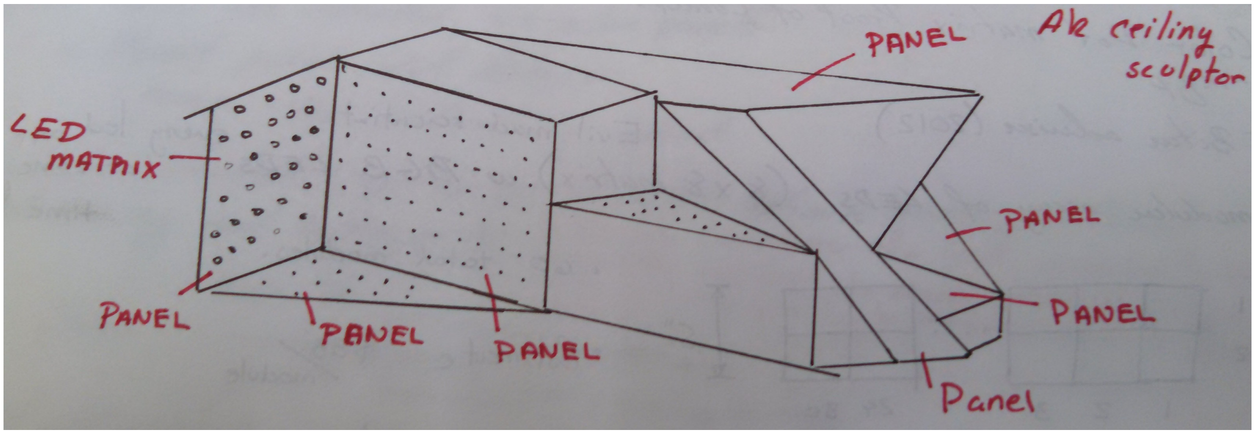


Figure 14: LED Panel Sculpture

After conducting research related to this subject, as expressed in Section 2.2.2, it is evident that sculptures in the form of cubes are popular. By following this example, the team could develop a panel sculpture that follows the same principles, but offers a unique, creative, and visually appealing structure. One of the major drawbacks of this idea is its limited potential for user interaction due to placement. As sculptures can take up a large amount of physical space, hanging from the ceiling or sitting on the side of the room becomes ideal. This location would minimize disturbances in traffic flow while maintaining consistent visibility at all angles. As a result, it may be hard for users to interact with the installation depending on the placement. In addition, it may also be difficult to purchase off-the-shelf LED matrix panels that come in different shapes other than rectangles or squares. This will require the development of new LED panels or modification of purchased panels, which could involve complex manufacturing techniques.

An alternative to the LED panel sculpture is a set of LED matrices organized into a cube as shown in Figure 8 in Section 2.2.2. This option would enable the development of three-dimensional images and messages through carefully indexed programming. The team would improve upon this design by developing a system that takes user interaction, via touch or infrared sensors, and responds through lighting patterns, messages, or games. Unlike the LED sculpture which would most likely have to be installed in a single orientation, the cubic structure has the potential to be placed on the floor, ceiling or wall. One drawback regarding this idea is limited display functionality. Given its size and the number of LEDs, messages would be difficult to read. Limitations on the amount of information that could be displayed at a given time due to its low resolution would be encountered.

A similar idea to the LED cube idea is to chain together a series of LEDs and hang them from the ceiling. This can be seen in Figure 10 of Section 2.2.3 LED Strings. After having reviewed many art pieces, the team determined that appropriate locations for this idea are the empty window frames in between the Pumpkin Lounge and the front hallway. These locations would enable users to view the sculpture or message from both sides of the wall. This idea would function very similarly to the LED matrix cube except that instead of a matrix, it would use a series of LED strings to achieve similar effects. One key challenge that could be faced with this idea is incorporating user interaction due to the string's susceptibility to damage or entanglement if misused. A solution includes encasing the sculpture and embedding it with touch sensors. This may not be the most ideal for displaying messages or information for similar reasons discussed with the LED matrix cube.

2.3.4 Other Display Forms

An interactive display explored was the inclusion of a mock wind turbine. This small-scale turbine located in the Pumpkin Lounge would spin at the same revolutions-per-minute of the wind turbine atop Atwater Kent or of the wind speed used to determine the WPI fountain height. LEDs could be added to the blades in order to show more information such as speed and power output using persistence of vision. Depending on which wind speed is used, whether the wind turbine on top of Atwater Kent or the wind speed from the fountain, the mock wind turbine could be impressive or unsatisfactory. This is an important feature to consider while designing. The idea of a display in the Atwater Kent lounge is to have interesting information for current students, prospective students, faculty, and visitors to use. In each design option, consideration is given to those which provide the most useful information to users.

2.3.5 Design Ideas Value Analysis

With multiple design ideas for implementation, it became apparent that an objective method of ranking each idea was required. The team developed a set of criteria. Each criterion – visibility, feasibility, interactivity, cost, and creativity – was defined by the group and given a value on a scale from 0 to 3, with 3 being the most desired.

Each of the criterion was weighted in order to effectively show the importance to the overall implementation. Visibility had the highest weighting because it was most important that users would be able to read the information delivered by the display. Next was feasibility, as it is crucial that a project with the correct scope and time frame was chosen in order to complete in the allotted time. Interactivity was the third most heavily weighted. In order for this system to be considered successful, it will be necessary to create something that is used by many individuals. By promoting interactive features, the system will provide more than simply a display. The next criterion was cost. While cost is important, the design should not be limited by this as the team is able to source additional funding from multiple grants available. Finally, although creativity was initially high on the list of importance, it had the least amount of weighting factor. This is due to the fact that the system itself didn't necessarily have to be creative, but rather the information it displays and functions it holds should be.

Though the process of value analysis is subjective, this was mitigated by including the opinions of all three team members in the discussion through reaching a consensus. The outcomes of the value analysis are shown in Table 2. The ranking and descriptions of how values were assigned is provided in Appendix A.

2.4 Initial Proposed System

The value analysis led to the development of an LED display panel mounted to the wall of the AK Pumpkin Lounge. The display would have an interactive feature which would also be mounted to the wall. A model of the proposed design was created in SolidWorks and can be seen in Figure 15. This shows the initial proposed system and location – between the AK 113 lab window and the whiteboards – as well as a sample of the four-screen display functionality. This model also included capacitive touch buttons below the display as the user interaction feature, which will be discussed in Section 4.4 Hardware User Controls.

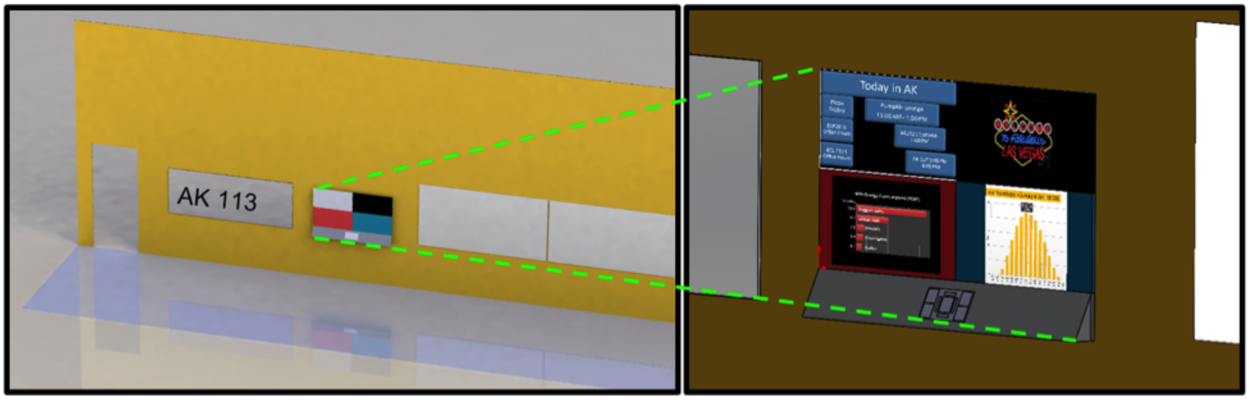


Figure 15: Initial Proposed Power Panel Display Model

After proposing the initial system design shown in Figure 15, it was clear that there were multiple ways to enhance the design. Though the display would be comprised of 36 LED matrices for a combined size of approximately 5 feet by 2.5 feet, the Panel did not make use of the large amount of space in the Pumpkin Lounge. By adding more displays, the Panel could make a larger impact on generating interest from students and visitors in the lounge. With an increased budget, the possibility to expand to include more display panels became apparent and was added in the final project decision section of this report.

3 Final Project Decisions

In order to take advantage of the space in the Atwater Kent Pumpkin Lounge, a slight redesign and expansion to the initial design was proposed. This redesign includes the addition of more panels that bridge across two sections of the lounge, while maintaining a PCB inspired layout. Figure 16 below shows an image of the redesigned system, where the initial 5 feet by 2.5 feet Main Display is kept, however adds several Children Panels, a Horizontal Ticker, and a Vertical Ticker.

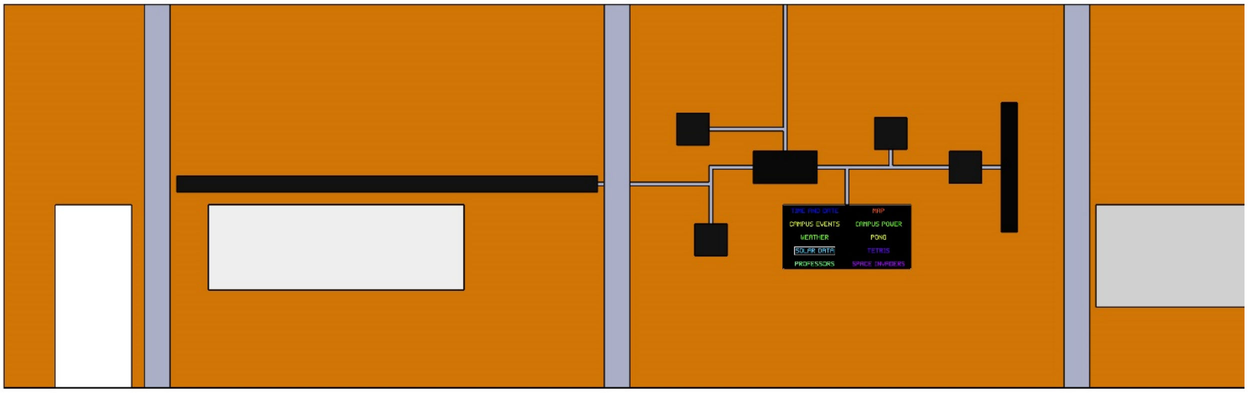


Figure 16: Final Power Panel Display Model

In addition to changes to the overall panel layout, the capacitive touch sensor's location was also reconsidered. The capacitive touch sensor was originally proposed and centered below the Panel. This would allow users the opportunity to select information for display. In order to use the capacitive touch controls, the user would need to be standing directly in front of the Panel, which may make it difficult to see the entire display. Thus, it was noted while expanding the Panel that the most convenient location to place the controls was towards the inside of a door frame between the hallway and the lounge.

The final major decision in this initial proposed system design was the display arrangement. The original idea was to have four quadrants of the Panel, each of which would display the object selected by the user. As testing began with LED matrices and software used for the graphics, it became clear quickly that each of the quadrants would be too small to provide useful information. The quadrant concept was reconsidered along with the overall system design and capacitive touch setup in order to come to the final project decision.

3.1 Features

In choosing the LED display and interactive features both mounted to the wall, a set of potential features was narrowed down. The first set of display items includes those related to the solar panels located on the roof of AK. Measurements including the power generated from the solar panels will be displayed throughout the course of the day. Along with this, historical trend data on building energy consumption will be shown. These energy statistics will bring awareness to consumption and generation by AK and the WPI campus in general.

The second most prominent use of the Power Panel is to provide information to students and visitors of AK. While brainstorming possible content to display on the LED display, the aim is to include information that would give students in Atwater Kent incentive to visit the display. For students, the Panel will display campus events extracted from the Student Activities Organization's calendar. The Power Panel is designed to be useful for students on a day-to-day basis. For visitors, the panel will be an attraction. Prospective students will obtain a greater understanding of the capabilities of the renewable energy related project work of the ECE department at WPI. The Panel's map functionality will help guide visitors to rooms during special events and open houses.

The final function of the Power Panel includes bringing creativity to the Pumpkin Lounge. Games such as Pong will increase the use of the interactive features. Animations, GIFs, or memes will be displayed. Interesting and fun facts will be incorporated for display in addition to clocks and countdowns to events such as graduation, the end of terms, and special events.

3.2 Block Diagram

The overall system design for the Power Panel has been developed and the block diagram can be seen in Figure 17. The system utilizes the previous MQP, Grid Independent Charging Display, in order to receive power generated from the solar panels. The voltage and current sensors from the past MQP serve as input to the computer module of the system to display solar panel statistics and data. The user is able to navigate the system through the capacitive touch sensor that will be directly inputted into the computer module. The computer module outputs to an LED display sending card which communicates with the LED display receiving card. The receiving cards connect to the LED matrix panels in order to mirror the screens displayed on the computer module. The computer module is powered through an external power supply.

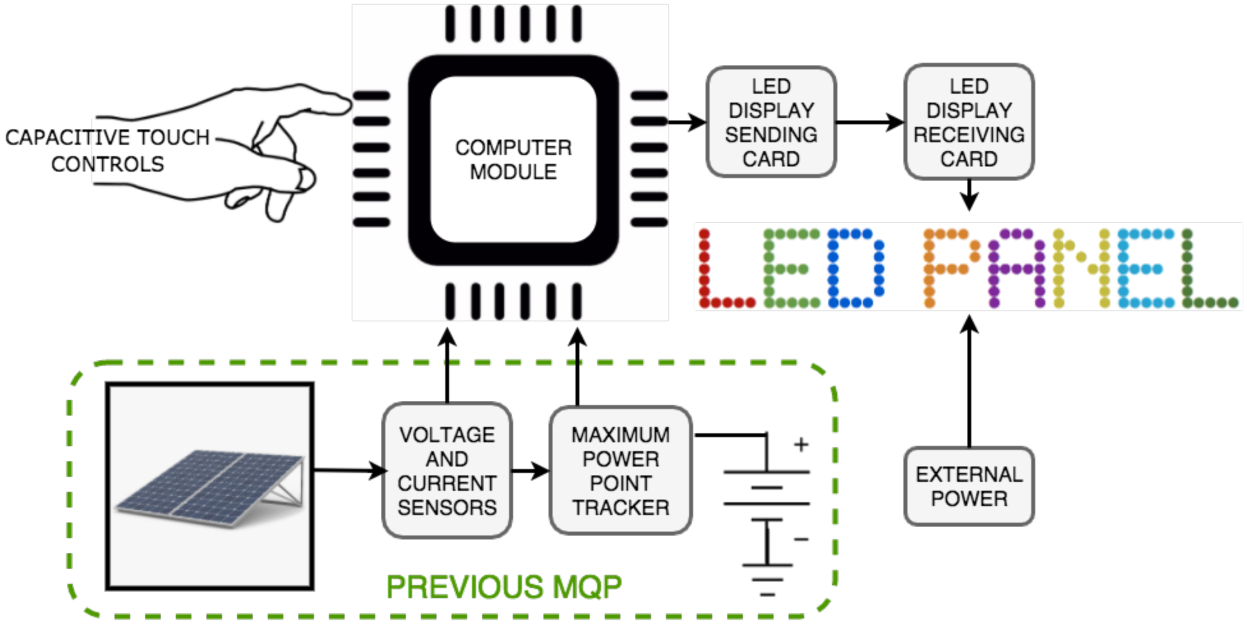


Figure 17: System Block Diagram

3.3 Design Requirements

Once an appropriate design was decided upon, design requirements were established. Based on discussion between the team members as well as the advisors, the following design requirements were defined:

- Flat panel design for easy mounting and installation
- Clear visibility for text and images

- Capacitive touch sensor control
- Intuitive menu navigation
- Display power generation from the solar panels
- Display energy usage data from historical data

Based on these design requirements, the team investigated and identified numerous components that would achieve the required functionality.The component selection and testing is discussed in Section 4.

4 Component Research

This section discusses the research completed on various components necessary to complete the implementation of the Power Panel in the Atwater Kent Pumpkin Lounge. Various types of LED Matrices and Display Controllers are considered to optimize user viewing experience. Multiple microcontrollers were compared to find the best solution for the Panel. Different solutions for interactive user controls are discussed. Components for power and wiring are explored in this section in order to move forward with design plans in future sections.

In addition to the physical system components researched, there was also exploration of software systems that would provide the proper environment for features desired for display. A few peripheral data sources were also researched, to narrow down options for providing a variety of information to the user.

4.1 Selection of LED Matrix

There are various LED panel configurations for purchase on the market today. It was decided that in order to spend maximum time and effort on overall capabilities of the Power Panel, LED panels would be purchased and configured, rather than building custom LED matrices.

First, an appropriate size LED matrix was decided upon. The 64x32 LED Matrix was most fitting for this application. This size matrix was available from multiple vendors and the cost was acceptable as compared to the size. In choosing the 64x32 LED Matrix, another option worth noting was the decision of the pixel pitch. Pitch is defined as the "distance from the center of an LED cluster to the center of the next LED cluster," (17) which relates to the display resolution. The 64x32 LED Matrix had options with 3, 4, 5, and 6 mm pitches. Pixel pitch is important for this application because the user should not strain their eyes to see the Power Panel.

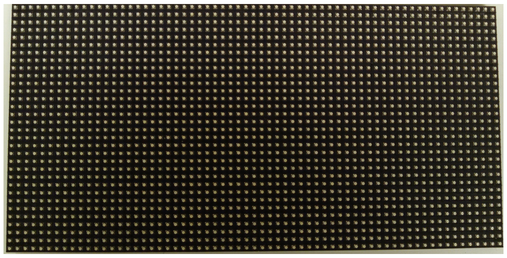


Figure 18: Front of 6 mm pitch LED panel

Figure 19: Back of 6 mm pitch LED panel

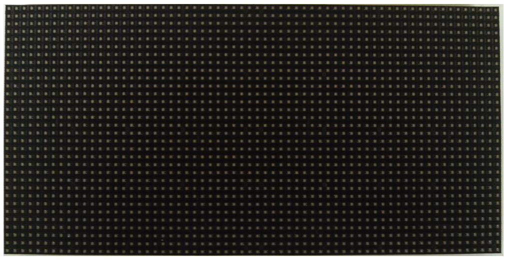


Figure 20: Front of 4 mm pitch LED panel

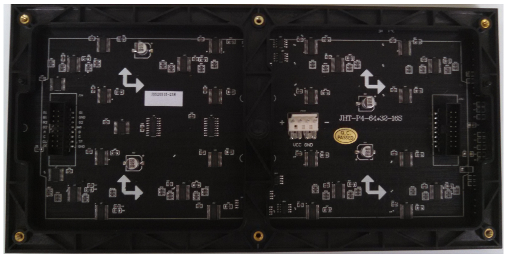


Figure 21: Back of 4 mm pitch LED panel

For the Power Panel, it was important to investigate the final display resolution when all individual LED panels were mounted together. One of the vendors selling the 64x32 pixel LED matrices, Adafruit, had images on their website of the panels in each of the pitch sizes which they sell. Of course, the smallest pitch size, 3 mm, produces the best pixel density and would be most ideal. However, it was necessary to weigh the benefits of the higher pixel density with final size of the display. A smaller pixel pitch may be easier to read but also results in a smaller overall display. In order to find the largest pitch size that would be acceptable for this application, the images from the website were displayed on an LCD monitor. Each of the different pitch types were considered at their actual size. This was an efficient way to compare resolutions without having the LED Matrices in hand.

Originally the Power Panel design included only a single Main Display, but as discussed in Section 3, additional children and ticker displays were added to the design. These Auxiliary Displays are to be installed higher up on the wall than the Main Display, and their purpose is to fill up the wall space more than display large amounts of information. Because of the differing requirement between the Main and Auxiliary Displays, the appropriate pixel pitch for each type was considered separately. After comparing pitch size, the 4 mm pitch was determined to be most acceptable for the Main Display. Though the 3 mm pitch has a higher resolution, this was not deemed necessary for the Main Display, as the 4 mm pitch was easy enough to read. The 5 mm pitch did not provide enough clarity that was needed considering the distance a user would view the display at. Additionally, the 5 mm pitch was the same price as the 4 mm pitch; therefore, purchase of the higher pixel density 4 mm pitch LED matrices was most logical. The 4 mm pitch size is described as having a 160-degree viewing angle and being acceptable for use indoors (18). Overall, as a result of the close proximity of the user to the display due to the shape of the Atwater Kent Pumpkin Lounge, a panel with an appropriate viewing angle and viewing distance was needed. With testing and the descriptions from the website, the 4 mm pitch fit for this application. The optimal pixel pitch was also determined for the auxiliary displays as well. Since quantity of information displayed was not as important of a factor, but large size was, the 6 mm pitch size was chosen for the auxiliary displays. The longer viewing distance for the auxiliary displays made readability of the lower pixel density 6 mm panels possible.

After determining which LED Matrix would be purchased, the overall size of the each of the displays was considered.

4.1.1 Main Display

Each LED Matrix used in the Main Display is 10 inches wide by 5 inches high by 0.6 inches thick (18). Due to the large amount of information required to for display on the Main Display, an adequate resolution was necessary while still keeping the cost reasonable. A grid of 36 LED matrices configured with 6 rows and 6 columns was decided upon. The Power Panel Main Display is 60 inches in width by 30 inches in height. With each panel having a resolution of 64 pixels wide by 32 pixels high, 36 panels will result in 384 pixels wide by 192 pixels high. Assuming ASCII characters that are 6 pixels wide by 8 pixels high , the Main Display allows for 64 characters across, with 24 lines vertically. If an average word length of 6 characters is assumed, including spaces, the Panel can display 256 words total. The cost of this array is $1080 at a cost of $30 per panel. This cost comes from a second distributor (19) with more economical pricing than Adafruit (18).

4.1.2 Horizontal Ticker

Each LED Matrix used in the Horizontal Ticker is 15.2 inches wide by 7.5 inches high by 0.6 inches thick (20). The Horizontal Ticker serves as a medium for displaying current event information. This Horizontal Ticker was designed as 12 panels long by 1 panel high. This size was decided upon based on the length of the first section of the Pumpkin Lounge above the window of the AK113 lab. The dimensions of the Horizontal Ticker are 182.4 inches wide by 7.5 inches high. As a result of each panel having a resolution of 64 pixels wide by 32 pixels high, the Horizontal Ticker has a total resolution of 768 pixels wide by 32 pixels high. The total cost of the Horizontal Display is $360 as each panel costs $30. The panels were purchased from distributor LED Control Card (20).

4.1.3 Vertical Ticker

Each LED Matrix used in the Horizontal Ticker is 15.2 inches wide by 7.5 inches high by 0.6 inches thick (20). The Vertical Ticker serves as a display medium for countdowns and can be modified to include other information in the future as well. The Vertical Ticker is designed as 1 panel wide by 4 panels high with overall dimensions of 7.5 inches wide by 60.8 inches high. The ticker will overall have a resolution of 32 pixels wide by 256 pixels high. The total cost of the Vertical Ticker is $120 as each panel costs $30 through the distributor, LED Control Card (20).

4.1.4 Children Displays

Each Child Display is comprised of LED Matrices which are 15.2 inches wide by 7.5 inches high by 0.6 inches thick (20). The Children Panels serve as additional displays to extend the Power Panel across the Pumpkin Lounge wall. In order that the display look aesthetically pleasing, different size Children Displays were created. There are 4 small Children Displays which are 15.2 inches wide by 15 inches high, or 64 pixels wide by 64 pixels high. The one larger Child display is 30.4 inches wide by 64 inches high, or 128 pixels by 64 pixels. In total, the Children Displays consist of 12 panels at a cost of $30 for each panel (20).

4.2 LED Display Controller

After deciding on the ideal display medium in Section 4.1 above, a method of controlling the array of LED matrices was required. The following criteria were developed:

- Cost - The price of the complete controller system. Since the controller is a part of the larger overall design, the cost needed to be low relative to the total budget.
- Scalability - How easy it is to increase the size of the display or the number of individual panels. During selection of the display controller, final size and shape of the display had not yet been determined. A format was needed that would allow for addition or removal of LED panels without significant reprogramming or rewiring.
- Complexity - The time required to have a functioning display. Since the LED display is a critical part of the project, a functioning display is needed as soon as possible. This is in order to eliminate risk and move on to other hardware components, as well as software and GUI programming.
- Interface - The method used for communication between the display and the video source. The interface to the video source plays an important role in the selection of the central processing unit itself. A more standardized video connection allows a larger range of computer types that can be used as well as simplifying the communication protocol as well.

While a custom solution is certainly possible, pre-built components dramatically reduce design and implementation time for this module. Two distinct options were clear. One method involved using a microcontroller or an embedded Linux based single-board computer (SBC) to drive the LED matrices. The other option was the LED Video Wall Controller, a pre-built and pre-programmed pair of modules in the form of a sending card and receiving card. The two options are discussed in detail in the following sections.

4.2.1 Microcontroller or Embedded Linux SBC

The availability of relatively inexpensive (under $100) microcontrollers and embedded SBC's in recent years has spurred an influx of do-it-yourself (DIY) communities in the electronics field. These communities have extensively explored the capabilities of these platforms, the most popular of which include the Arduino, Raspberry Pi and BeagleBone. During research of the LED panels, several hobbyist projects using one of the three above options to drive one or more LED matrix panels were found (6; 21; 22; 23). The low cost of these boards was attractive, with the Arduino Uno, Raspberry Pi Model B, and BeagleBone Black costing $30, $35, and $55 respectively (24). However, these boards are not dedicated LED display controllers, so their flexibility comes at a cost of development. For all of the platforms, custom code is required to both draw to the LEDs and provide an interface between the image or video to be displayed and the display itself. Writing custom code is certainly possible, but given the scale of the rest of the project, is not ideal.

One important feature of the LED display controller is the ability to add additional LED panels to increase the size of the full display. The Arduino platform uses microcontrollers running at relatively low clock speeds, either 8MHz or 16MHz (25). The low clock speed, in comparison to the high processing demand of even a single 64 by 32 pixel LED matrix, severely limits the total size of the display. Although the LED panels chosen can be linked together, an Arduino would not be able to drive more than a few panels. Higher power devices such as the Raspberry Pi and BeagleBone would be better in this regard. The clock speed of the Raspberry Pi Model B (700MHz) and the BeagleBone Black (1GHz) allow for more LED panels to be connected together and driven, but are still not capable of the large array of LEDs desired for this project (25; 26). Although these microcontrollers are not suitable for driving large arrays of LEDs efficiently, they are ideal the main controller for the panel software and peripherals.

4.2.2 LED Video Wall Controller

When researching the choice of LED matrices, the particular style of LED panels chosen was similar to those used in large format electronic billboards. The significant use of these LED panels in the commercial industry prompted the question of what controller was used to drive them. On the Adafruit website, the distributor where the LED panels were first found, an "LED Video Wall Controller" (27) was found as seen in Figure 22 below.

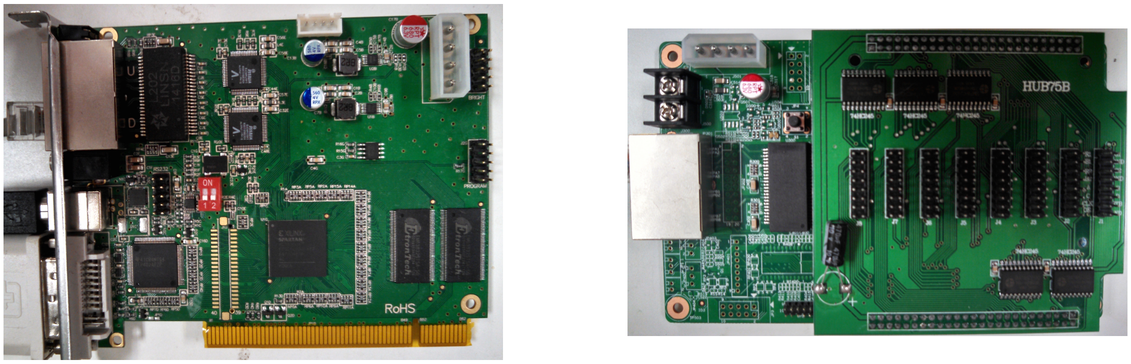


Figure 22: LED Display Sending (left) and Receiving (right) cards

The LED Video Wall Controller takes a DVI (Digital Visual Interface) video input on the sending card, decodes it, and sends the video data via Ethernet to the receiving card. The receiving card then provides breakout connectors for up to 8 rows of panels, each up to 1280 pixels long (27). Although the component on the Adafuit website did not have a part number, using the close-up images provided, the team found that the package was composed of one TS802D sending card, one RV908 receiving card, and one HUB75B breakout board. The boards do not have a specific manufacturer, and because of this there is limited documentation on the operation. The only user documentation that could be found was a guide to the software used to configure the boards (27).

Despite the relatively high cost of $300 for the sending and receiving card combined, this option was used for several reasons. The system can be connected to either one panel or up to 160 64x32 pixel LED panels for a maximum 1280x256 resolution. Additional receiving cards can be chained together to take full advantage of the sending card's maximum resolution of 1280x1024. All that is required to configure the additional panels is to change the panels' layout in the provided free configuration software. The system is simple to use, with no coding or external circuits required. Finally, the system uses a widely accepted video standard, DVI. DVI is directly compatible with HDMI and Display Port allowing nearly any source to send video to the display (28).

With the addition of the Children Displays, Horizontal Ticker, and Vertical Ticker, the decision to purchase and implement an additional receiving card became necessary. Overall, simplicity with regard to installation was gained by adding this receiving card. To keep the overall layout, wiring, and software organized, one receiving card was used for the Main Display. The second receiving card was used for all of the Auxiliary Displays. The receiving card connected to the Main Display will use a resolution of 384 pixels wide by 192 pixels high. The receiving card connected to the Auxiliary Displays will utilize a resolution of 832 pixels wide by 224 pixels high. Each receiving card has space to add more display panels if desired in the future.

4.3 Microcontroller Selection

It is important to select an appropriate microcontroller or computer module that will easily integrate with the LED Matrix panels, LED Wall Controller, and capacitive touch user interface. Based on these components, a set of requirements for selecting a microcontroller or computer module was developed.

Computer Module Requirements:

- At least 16 MHz processing power
- At least 10 digital I/O pins for user interaction
- Internet compatibility
- Analog to digital converters for measuring current and voltage of solar panel
- HDMI or DVI video output for wall controller compatibility
- Adequate operating system for graphic signal output
- Sufficient memory (RAM, Flash, SD expandable)

4.3.1 Arduino Development Board

In recent years, the Atmega 328P microprocessor has been a popular choice among hobbyists in electronics for its easy to use Interactive Development Environment (IDE), expansive support community, and numerous accessories. For these reasons, it was expected that an Arduino play an active component in the design of the Power Panel system. Unfortunately, the Arduino lacks sufficient processing power, Internet capabilities, and a video output (24). There are numerous Arduino "shields" that could provide this functionality but it was more beneficial to determine another option that could provide all these features in a single package. Despite that an Arduino was not used for interfacing with the LED Video Wall Controller, it was used for collecting data from the current and voltage sensor of the solar panel.

4.3.2 Raspberry Pi

The Raspberry Pi (RPi) is a relatively well-known single-board computer that can run the Linux operating system. It satisfies many of the system requirements such as its 700MHz processor, Ethernet compatibility, and an HDMI output. The major drawback behind the RPi is its lack of any analog to digital converters as well as its limited number of general purpose input/output (GPIO) pins (24). A solution to this drawback is to use the RPi in conjunction with an Arduino. This could be accomplished through programming the Arduino from the RPi directly, thus any data that is collected through the Arduino would relay to the RPi.

Rather than collecting data via the Arduino and then relaying the data back to the RPi, it would be cheaper and more straightforward to use the JeeLabs Analog Plug. This breakout board can take up to four Analog input signals and then using the MCP4324 Analog to Digital converter pin, outputs binary values through the I2C connection (29). This would provide the required functionality for this project, but may hinder future projects because of the continued limitation of GPIO and Analog input pins available from the RPi and JeeLabs breakout board.

4.3.3 BeagleBone Black

Another potential option that was considered was the Beaglebone Black (BBB). An image of the board is shown below in Figure 23.

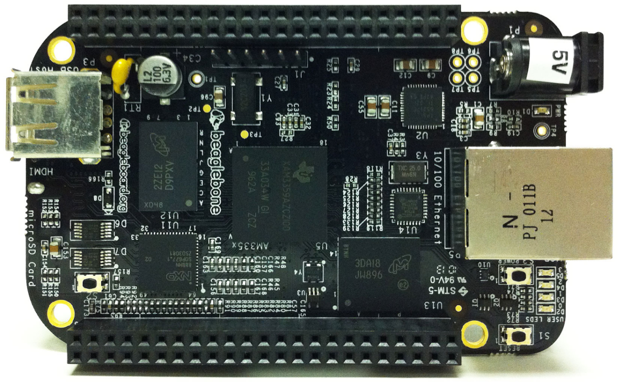


Figure 23: BeagleBone Black Compact Linux Computer (24)

The BBB features an ARM Cortex A8 32-Bit RISC Microprocessor from Texas Instruments that is capable of running the Linux operating system. The BBB makes it easy to interface with external sensors, hardware, and breadboards through its 65 GPIO pins and 7 analog input pins. Compared with the Arduino, it runs at a faster clock speed, 1GHz versus 16MHz, and has easy accessibility to the Internet via Ethernet or a Wi-Fi dongle. In addition to this, the on board HDMI connects directly to TV's and monitors, which will make it easy to install software, write programming, and collect data within one compact unit (24). Based on this information, the team considered using the BBB as the computer module.

4.3.4 ODRIOD XU4

The final computer module under consideration was the ODROID XU4, which runs a Cortex A-15 Processor with a clock speed of 2GHz. The ODROID XU4 shares many similar features to the other considered options such as running Linux OS, GPIO and analog pins, in addition to an HDMI video output. It also runs a more developed version of the Ubuntu OS allowing for simple installation of programs such as Processing and minimize the amount of time spent on editing the operation system's settings to allow for dependable installation. From all the considered options, the ODROID XU4 has the highest clock speed enabling it to run Processing very smoothly compared to some of the other options. As a result of its higher clock speed and an increased power consumption, a small fan is required to cool the system during intense heat dissipation.

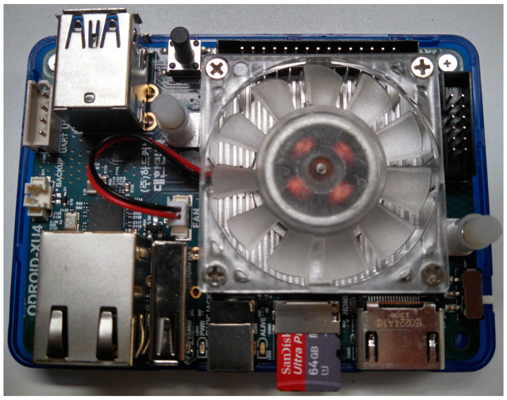


Figure 24: ODROID XU4

Table 3 compares various technical specifications of the Arduino, Raspberry Pi, Beaglebone Black, and ODROID XU4. From this comparison table, it is evident that the ODROID XU4 can provide the necessary processing, hardware integration capabilities, and Internet connectivity, due to its superior hardware and software specifications.

Name	Arduino	Raspberry Pi	BeagleBone	ODRIOD
Model Tested	Uno R3	Model B	Rev C	XU4
Price	$30	$35	$55	$74
Size	2.95” x 2.1”	3.37” x 2.125”	3.4” x 2.1”	3.22” x 2.28”
Processor	ATMega 328	ARM 11	ARM Cortex A8	Cortex-A15
Clock Speed	16MHz	700MHz	1GHz	2GHz
RAM	2kB	256kB	256kB	2GB
Flash Memory	32kB	(Micro SD Card)	4GB (Micro SD Card)	(Micro SD Card)
Operating Voltage	7-12V	5V	5V	5V
Minimum Power	42mA (0.3W)	700mA (3.5W)	170mA (.85W)	4A (20W)
Digital GPIO	14	8	66	40
Analog Inputs	6 10-bit	N/A	7 12-bit	10-bit
PWM Pins	6	N/A	8	N/A
TWI/I2C Pins	2	1	2	1
SPI Pins	1	1	1	1
UART Pins	1	1	5	
IDE	Arduino	IDLE, Scratch, Squeak, Linux	Python, Scratch, Squeak, Cloud9, Linux	Ubuntu 15.04, Android, Debian
Ethernet	N/A	10/100	10/100	10/100/1000
Video Out	N/A	HDMI, Composite	Micro HDMI	HDMI
Audio Out	N/A	HDMI, Analog	Micro HDMI	N/A

Table 3: Comparison of Arduino Uno, Raspberry Pi, Beaglebone Black, and ODRIOD (24)

4.4 Hardware User Controls

An important aspect of the Atwater Kent Power Panel is the quality of the user interaction. In the brainstorming phase, the team determined that in order to maximize interest and usage of the panel, some form of user control was necessary. Unlike typical lobby displays that cycle through a predetermined sequence of video clips or information sources, the Panel allows the user to choose what is displayed. The team developed the following set of criteria to narrow down the possible options:

- Uniqueness – How interesting and engaging the controls are for users. Following with the creative theme for the rest of the Power Panel design, the controls must attract the user and make interaction enjoyable.
- Ease of Use – The learning curve and efficiency of the controls to a new user. The controls must be intuitive enough in order to not discourage first time users.
- Integration – How easily the controls interface with the central processing unit. A

plug-and-play unit reduces valuable development time compared to a method with custom wiring and code.

- Durability – How well the controls stand up to physical wear. The public location of the Power Panel will inevitably result in repeated use that may be overly forceful or accidentally damaging. A sturdy control system is required to last for many years to come.
- Cost – As with all components involved in this project, a relatively high price may make a more ideal option less desirable.

Research resulted in three different options to investigate. Although more common methods of control such as mouse, keyboard, or mechanical buttons were adequate, focus was directed towards solutions that satisfied the uniqueness criteria.

4.4.1 Infrared Gesture Recognition

The most novel method of control found was one that involved no physical contact with the controls: touch-less gesture recognition. There are several products that use infrared transmitters and receivers to track a hand in two-dimensional or three-dimensional space. The most advanced product is the Leap Motion, which is able to detect multiple hand gestures within a 2 foot radius of the device (30). Figure 25 below shows an image of the Leap Motion device.

Figure 25: Leap Motion Controller (foreground) with Laptop for Scale (31)

The unit costs a relatively high $70 and interfaces with a Mac OSX or Windows operating system (32). The Leap Motion is very unique in that it allows the user to control multiple actions with hand motions. This input method is certainly unique, but perhaps not very practical. When installed in Atwater Kent, the Power Panel will be in a relatively high traffic area. Not all people walking by will be trying to control the Power Panel, but with the 2 foot sensing radius, the Leap Motion may pick up unintended movements leading to erratic operation. Although gesture based control is intuitive once all of the gestures are understood, a first time user may have difficulty figuring out the controls unless a guide is provided. As a result of touch-less operation, the Leap Motion will not have a problem with physical wear. Combined with its small size, the Leap Motion can be easily integrated directly below the LED display.

One significant restriction of the Leap Motion is its compatibility with only Windows and Mac OSX operating systems. A less expensive Linux SBC or microcontroller would not be able to interface with the device. This limitation combined with the potential problems of gesture based control make the Leap Motion controller fail several of the critical requirements.

4.4.2 Capacitive Gesture Recognition

An alternative method of gesture recognition uses capacitance sensing to track a hand in three dimensions. The Microchip MGC3130 is an IC that when combined with a specific layout of electrodes can detect both directional movements in the air as well as touch events on the electrodes themselves (33). Microchip also sells a development board for the IC that includes all necessary electrodes integrated into a PCB for $180, although a 3rd party vendor, Hover Labs, sells an equivalent kit for $39 (34; 35).

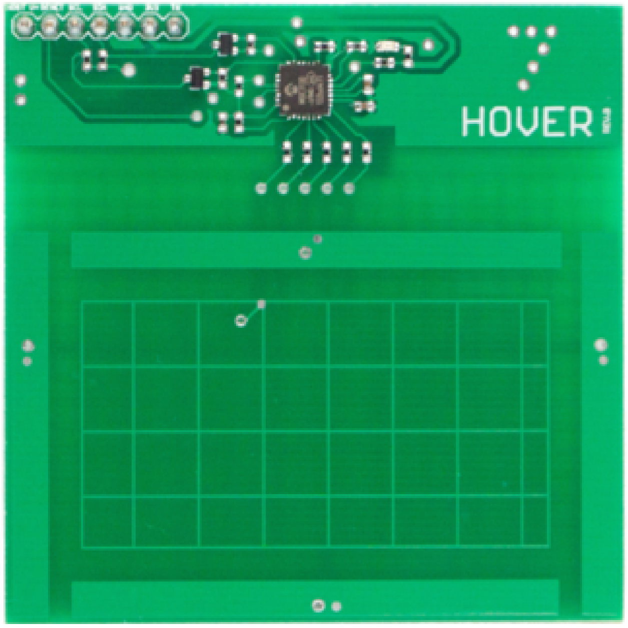


Figure 26: HoverLabs PCB board for the MGC3130 (35)

This solution is similar to the Leap Motion in that it detects gestures, but differs as it recognizes only much simpler movements and at a much closer distance of 0-15 cm (33). The MGC3130 has the benefits of communicating via I2C, making integration with simpler processors possible. In addition to tracking gestures, the MGC3130 can also detect touches to the electrodes on the PCB. The touch-based interface may be easier for the first time user to understand, but durability compared to the Leap Motion suffers because of the physical contact that is required. The capacitive touch aspect of the MGC3130 inspired the idea of controls that were only capacitive touch based.

4.4.3 Capacitive Touch

Using the same basic principle as touch-less capacitance sensing, a capacitive touch sensor uses a conductive material that changes capacitance when touched by a grounded object such as a hand (36). The sensor can be any conductive object, thereby removing any limitation on the design of the touch surface. Although a touch based control system may not have the novelty of a gesture based one, capacitive buttons can be labeled and laid out in a much more intuitive manner. Some capacitive touch specific solutions exist on the market, but nearly any microcontroller with analog input pins can be used to detect capacitive touch. The Arduino microcontroller, as described in Section 4.3, Arduino Development Board has libraries that support capacitive touch recognition with the benefits of low cost and ease of programming (24).

The touch pads themselves can be manufactured out of any conductive material that has excellent hardness and strength properties compared to the human hand. Additionally, the pads can be designed in a custom layout that fits the Power Panel's user interface and can be easily interfaced though an Arduino to the central processor. Because of these positive aspects, a capacitive touch interface will be utilized for the user interaction portion of the Power Panel.

4.5 Power and Wiring

Due to the large scale of this project, special consideration needed to be made toward the method of powering the electronic components and wiring them to the selected power sources. The LED panels themselves require the majority of power consumption as compared to other components, so a focus was put on the power supply and wiring scheme for the LED panels. All of the components used for this project run off of 5 VDC. The common voltage is convenient and allows a single power supply to power multiple components. However, the low operating voltage of the panels results in a relatively high current draw. The low voltage, high current requirement is not a problem for the low power devices such as the microcontrollers and LED display sending and receiving cards, all of which require under 1W, often only a few milliwatts. The LED panels, however, were experimentally measured to draw 20 W at maximum power. This was determined by setting the panels to all white at full brightness and measuring the current delivered by a 5 V power supply. The 20 W at 5 V equates to 4 A per LED panel. This current draw becomes significant when the entire displays are considered. Table 4 below shows the current and power demands of all of the displays.

Display	Number of Panels	Total Power Draw [W]	Total Current Draw [A]
Main	36	720	144
Horizontal Ticker	12	240	48
Vertical Ticker	4	80	16
Large Child	4	80	16
Small Child	2	40	8
Total	64	1280	256

Table 4: Summary of Power and Current Demands for all Displays

As seen in the table, the total current draw for the larger displays especially is substantially high and requires special consideration. High current poses both a safety risk and requires bulky, expensive lower gauge wire to handle the high current. The high current involved prompted the investigation of using higher voltage rails that would be stepped down to the 5 V that the panels operate at. The higher voltage rails would provide the same amount of power to the panels at a lower current.

Supplying power to the LED panels requires several external components in addition to the LED panels themselves:

- A power supply that converts 120 VAC to DC voltage in order to run the panels
- Stranded, insulated wire to connect the power supplies to the LED panels
- Optional: A DC to DC converter that steps down higher voltage DC to 5 VDC

If 5 VDC power supplies are used, the DC/DC step down converter is not needed, but if a higher voltage rail is used, one DC/DC converter will be needed per panel. With 64 panels in the design, the cost per converter needs to be low to make purchasing 64 of them within budget.

4.5.1 DC/DC Step Down Converter

There were five criteria developed in deciding on a DC/DC converter to use:

- Low Cost - Since each of the 64 panels would require and individual converter, each converter must cost under about $5 to remain within budget.
- 5 VDC Output - The converter must be able to output 5 VDC with reasonably low noise and ripple, either adjustable of fixed.
- At least 24 V maximum input voltage - In order to experience the benefits of lower current at a higher voltage, the voltage rail must be significantly higher than 5 V.
- At least 4 A current capacity - The panels consume a maximum of 4 A at 5 V, so the converter must be able to supply 4 A plus at least a ≈20% safety margin.

- High Efficiency - Excessive power loss in the converter would defeat the purpose of reduced voltage drop due to lower currents.

After extensive research, only one product that fit the above criteria could be found. The XL4015 DC/DC buck converter mounted to an PCB with necessary external components costs about $1.60 and is shipped directly from Hong Kong, China. Linear voltage regulators are relatively inexpensive but are simply too inefficient for this relatively high power application. All other options were simply too costly to either purchase a pre-made solution or use an appropriate IC in a custom design. The XL4015 assembled board can be seen in Figure 27 and associated specifications can be found in Table5.

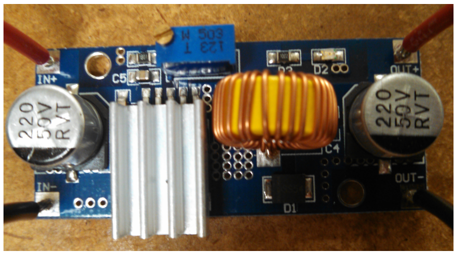


Figure 27: XL4015 DC/DC Buck Converter Board with External Components

Input Voltage Range	8-36 VDC
Output Voltage Range	1.25-32 VDC
Minimum Drop Out Voltage	0.3V
Constant Current Output	5A
Efficiency	See Figure 28
Switching Frequency	180kHz
Package Type	TO263-5L

Table 5: XLSEMI XL4015 Specifications

The maximum input voltage of the XL4015 is 36 VDC. For the purpose of unifying all further research, a supply voltage of 36 VDC was used in order to maximize the low current - high voltage benefit. Being a switching regulator as opposed to a linear regulator, the XL4015 exhibits impressive efficiency. At the maximum expected load of 36 V 4 A, the specified efficiency is about 85% as seen in Figure 28 below.

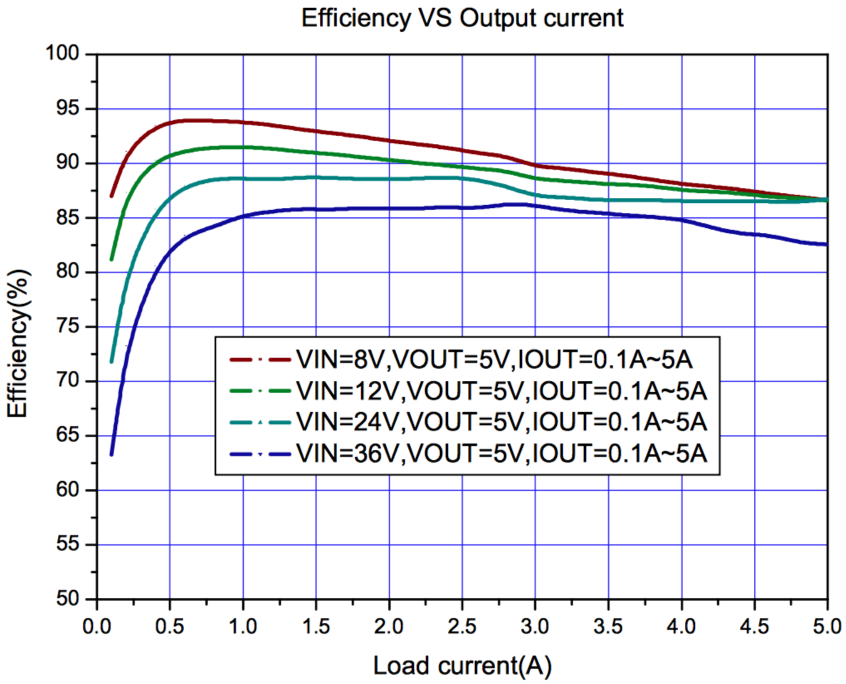


Figure 28: Efficiency Versus Output Current at 5 VDC Output

Due to the shipping time for the XL4015 boards from China, much speculation was made on the XL4015's capabilities before a sample was available to test. Section 5.2.1 describes the results from driving the XL4015 under load.

4.5.2 AC to DC Switch-Mode Power Supply

The Power Panel will be powered by 120 VDC from the building. An intermediary voltage converter is needed to step down the voltage and convert it to DC to be used by the LED panels. The two major types of AC to DC converters are linear and switch mode power supplies (SMPS). Linear AC/DC converters rectify the AC signal using diodes, smooth the output using capacitors, and then regulate the output to at set DC value. Although simpler than a SMPS, linear converters tend to have lower efficiencies than SMPS's, around 60% compared to 80% or more respectively (37).

Due to the Power Panel's focus on energy monitoring and sustainability, the higher efficiency SMPS's are more appropriate for this application. The inherent benefits of linear converters - low ripple and noise as well as faster transient response - are not as important for the LED panels, as they are not sensitive to minimal voltage fluctuations. When researching options for AC/DC SMPS, one series - LRS by Mean Well - stood out due to their high power output to price ratio. They are produced in seven power outputs up to 350 W and six voltage outputs up to 48 V, including the 5 VDC that the LED panels operate at. Standby power usage is a low 0.2-0.75 W, appropriate for the energy sustainability focus of this project. The Power Panel does not require SMPS's rated for medical use or in harsh environmental conditions that cost more than the LRS series. Additionally, the LRS series has consumer safely ratings described in detail in Section 5.5. The two voltage outputs of interest were 5

VDC and 36 VDC. 5 VDC is what the LED panels operate at, and 36 VDC is the maximum input voltage of the XL4015 step-down converter. Table 6 summarizes the specifications of both types (38).

Model	Rated Power [W]	Rated Current [A]	Voltage Ripple [mV_{pk-pk}]	Output Voltage Range [V]	Efficiency [%]	Length [in]	Width [in]	Height [in]	Price [$]
LRS-35-5	35	7	80	4.5-5.5	82	3.64	3.23	1.18	13.30
LRS-50-5	50	10	80	4.5-5.5	83	3.64	3.23	1.18	14.10
LRS-75-5	70	14	100	4.5-5.5	89	3.64	3.82	1.18	16.60
LRS-100-5	90	18	100	4.5-5.5	86	4.82	3.82	1.18	18.40
LRS-150F-5	110	22	100	4.5-5.5	85	6.00	3.82	1.18	26.10
LRS-200-5	200	40	150	4.5-5.5	87	8.46	4.53	1.18	30.07
LRS-350-5	300	60	150	4.5-5.5	83.5	8.46	4.53	1.18	34.83
LRS-35-36	36	1	200	32.4-39.6	88	3.64	3.23	1.18	13.30
LRS-50-36	52.2	1.45	200	32.4-39.6	89	3.64	3.23	1.18	14.10
LRS-75-36	76.8	1.6	200	32.4-39.6	91.5	3.64	3.82	1.18	16.60
LRS-100-36	100.8	2.8	200	32.4-39.6	90.5	4.82	3.82	1.18	18.40
LRS-150F-36	154.8	4.3	200	32.4-39.6	89	6.00	3.82	1.18	26.10
LRS-200-36	212.4	5.9	200	32.4-39.6	89.5	8.46	4.53	1.18	30.07
LRS-350-36	349.2	7.3	200	32.4-39.6	88.5	8.46	4.53	1.18	34.83

Table 6: Mean Well LRS Series 5 and 36 VDC Output Specifications (38)

The 5 V and 36 V versions share the same dimensions and prices but are otherwise relatively different. Although each has seven power output versions, the 36 V output version consistently has a slightly higher output, most likely due to the significantly higher efficiencies at all power ratings. The voltage ripple of the higher voltage versions is 50 to 120 mV higher depending on output power but still within operating range of the LED panels. When choosing specific power supplies for each display, the power requirement of the display plus a 20% safety margin is used as the minimum power output needed.

4.5.3 Wiring and Connectors

The connection between the DC output at the AC/DC power supplies to the DC input that panels require needs special consideration given the relatively high current involved in the Power Panel. Each panel has a four pin power connection, with two pins for 5 VDC and two pins for ground. The LED panels are supplied with a cable assembly seen in Figure 29 that has two four pin power connectors wired in series terminated by spade terminals. Two 18 AWG wires are used for both 5 VDC and ground, making the effective wire gauge 15 AWG for both 5 VDC and ground.

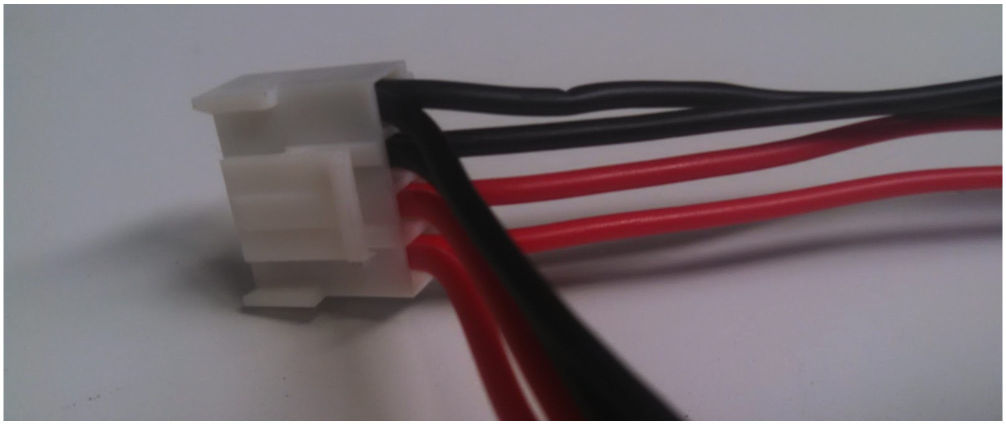


Figure 29: Example of Two 18 AWG Cables Crimped into a Single Pin Used in Supplied LED Panel Cable Assembly

Due to the custom configurations of the Power Panel displays, multiple wiring configurations are possible. The limiting factor for most configurations is the maximum current carrying capability of the wire. To aid in the wiring analysis, Table 7 was created to set the current capacity of various wire gauges and their average prices. The current rating of a wire depends of many factors such as number of strands, ambient temperature, insulation material, allowed voltage drop, and number of wires in a bundle. A conservative rating for current capacity is 700 circular mils per amp (39). For every amp, the conductor must have 700 circular mils of area for the current. A conservative rating was chosen due to the potential for the Power Panel to be operating twenty four hours a day for years to come.

Gauge [AWG]	Circular Mils [mils]	Resistance per 1000 ft at 20°C [Ω]	Current capacity [A]	Price per foot [$]
18	1624	6.385	2.32	0.25
16	2581	4.016	3.69	0.28
14	4109	2.525	5.87	0.30
12	6529	1.588	9.33	0.35
10	10384	0.9989	14.83	0.70
8	16512	0.6282	23.59	1.00
6	26244	0.3951	27.47	1.60
4	42738	0.2485	59.63	2.00

Table 7: Electrical and Mechanical Specifications for Single Conductor Wire. Current Capacity is Based on 700 Circular Mills per Amp Rule.

Higher gauge, smaller wire is preferred due to its lower cost and overall ease of use. However, larger lower gauge wire is required as currents increase. The current capacities above are considered when determining the required wire gauge in Section 5.2.2 below.

4.6 Graphical User Interface

Through the course of this project, the team has researched the most advantageous software platform for the Power Panel. Initial research led the team to explore Processing further. Processing is an open source java software package and integrated development environment that is primarily used for graphic and image processing. Processing was designed for teaching people how to code through images and graphics, but since its release in 2001 it has been used for a variety of image-based applications. Unlike many other programming IDEs, Processing's self-contained executable applications makes it easy to run and install without having to manipulate system settings and preferences of the computer. In addition to this, the IDE is very simple and makes it easy to import programs written on other operating systems. The most impressive benefit that Processing has to offer its users is its extensive support for image-based programming (26).

For the reasons described above, Processing was used in order to display images and text to the LED Matrix Panels. Since Processing is an open source programming package it is freely available for the Linux operating system that that is run by the ODRIOD XU4.

Appendix B shows a high-level software implementation as to how the team programmed Processing on the ODRIOD XU4 for the Main Display. In order to accommodate the various user display settings, the team has organized the software implementation as a state machine. The program begins by setting up the appropriate libraries, variables and function prototypes and then quickly moves on to the menu display. It then transitions to a state machine based format. Using a state machine format helps separate different parts of the system, such as menus, to make it easier to display one type of information over another. The system focuses on three main states: the solar panel energy generation, campus wide message board, and monitoring the campus wide energy consumption. Other states are contained as well however these three will consist of the majority of project work. During each of these states, the program displays the appropriate information, consistently check for user input, as well as collect data via the analog to digital input pin from the solar panel.

In addition to programming the Main Display, the Auxiliary Displays have been programmed in a Processing sketch as well. Unlike the Main Display, the Auxiliary Displays are not interactive. These panels will update on their own and are programmed currently with the features as shown in Figure 30.

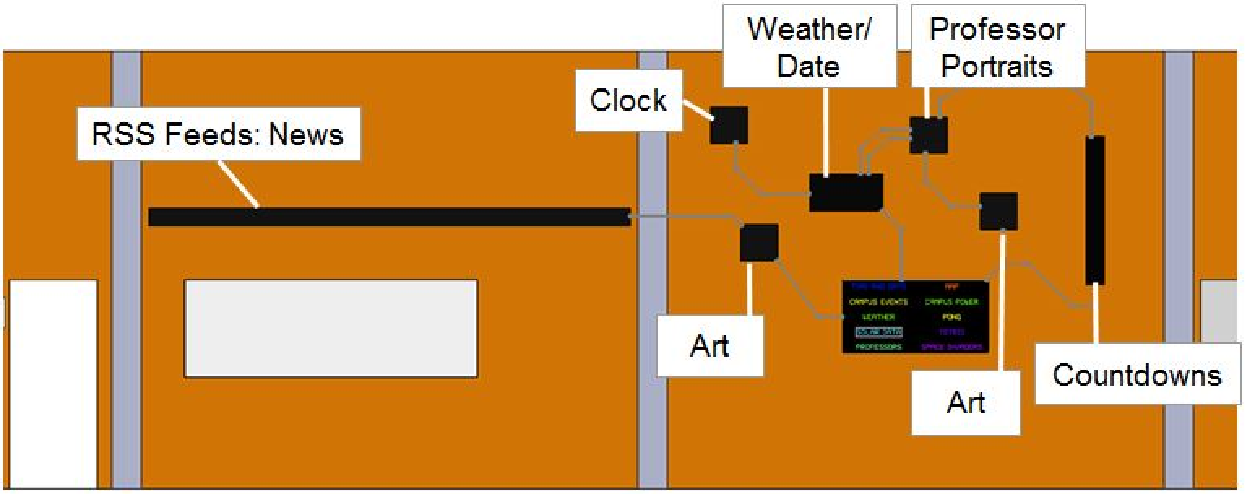


Figure 30: Features Programmed in Processing for Children Panels

The unique features of Processing easily allow for expansion of each feature set. The display functionality can be changed in order to accommodate desires of students and faculty in Atwater Kent and WPI as a whole. Overall, Processing provided an equal balance of appropriate capabilities and ease of use in order that the team could focus on content for display.

4.7 Peripheral Data Sources

Integrating various portions of the Power Panel as included in the system block diagram began early in the project. Advances were made with regard to the testing of the Grid Independent Charging Display MQP. The team has also researched obtaining access to power consumption statistics across the WPI campus. Lastly, the team met with IT specialists in AK to determine the feasibility of determining lab occupancy through the network. Each of these topics is discussed further throughout this section.

4.7.1 Integrating Previous MQP

Initially, this MQP was largely focused on incorporating the power generated by the wind turbine, but due to the limited amount of wind in the area, the wind turbine rarely spun to generate any power. This would limit the team's ability to debug and test the project to windy days and certain times of the year. For this reason, the team decided to focus on using the power generated from the solar panels.

Once this decision was made, the team was directed to the "Grid-Independent Charging Display" MQP that measured the voltage and current output from the solar panels atop the roof of Atwater Kent (40). The final goal of this project was to have the system mounted in the Pumpkin Lounge where it would consistently monitor the power generated from the solar panels. In addition to this power-monitoring feature it also charged a 12 V sealed lead acid battery that could be used for charging laptops or handheld devices through 120 VAC and 5 V USB power plugs. Figure 31 shows a block diagram of their overall system.

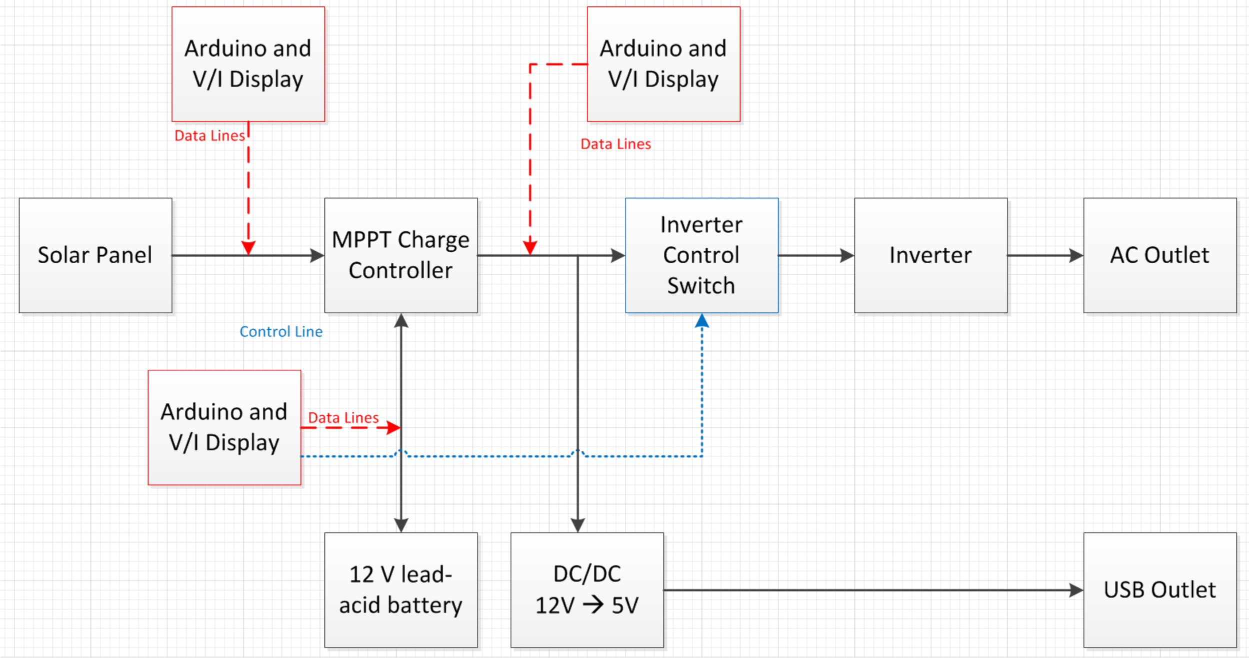


Figure 31: Grid-Independent Charging Display Block Diagram (40)

The MQP is made up of three Arduino Unos with 2.8 inch touchscreen LCD displays, a 12 V lead acid battery, a Tracer 2210RN Solar Charge Controller, a Sunpower 230 W solar panels, a Samplex PST-30S-12 A inverter, three ASC712 Hall Effect Current sensors, 120 VAC outlets, and USB outlets.

In order to calculate the power supplied by the solar panels it was necessary to monitor the voltage and current of the solar panels. The analog to digital converter pins on the Arduino can only accept voltage values within 0 V to 5 V, so it was necessary to drop the voltage down with a voltage divider. The equation below shows the resistor ratio that was used to accomplish this.

$$V_{SolarPanel}/V_{Arduino} = 1k\Omega/(1k\Omega + 9.1k\Omega) = 0.099 \tag{1}$$

Next, a continuity test was conducted on one of the modules to map all the interconnections. An oscilloscope was used to probe each point and was mapped to the system's input and outputs. Figure 32 shows a simple mapping scheme for one of the modules. This diagram was helpful in testing the MQP as well as determining how the system worked.

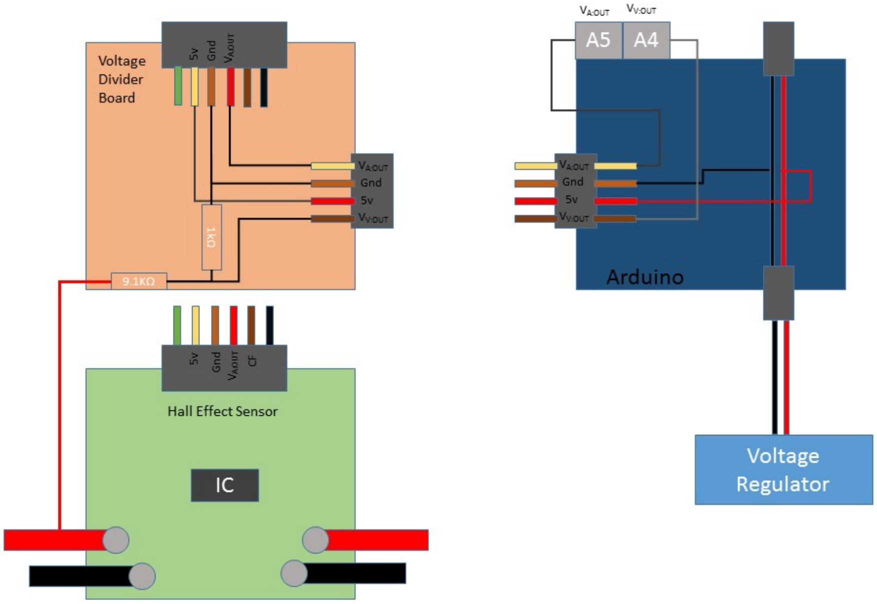


Figure 32: Grid-Independent Charging Display Module Mapping

Data Acquisition of the Solar Panels Since the power generated from the solar panels atop of Atwater Kent was not being used, it was important to ensure that they were still functional. In order to test this, an Arduino Uno was programmed in order to serve as a data acquisition device that used the sensitivity of the Hall Effect sensor and the voltage divider ratio to calculate the output power. The code developed for this purpose would serve as a simple building block for when the system is ported over to a main computer module (ODROID XU4). Using the resistor ratio, the voltage of the solar panel was determined based on the input voltage from the Arduino. Next, it was necessary to review the data sheet of the ASC712 in order to gather information on the sensitivity in volts per amp. Table 8 below shows the information from the ASC712 data sheet.

Current Range [A]	Sensitivity [mV/A]
±5	185
±20	100
±30	66

Table 8: ASC712 Hall Effect Sensitivity (41)

While connecting an oscilloscope probe to VA_{out}, the voltage values never exceeded 2.5 V to 2.6 V, which according to the data sheet indicated current within the -5 A to 5 A range. This information indicated that an appropriate sensitivity for this application is 185 mV/A (41). Equation 2 shows the relationship between the Hall Effect output voltage and the calculated current.

$$Current[A] = [A]/(185[mV]) * V_{Currentoutput} \tag{2}$$

4.7.2 Measuring Power Consumption

One of the primary objectives of this project is to explore display options of power consumption statistics on buildings across the WPI campus. In order to gather this information, an understanding of power distribution and monitoring systems became necessary. For this, the campus engineer, William (Bill) Grudzinski, was contacted. During meetings with Bill and Dr. John Orr, WPI's Director of Sustainability, many aspects of the power grid of WPI were explored. The campus currently uses E-Mon D-Mon sub-meters in several of the 29 metered buildings on campus. The Class 3400 Smart Meter has advanced displays and network capability. The meters measure "kWh, kWh/Demand (with peak date and time), Power factor per Phase, Real- time load in kW, Amps per Phase, and Volts per Phase" (42). Currently, WPI has access to this meter information through Honeywell software, although not readily accessible on the internet.

The team met with Will Grudzinski and Kevin McLellan who shared information about current and future projects relating to energy monitoring on the WPI campus. WPI is beginning to install meters with a larger set of capabilities. Meters from Automated Logic will enhance the portfolio of the campus' monitoring system, and allow for better access to data systems. Currently, these meters have been installed in Goddard Hall, Atwater Kent, and Morgan Hall. These meters provide data on current demand statistics for each of these buildings, accessible through the internet. Figure 33 shows an example of the demand data available to users by the Automated Logic system. The data shown measures kW for one week in Atwater Kent.

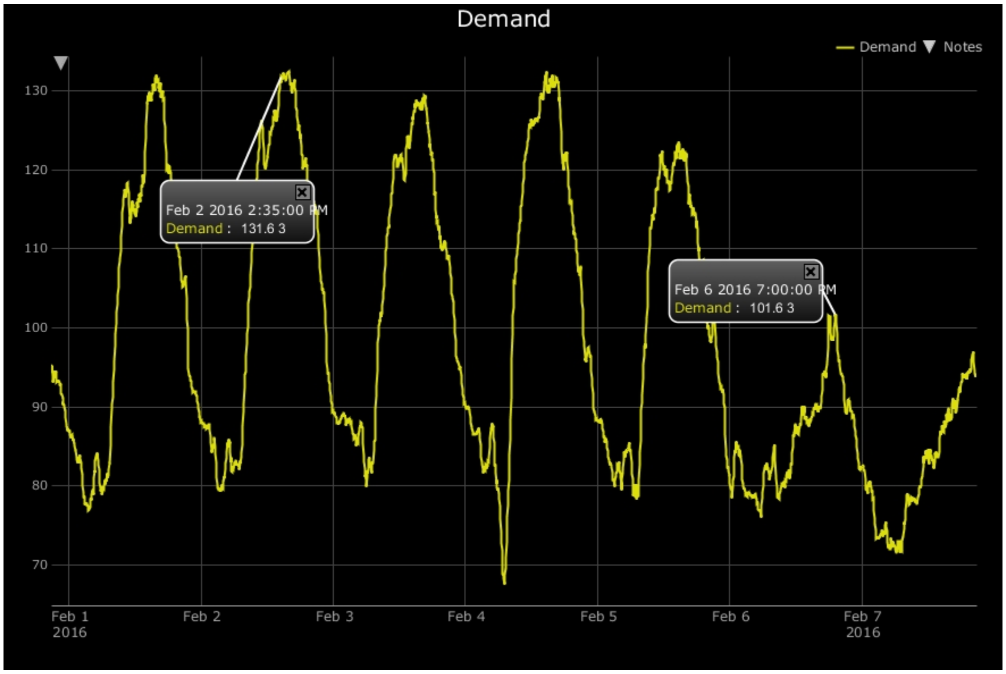


Figure 33: One Week of Demand Data for Atwater Kent in kW

Due to security precautions, this information is only available to those given access by the IT department. Because of limitations due to these precautions, the Power Panel will display historic energy information on Atwater Kent, in a format similar to the weekly data as shown in Figure 33. This will allow visitors and students to recognize energy usage pattens. There is room for expansion with this feature but this project focused on working with facilities and the IT department to obtain access for groups interested in this information.

4.7.3 Atwater Kent Lab Occupancy

One of the most important resources Atwater Kent provides to students is the multiple twenty-four hour access labs. There is one lab on each floor of the three-story building. The labs' popularity, especially during finals week, can result in a limited number of lab stations available. When the labs are at or near capacity, students waste time scanning the labs for open seats. A live record of the number of lab stations free in each of the three labs would be a useful addition to the Power Panel display. Since this information would not be critical to the functioning of the display, it would only be pursued as an option if implementation was quick and straightforward. Therefore, methods of detection that used any type of hardware sensor installed in the lab were avoided. In addition to design time and cost, hardware sensors would be prone to wear and tear that is inevitable in a public space such as the Atwater Kent labs. The only option discussed that did not involve any additional hardware is to monitor the lab computers for activity. If a computer is logged in, it is safe to assume that that lab station is occupied.

The idea was discussed with Edward Burnham, the Atwater Kent IT manager, who shared the concern of a security risk. Although all that would be required to check lab occupancy is anonymous login information, the WPI's login system works on a per-user basis, not a per-computer basis. Therefore, in order to check if a computer was logged into or not, the login information of the student information would also have to be known. Due to WPI's network security policy, the information that would allow us to extrapolate lab occupancy is inaccessible. Since this feature was determined to be non-critical, it will not be further pursued in order that time is dedicated to other features.

5 Detailed Design

This section explores the design that was conducted once components were selected. Specifically, the capacitive touch pad design and testing is considered in order that the optimal user interface could be implemented. This section also includes power and wiring considerations for the Main Display and Auxiliary Displays. The frame design for installation is briefly discussed in addition to the standards met by components used in the construction of the Power Panel.

5.1 Capacitive Touch

As described in Section 4.4, a capacitive touch system was chosen to as the method of user control for the Power Panel. A PCB is the best medium to design the touch pads on, as it combines a good conductor (copper) with a good dielectric (FR4) in a single component with the option to add circuit elements easily. Additionally, as this is a electrical engineering project to be installed in the electrical engineering building, a PCB was appropriate.

5.1.1 Capacitive Pad Design

The two options for capacitive sensors - mutual and self capacitance - were explored in the prototype phase. Each option was considered through the pad design and is discussed below.

Self Capacitance Self Capacitance measures the capacitance between the touch pad and ground and requires a single conductive pad per sensor. Self capacitance for purposes of this design was tested with a solid conductor pad. With self capacitance, the shape of the pad is important; sensitivity theoretically falls at the edges of the pad so having an over sized pad compared to the key symbol printed on the pad is necessary (43). It was important to test multiple pad sizes for this reason. Sensitivity of self capacitance is from the area only where touched, therefore simple shapes, such as squares or triangles, are preferred over complex shapes (43).

Mutual Capacitance Mutual Capacitance measures the capacitance between two adjacent touch pads and therefore requires two conductive pads per sensor. Mutual capacitance is formed by these two electrodes, often referred to as X and Y, which are often interdigitated and form fingers (43). By experimenting with different size fingers and pads, mutual capacitance sensitivity can be calculated and the optimal design can be determined. With the X electrode surrounding the Y electrode, theoretically, it is optimal to have the Y electrode as thin as possible to minimize noise coupling (43). A wide X electrode is ideal in order that it is able to shield the Y electrodes. These characteristics were considered while designing and testing the capacitive touch sensors in order to better understand which pad would serve as an ideal pad for the final design.

5.1.2 Circuit Design

In order to implement and integrate a capacitive touch sensor, two methods were explored. The first method used a 555 timer, four bit counter, and constant resistance to output a variable frequency to an Arduino for further processing. The second method utilized a simple RC circuit connected to numerous general input and output pins (GPIO) on the Arduino to monitor the amount of time it takes to achieve a certain voltage level on an input pin. The following requirements were specified for the design of this sensor:

1. Sense a change in frequency in response to a capacitive change
2. Output keyboard command to the computer module via USB

5.1.3 Capacitive Touch Test PCB

Prior to designing the appropriate system for interfacing the capacitive touch sensor module and the Arduino, the sensitivity of the solid and interdigitated capacitive pads was investigated. The best way to determine the sensitivity between both configurations was to develop a simple PCB with different configurations in order to identify the best option. Figure 34 shows an image of the designed PCB. For this investigation, there were 12 capacitive sensor pads, each of which differed in either size, finger width, and/or type, as described in Table 9.

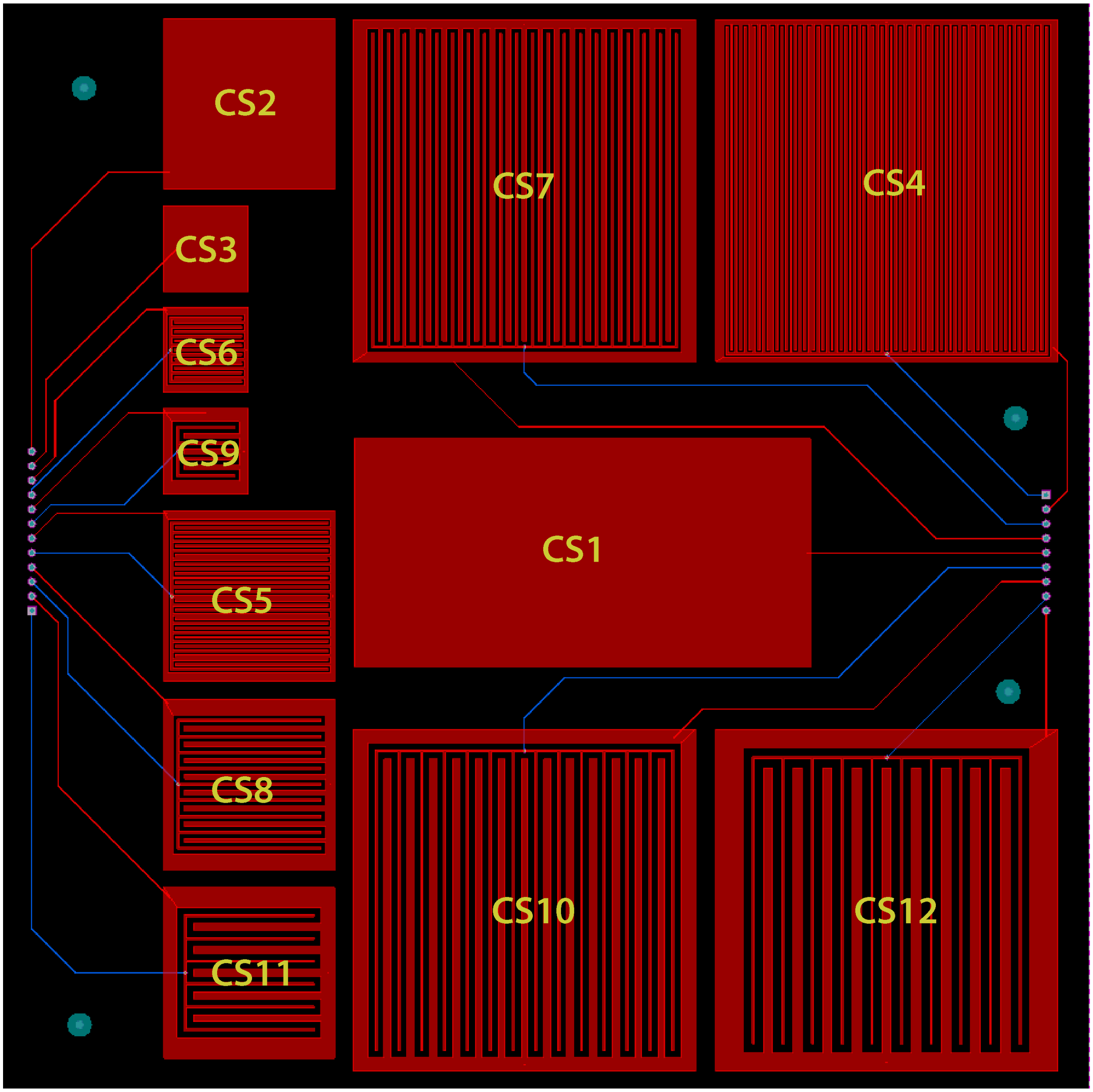


Figure 34: Capacitive Touch Sensitivity Test PCB

Name	Type of Capacitance	Area $[cm^2]$	Finger Width $[mm]$
CS1	Self	36	N/A
CS2	Self	9	N/A
CS3	Self	2.25	N/A
CS4	Mutual	36	0.4
CS5	Mutual	9	0.4
CS6	Mutual	2.25	0.4
CS7	Mutual	36	0.8
CS8	Mutual	9	0.8
CS9	Mutual	2.25	0.8
CS10	Mutual	36	1.2
CS11	Mutual	9	1.2
CS12	Mutual	36	1.6

Table 9: Descriptions of Capacitive Touch Pads Used in Test PCB

To determine the capacitive pad with the best response, the RC circuit shown in Figure 35 was developed. With a square wave input of 100 Hz and a 100 kΩ resistor, the 10-90 percent rise time and the f_{3dB} equations shown below can be used to isolate and calculate a value for capacitance.

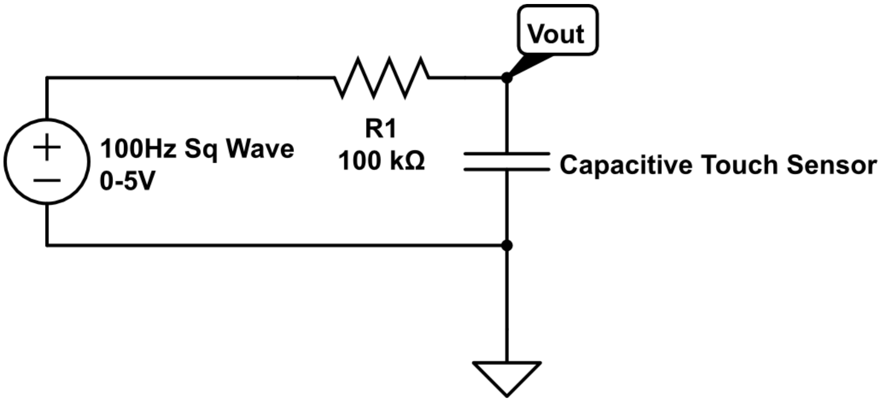


Figure 35: First order RC circuit used for testing

$$f_{3dB} = \frac{1}{2 * \pi * RC} \tag{3}$$

$$0.35 = t_r * f_{3dB} \tag{4}$$

$$C = \frac{t_r}{.35 * 2 * \pi * R} \tag{5}$$

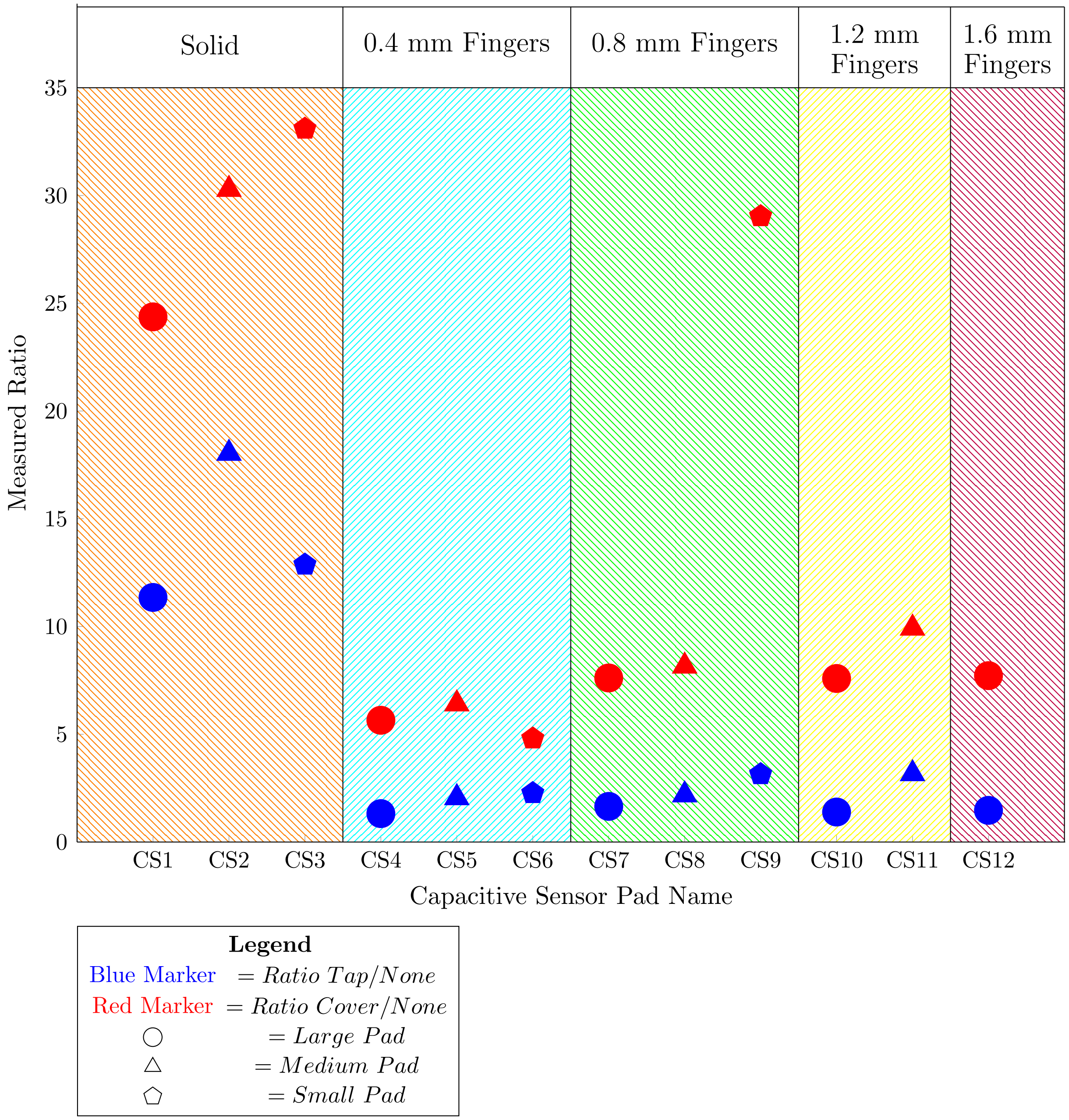
The capacitance for each of the pads was calculated under three different levels of touch: no touch, single tap, and complete cover. For the single tap, equal amounts of pressure were applied to the center of each of the capacitive sensor pads.

To determine the maximum capacitance available for each pad, one or more fingers were used. By covering more surface area, the capacitance between the user's fingers and pad increased, which directly increased the RC time constant and the rise time. Refer to Appendix C for complete tables of the measured rise time and calculated capacitance values for each pad under the three varying levels of touch.

Figure 36 shows the ratios measured between no touch and a single tap for each of the capacitive pads, marked by blue symbols. In red symbols, the ratios shown are between no touch and complete cover. From the graph, the pads that changed the most between no touch and single tap were CS1, CS2, and CS3, all of which are solid pads. Initially, it was thought that CS4 would provide the most sensitivity and highest capacitance because of its finer finger length (0.4 mm) and spacing. After calculating each of the capacitance values, CS4 was found to have the greatest capacitance but the least sensitivity of all the pads. This graph also shows that between no touch and complete cover CS1, CS2, CS3, and CS9 have the largest ratios, indicating the largest amount of relative change. The outlier resulting from the test where CS9 was covered was due to touching an exposed via on the PCB. This skewed the results of this pad and had the via not been exposed, the measured ratio is expected to have been low, similar to the other pads.

Since a majority of user control will require simple tapping for menu navigation and selection, it was more important to consider the sensitivity change of a single tap than the complete cover. From the measured data, the team concluded that a solid pad should be used over an interdigitated pad for the capacitive touch sensor. The solid pads provided the greatest amount of sensitivity between each of the different touches, but had the least capacitance when the pad went untouched. Section 5.1.4 discusses the circuit implementation of the capacitive touch sensor and the issues encountered due to the low capacitance of the solid pads while untouched.

Figure 36: Capacitive Touch Sensor Test Results for Tap and Cover Ratios



5.1.4 555 Timer Implementation

A 555 timer is an integrated circuit that is widely used to produce oscillating signals, pulses, or timing delays with the correct configurations. These timers can be configured to function in two different modes of operation: monostable and astable. In monostable, an external trigger can cause the 555 timer to output a pulse signal. In astable mode, the 555 timer is capable of outputting a constant frequency of pulse signals depending on the resistor and capacitor values attached to its pins. For the capacitive touch sensor, using a 555 timer was considered where varying the capacitance from the capacitive pad would alter the frequency output. The frequency output was then directly connected to the Arduino which resulted in a keypad command to the computer module. Figure 37 shows the circuit configuration of the 555 timer while under astable operation. In this configuration, the C, R_A, or R_B elements could be altered in order to adjust their output frequency accordingly for a specific frequency or duty cycle. Equations 6 and 7 show the derived functions for frequency and duty cycle for the 555 timer under monostable operation.

$$Frequency = \frac{1}{ln(2) * (R_A + 2R_B) * C} \tag{6}$$

$$Duty\ Cycle = \frac{R_A + R_B}{R_A + 2 * R_B} \tag{7}$$

For the capacitive touch sensor design, R_A and R_B remain constant, while the capacitive pad changes according to the amount of surface area covered on the pad by a finger or hand. According to Equation 6, any increase in capacitance should decrease the frequency inputted to the Arduino. The Arduino could then be used to either measure the square wave frequency or period.

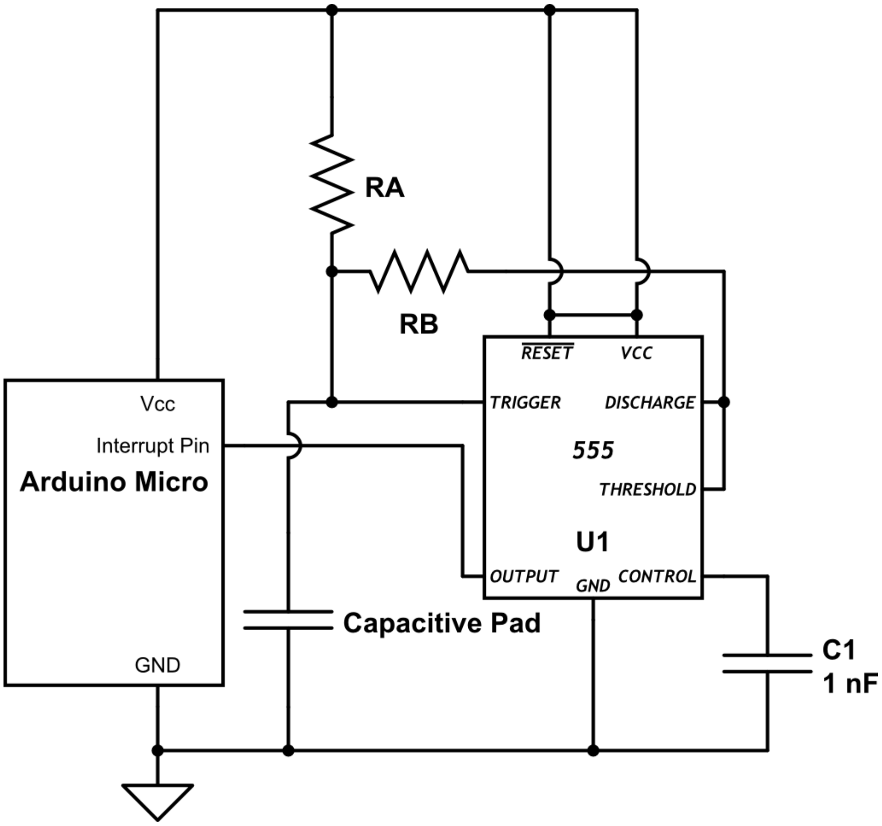


Figure 37: Circuit Configuration of 555 Timer in Astable Operation

For this design, it was not important to quantify frequency or period of the signal outputted by the 555 timer, only to detect a change. With this consideration, there were two methods reviewed. The first required using an Arduino function called *pulseIn()* which returns the amount of time that a signal remains either low or high. The next option was using the external interrupt pins on the Arduino to trigger an interrupt whenever the input was high causing a counter variable to increment. Another interrupt service routine would trigger after a certain period of time and clear out the variables. By counting a certain number of cycles in a given time period, the frequency could be determined based on the total number of counts that the variable reached. The following list shows some important strengths and weaknesses that were discovered while evaluating each method.

Pros	**Cons**
PulseIn Function	
• Simple to implement in code • Use any available input pin	• Limit to 50 kHz frequency input pin • At lower frequencies, cycling time to cycle through inputs increases
External Interrupts	
• Can accurately determine input frequencies • Approximately read frequencies to 150 kHz	• At high frequencies some inputs are neglected • Harder to implement due to interrupt management • Limited number of interrupt pins available

Table 10: Comparison of PulseIn Function and External Interrupts

Since both of these methods are limited by frequency, using Equation 6, expected frequency values were projected under different resistor values (R_A+ 2*R_B). Refer to Appendix C for the calculated frequency values.

Figure 38: Graph of Capacitance Versus Frequency for Various Resistances

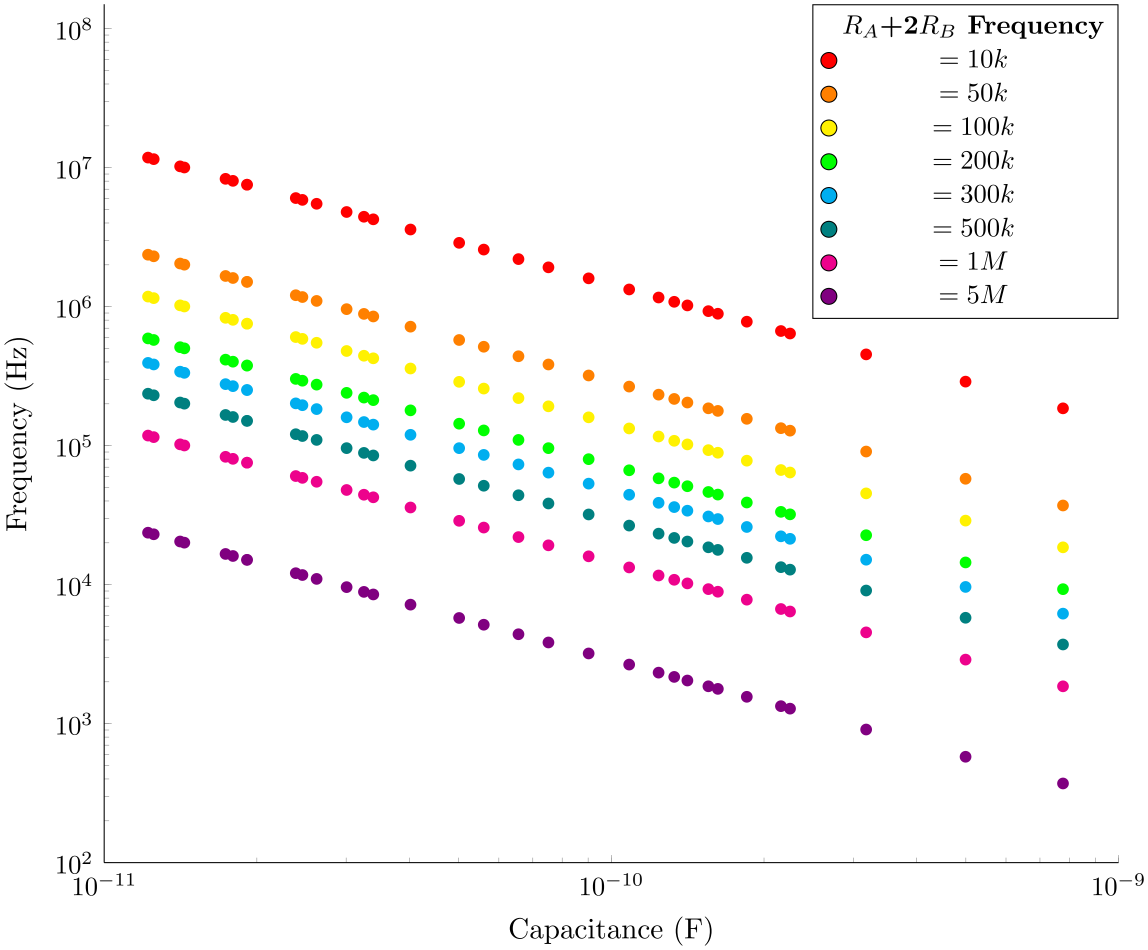


Figure 38 shows a linear relationship between the capacitance and expected frequencies at different resistor values for the 555 timer. For each of the capacitive pads, the resistance values can be altered in order to achieve a frequency output within the Arduino requirement. For the Arduino, the largest frequency input that could be read was 150 kHz, thus to ensure each pad would function within that range, the required resistance combination would have to be 5 MΩ which is extremely large.

Figures 39, 40, and 41 show the expected frequency output of all the capacitive pads with three different resistor combinations, 10 kΩ, 500 kΩ, and 1 MΩ. The shape of the plots are identical and differences can be seen in frequency. The similar shape of the plots is a good indication that the resistor values will not effect the system other than to decrease the frequency, making all resistor values a viable option. However, because as resistor values increase frequency decreases, the importance of selecting a high resistor value for proper use with the Arduino becomes apparent.

Figure 39: Output Frequency with Different Capacitive Pads and 10 kΩ Resistor Combination

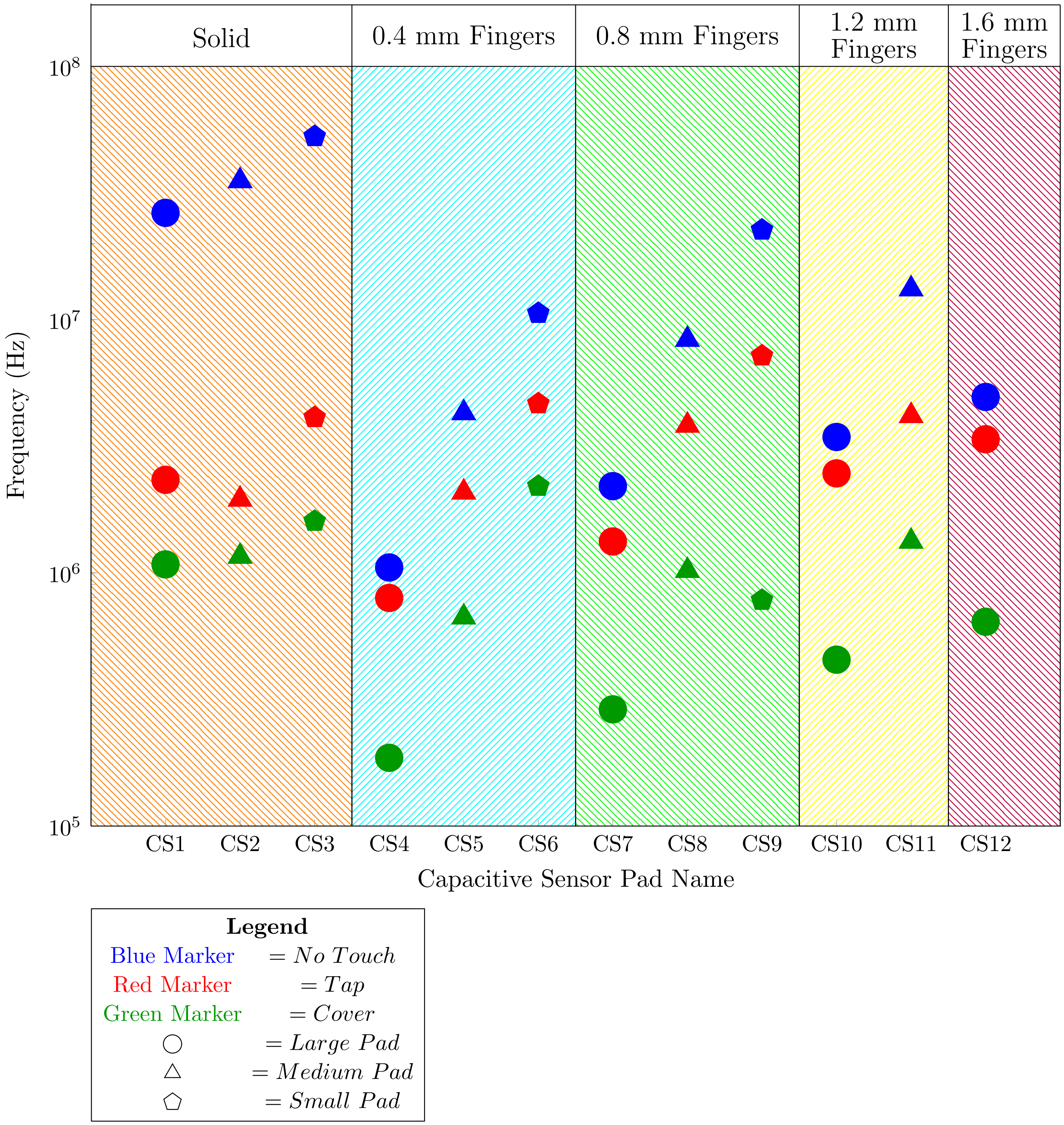


Figure 40: Output Frequency with Different Capacitive Pads and 500 kΩ Resistor Combination

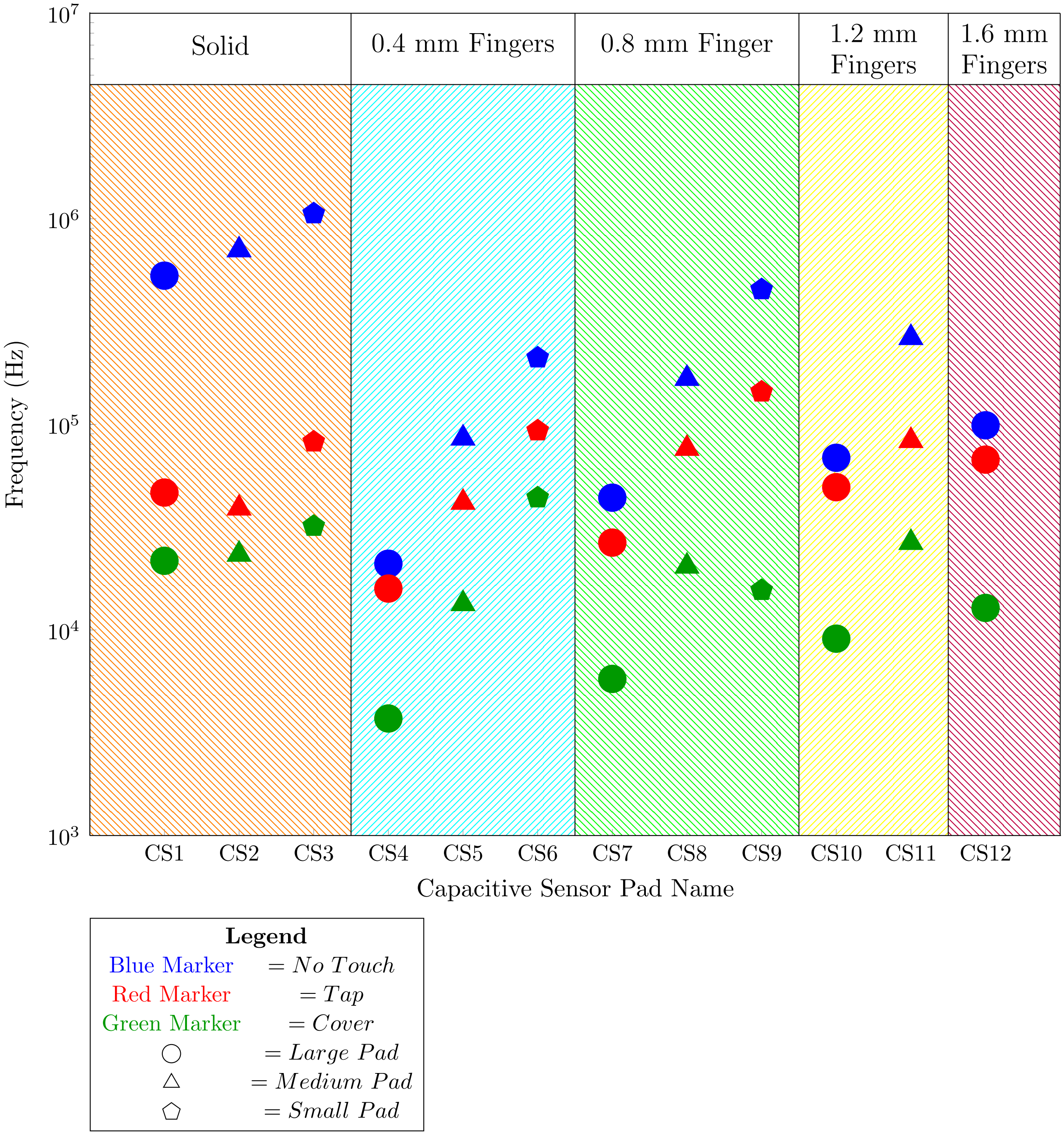
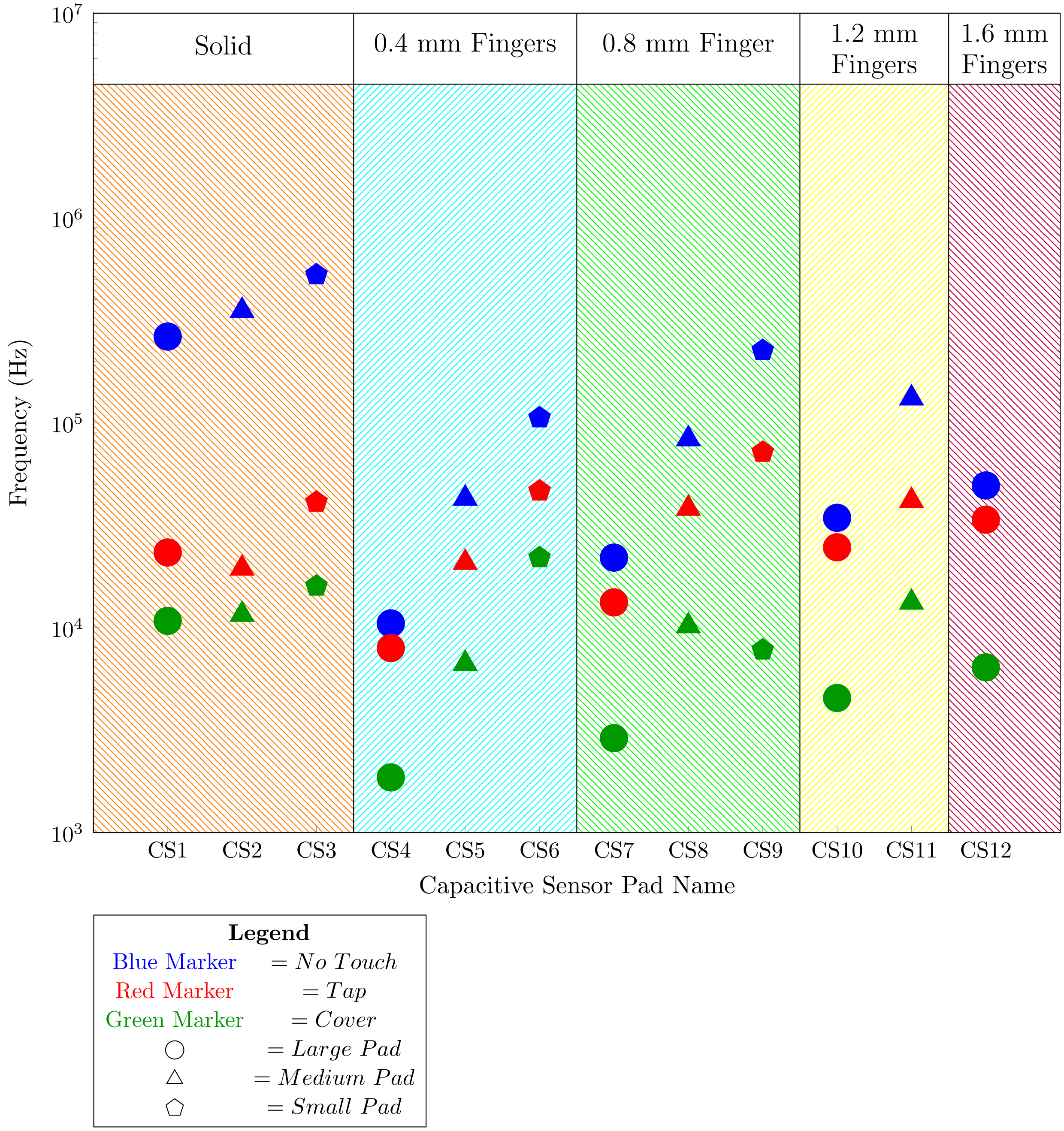


Figure 41: Output Frequency with Different Capacitive Pads and 1 MΩ Resistor Combination



In Section 5.1.3, it was found that capacitor pads 1, 2, and 3 had the largest sensitivity between the single tap and full cover touches to the no touch. In order to preserve as much sensitivity as possible, the team decided to use a solid capacitive pad for the sensor. Capacitor pads CS1, CS2, and CS3 are extremely low values of capacitance when they are untouched, which require large resistors in order to reduce the signal to a usable frequency. Figure 41 shows that even with a resistor combination of 1MΩ, the expected output frequency from the capacitive pads is much too high to be integrated with the Arduino. In order resolve this issue there were a few plausible options. First, a capacitive pad with higher capacitance at the expense of reduced sensitivity could be used. The second option is to implement a counter to reduce the output frequency to a usable range. As the third and final option a MPR121 multiplexing board could be used that is specifically designed to work with capacitive touch sensors that would register touches and communicate via I2C. In order to retain as much sensitivity as possible, a counter was integrated into the circuit configuration. Figure 42 shows the circuit configuration of the 555 timer with an included 4 bit binary counter.

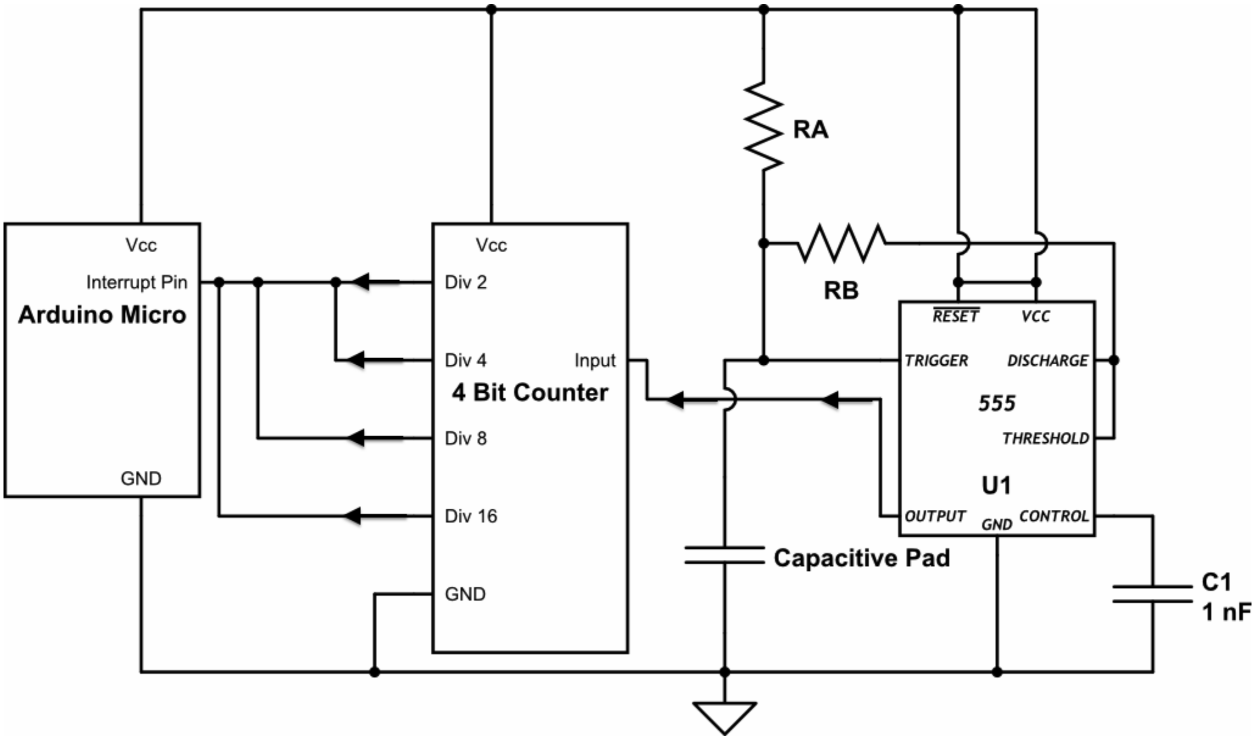


Figure 42: Circuit Configuration of 555 timer with 4 bit Counter

Prior to implementing a final circuit design, the circuit configuration shown in Figure 37 was built and probed in order to confirm if the behavior matched what was expected. For the first test, R_A and R_B were both set to 1 kΩ while using CS1 for the capacitance. From the data, the value of CS1 was found to be approximately 5.46 pF. Equation 8 shows the expected duty cycle at the output pin of the 555 timer under astable operation.

$$Duty\ Cycle_{Expected} = \frac{R_A + R_B}{R_A + 2 * R_B} = 66.66\% \tag{8}$$

Figure 43 shows an oscilloscope screen capture of the outputted waveform and Equation 9 shows the calculated duty cycle.

$$Duty\ Cycle_{Measured} = \frac{4.5200\mu s}{4.8000\mu s} = 94.166\% \tag{9}$$

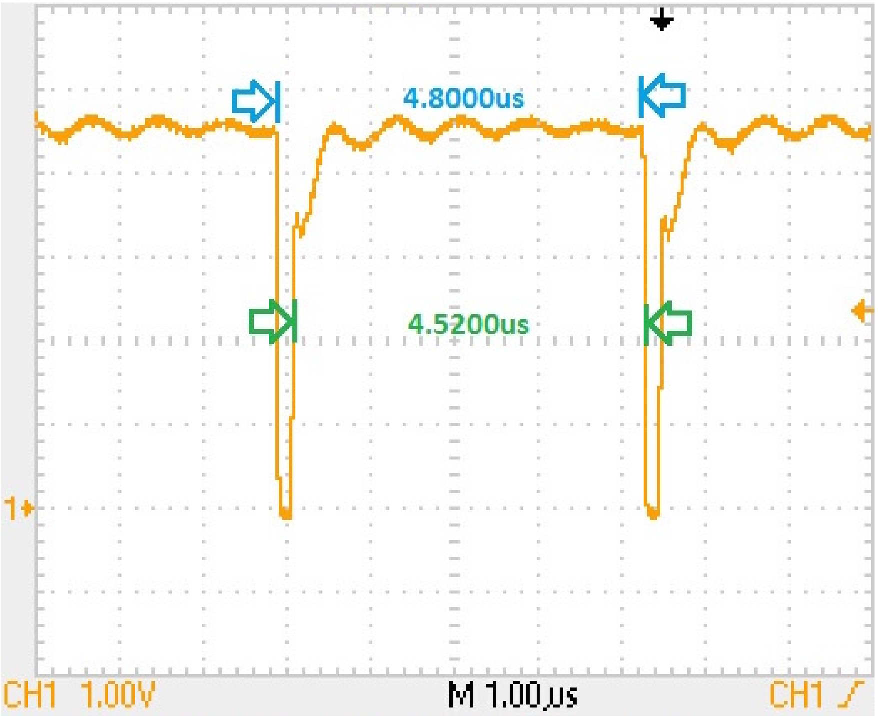


Figure 43: Measured Duty Cycle with $R_A = 1$ kΩ, $R_B = 1$ kΩ, Capacitance = CS1

The expected and calculated duty cycles are very different from one another indicating that the 555 timer was not working as expected. Figures 44 and 45 show images of the charging and discharging capacitor (CS1 with No Touch). For a 555 timer to function as expected in this configuration, the capacitance was expected to charge to 2/3 Vcc (≈3.33 V) and then discharge to 1/3 Vcc (≈1.66 V). From the figure, the capacitor is clearly charging and discharging beyond those boundaries, indicating that the 555 timer was not signaling an internal switch fast enough.

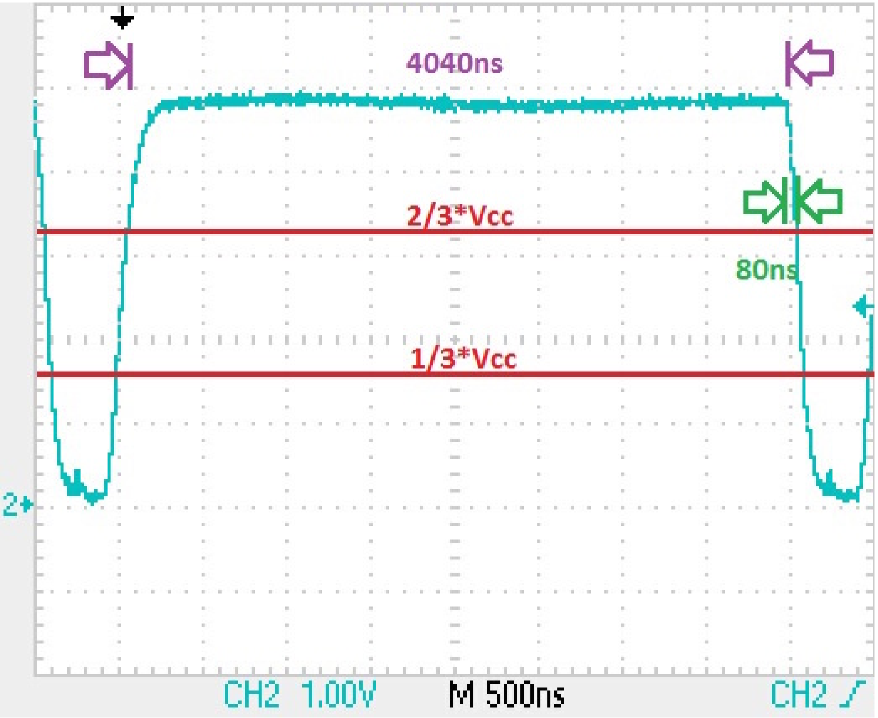


Figure 44: Image of Charging to Discharging Transition on Trigger and Threshold Pins

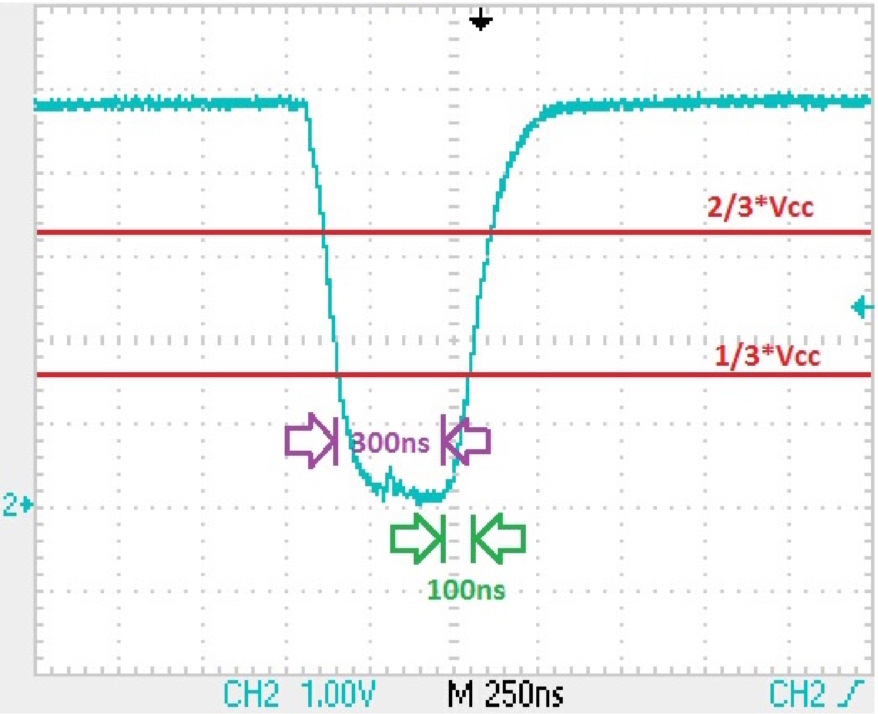


Figure 45: Image of Discharging to Charging Transition on Trigger and Threshold Pins

Figure 46 shows an internal functional block diagram of the 555 timer. Internally, the 555 timer has a switching transistor that is responsible for discharging the capacitor at the appropriate times. Ideally, the transistor should close when the capacitor reaches 2/3 Vcc to allow for discharging to ground and it should open when the capacitor reaches 1/3 Vcc. Given that the capacitor is charging and discharging beyond its boundaries, a reasonable assumption is that the output frequency of the 555 timer is limited by the fixed timing delays of its internal transistor. In Figures 44 and 45 the labeled purple boundaries are the time delays associated with the switching transistor while the green labels show the amount of time it takes for the signal to reach either 1/3 Vcc or 2/3 Vcc from outside the boundary limits. The 555 timer data sheet does not specify any information or details on the internal switching transistor but based on Figures 44 and 45, the rising time and falling time are 4.04μs and 300ns, respectively.

Appendix D.3 shows a re-derivation of the duty cycle and frequency equations while accounting for these internal timing delays. Inputting the timing delays found in Figures 44 and 45 into the re-derived equations yielded frequency values of 229 kHz and a 92.6% duty cycle. These values were fairly close to the measured values of 207 kHz and a 95% duty cycle.

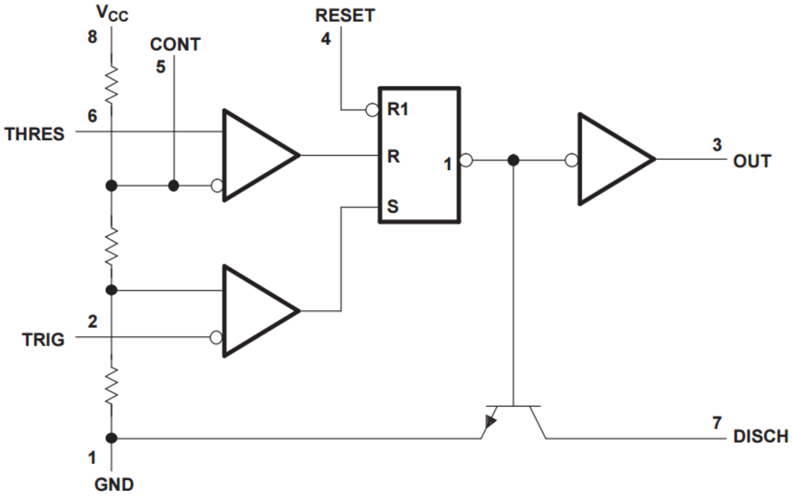


Figure 46: Functional Block Diagram of 555 Timer

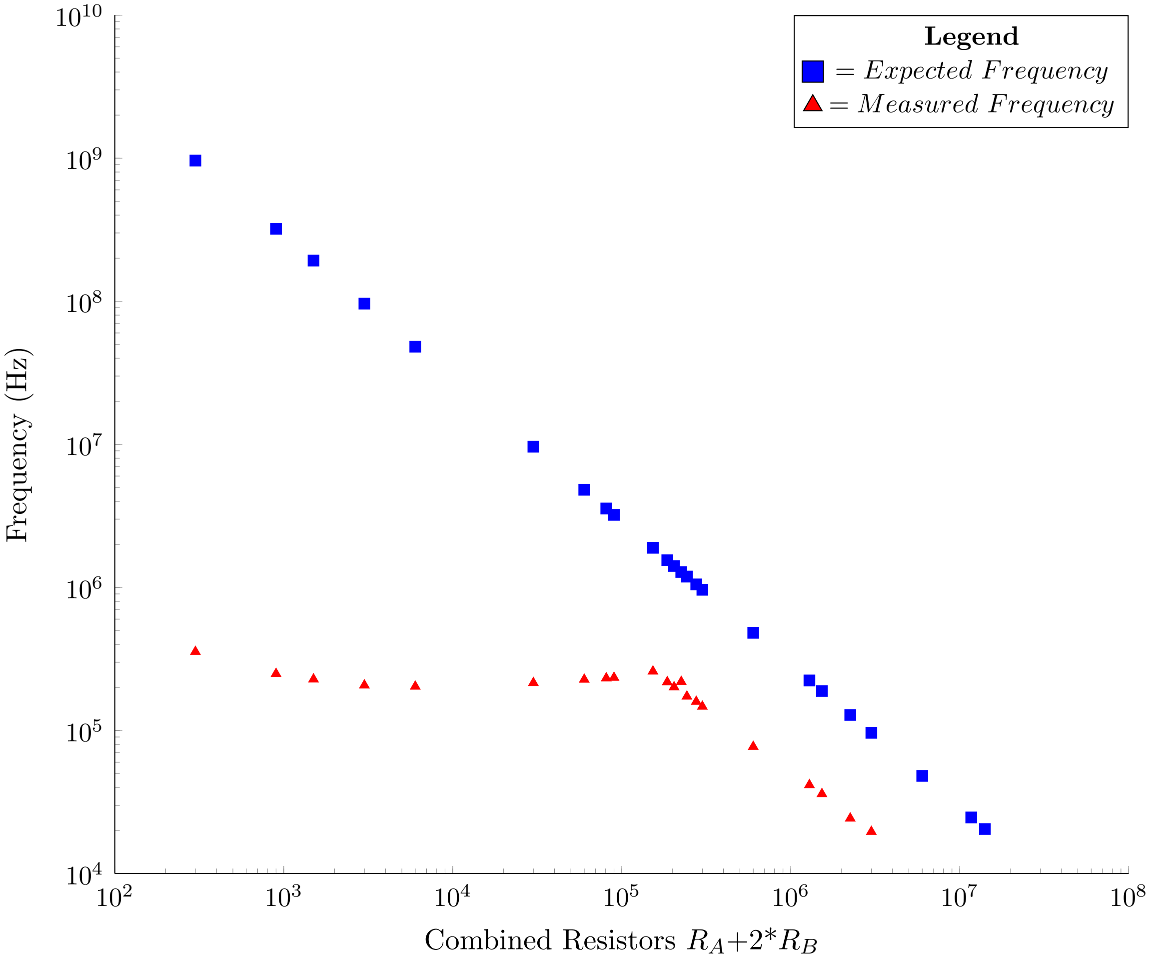
With regard to the circuit configuration, this issue could be the result of a very small RC time constant. In another test, where the capacitor (CS1) was replaced with a 0.1 μF capacitor, the 555 timer operated with the appropriate duty cycle and frequency. Given that capacitance of CS1 was extremely small, fairly large resistors would be required to compensate for it and increase the RC time constant to avoid this issue.

Figure 47 shows a graph of the expected output frequencies while varying the resistor combinations, R_A + 2*R_B, under the 555 timer implementation. This shows that under various resistor values the outputted frequencies while using the CS1 pad can range between 20 kHz and 1.9 GHz. Given that the Arduino can accurately read square wave inputs at around 150 kHz, the required resistor combination would have to be approximately 2.25 MΩ or R_A and R_B equal to 750 kΩ. Figure 47 also shows the measured output frequencies of the 555 timer implementation. The figure shows that the measured frequencies are much lower than the expected frequencies. This data shows that an appropriate output frequency could be achieved with a resistor combination of approximately 92 kΩ, 8.15 times smaller than what was thought to be required from the calculated frequencies.

This strange behavior could again be attributed to the small CS1 capacitance. Recall that in Figures 44 and 45 the capacitance was charging and discharging beyond the the 1/3 Vcc and 2/3 Vcc thresholds which resulted in lower than expected frequencies.

For this implementation, these lower frequencies would allow for easy reach of the target frequency (approximately 150 kHz) while keeping the resistances low and avoiding the need to include a four bit counter for frequency reduction. The problem with using the 555 timer under these conditions is that its output behavior is directly tied to an internal component not functioning as expected. In other words, a transistor was not switching fast enough and thus introduced unexpected timing delays. In this application, it may be fine to use a component in a manner it wasn't intended to but in other projects with tighter restrictions and requirements this is considered bad practice.

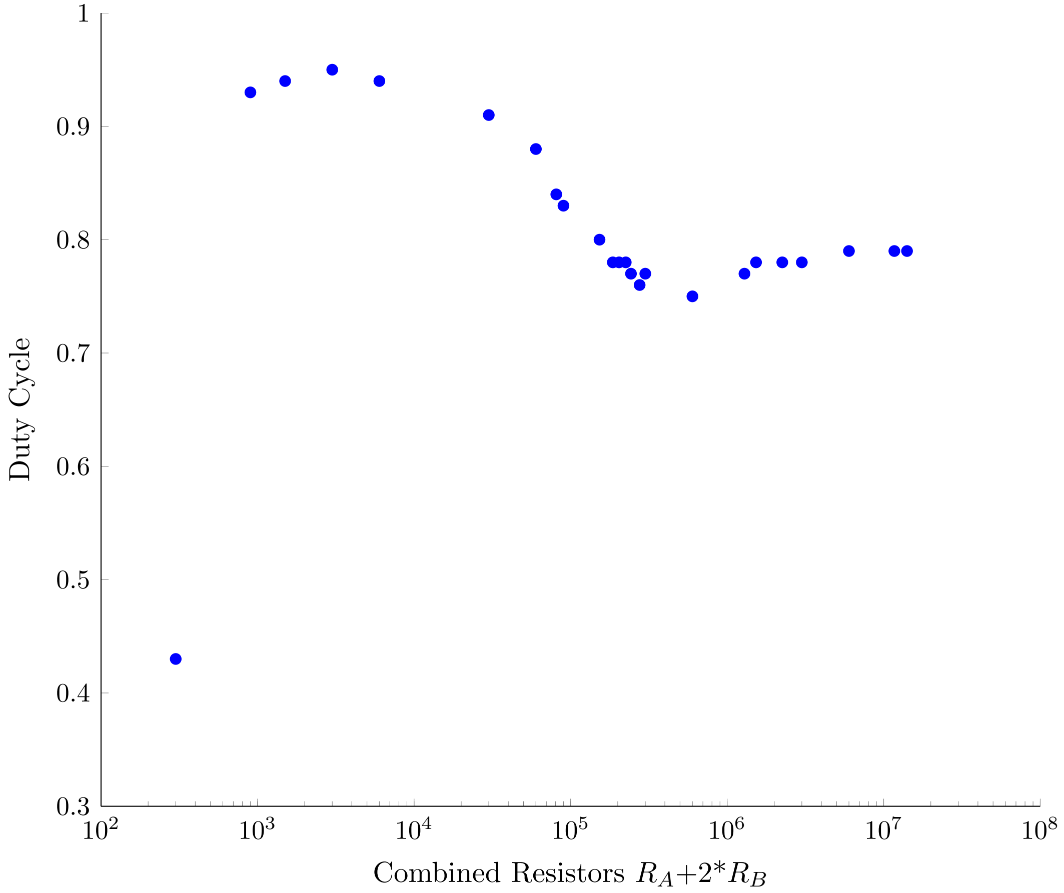
Figure 47: Expected and Measured Frequency Versus Resistance for CS1 with No Touch



This issue is also reflected when measuring the duty cycle. To simplify testing, R_A and R_B were set equal to one another. Thus, in each case the duty cycle was expected to be 66.66%. Figure 48 shows a graph of the duty cycle at various combined resistances. The graph shows that at low combined resistance values the duty cycle reaches slightly above 90% and slowly decreases as the resistance values increases. It was expected that as resistances increased the duty cycle would slowly approach the 66.6% duty cycle but even with resistor combinations of 14 MΩ (R_A and R_B equal to 4.7 MΩ) the output signal did not reach the expected 66.66% duty cycle. In order to get the expected operation from the 555 timer the resistance would have to be extremely large.

As a simple comparison, a 0.1 μF capacitor with a resistance combination of 10 kΩ results in a RC time constant of 1 ms. If the 0.1 μF capacitor were replaced with the 5pF capacitive pad then it would require a 200 MΩ resistor. A 0.1 μF capacitor was used for this comparison because even with fairly low resistance values the RC time constant is large enough to allow the 555 timer to operate normally.

Figure 48: Resistance Versus Duty Cycle for CS1 with No Touch



In addition to dealing with issues of 555 timer behavior and functionality, integrating this with software was also a challenge. For this implementation, the 555 timer will output a variable frequency dependent on the covered surface area of the capacitive pad. The Arduino is then tasked to identify changes in frequency of period. The best way to identify changes in frequency is to count the number of clock edges into the Arduino in a given time interval. The first issue with this is that external interrupts would need to be used so that at every clock edge a process within the Arduino triggers to increment an internal counter.

The Arduino Micro only has five external interrupts which is not enough for the number of keypads expected for the touch sensor. A potential solution to this is to upgrade to the Arduino Due, a microcontroller with ten times the amount of external interrupts,although twice the price. In this case, instead of using two Arduino Micros (one for each touch pad) one Due would manage both, handling 18 input signals. With 18 input signals, each at around 150 kHz, the external interrupts would constantly trigger and prevent some inputs from ever being recognized. A solution to this is to have the Arduino behave as a multiplexer, where it activates and deactivates certain pins while only testing one input pin at a time. Unfortunately, this behavior was never successfully implemented because of coding bugs that could not be easily resolved. After analyzing this approach, a simpler more straightforward approach that could achieve the same functionality was necessary.

5.1.5 Arduino Direct Input Pin Implementation

The next option evaluated for the capacitive touch sensor is shown in Figure 49. In this configuration, various digital pins are configured as receiving pins or sending pins. The Arduino pulses a digital signal high through the sending pin and the receiving pin waits until the voltage is equal to that of the sending pin. The amount of time that it takes for the voltage at the receiving pin to equal that of the sending pin is used to calculate the capacitance in arbitrary units. Since the capacitive touch sensor is only required to sense a change between the untouched and touched states of the capacitive pad, using arbitrary units satisfies the requirements for this design.

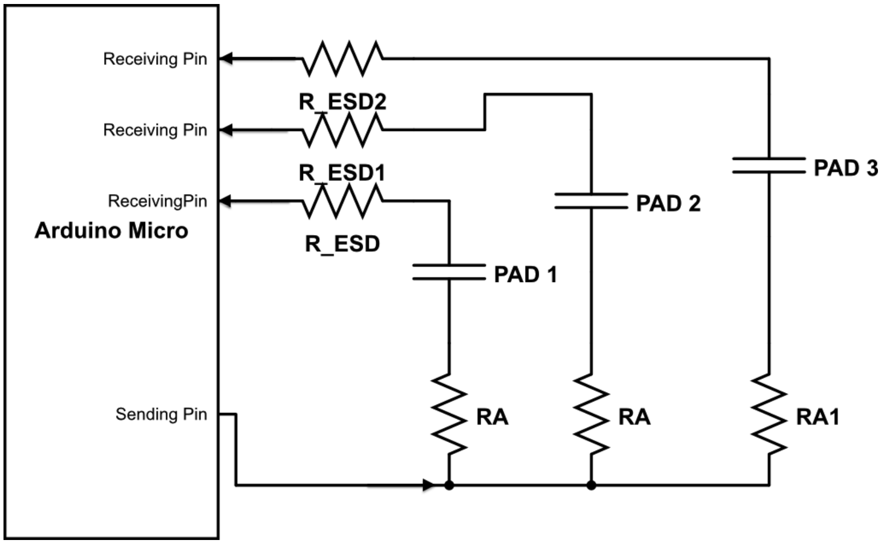


Figure 49: Connecting Capacitive Pad with Resistor Directly to Arduino

Figure 50 shows an oscilloscope screen capture of the receiving pin (yellow) and sending pin (blue). This implementation works by pulsing the sending pin high, then through an RC circuit configuration between the pins, the capacitance in the capacitance pad will then charge until it reaches approximately 2 V. At this point, the receiving pin is temporarily set high in order to fully charge the capacitor and then set low to allow for discharging.

The send pin then goes to 0 and waits until the voltage at the receiving pin reaches 1.8 V. The receiving pin is then pulled low to quickly discharge the capacitance and repeat the cycle. Each time the receive pin alters between a high and low state, an internal variable is incremented within a while loop in order to time the transition between states. This internal variable is then used to identify touches to the capacitive pad based on changes in the RC time constant.

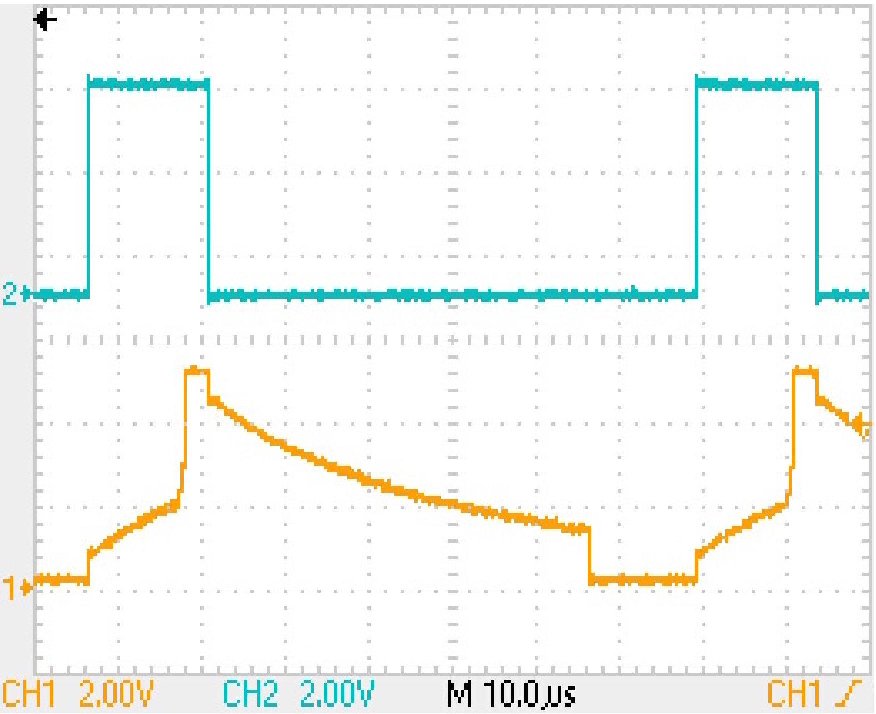


Figure 50: Signal at Receiving Pin and Sending Pin

Figures 51 and 52 show the signal at the receive pin while under conditions of no touch and touch. When applying a touch, there is a larger amount of time that is required for the receiving pin to match the sending pin because of the increased RC time constant. Figure 52 shows increased values for the amount of time that it took the capacitor to charge and discharge compared to Figure 51. The internal variable keeping track of time between state changes could then be used to trigger other processes, such as keyboard output commands, within the Arduino if its value reaches a certain number.

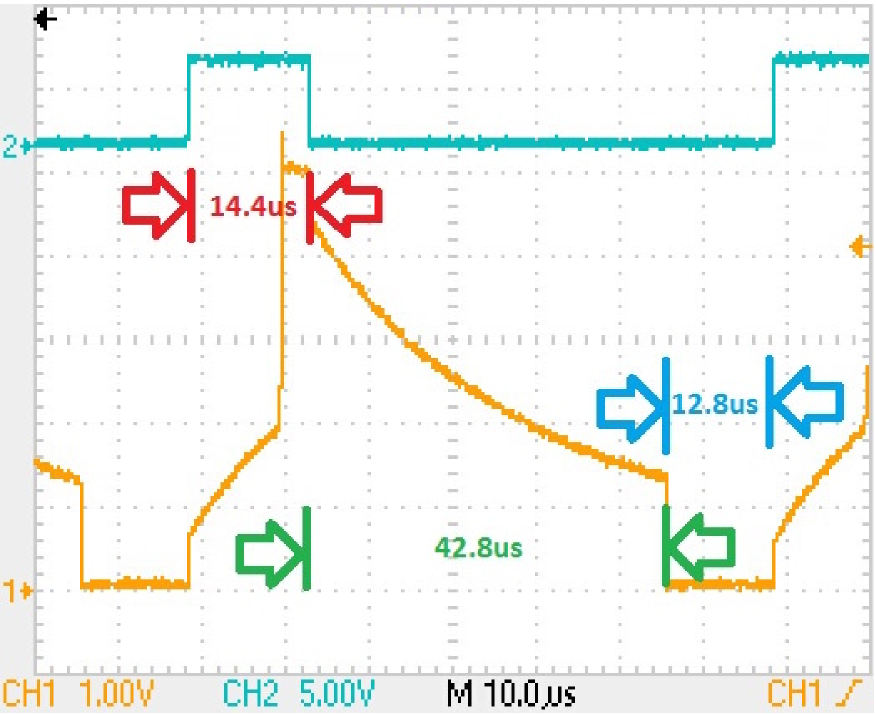


Figure 51: Signal at Receive Pin with No Touch

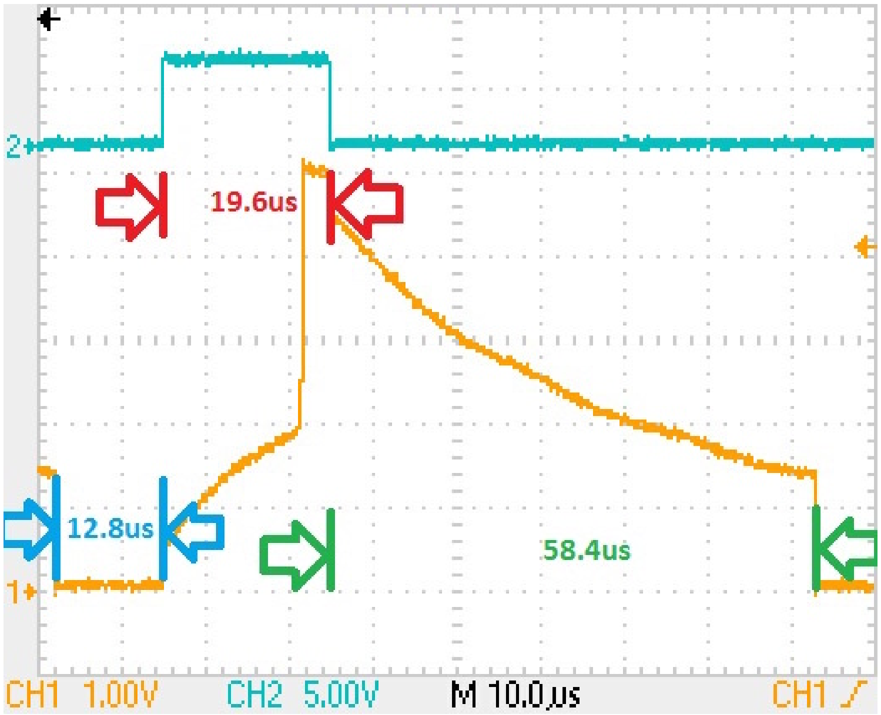


Figure 52: Signal at Receive Pin with Touch

As a simple check, Figure 53 shows another markup of the receive pin signal that was used to confirm the capacitance at this pin. From earlier testing it was found that the capacitance at should be 20.96 pF with the parasitic capacitance of the breadboard. Using Equation 10, a value for C was isolated and found to approximately match the expected value. Performing this comparison helped reassure that the behavior at the receive pin was functioning as expected with the specified resistance and capacitor values.

$$t_r = 2.2 * R * C \tag{10}$$

$$C = \frac{50\mu s}{2.2 * 1M\Omega} = 22.72pF \tag{11}$$

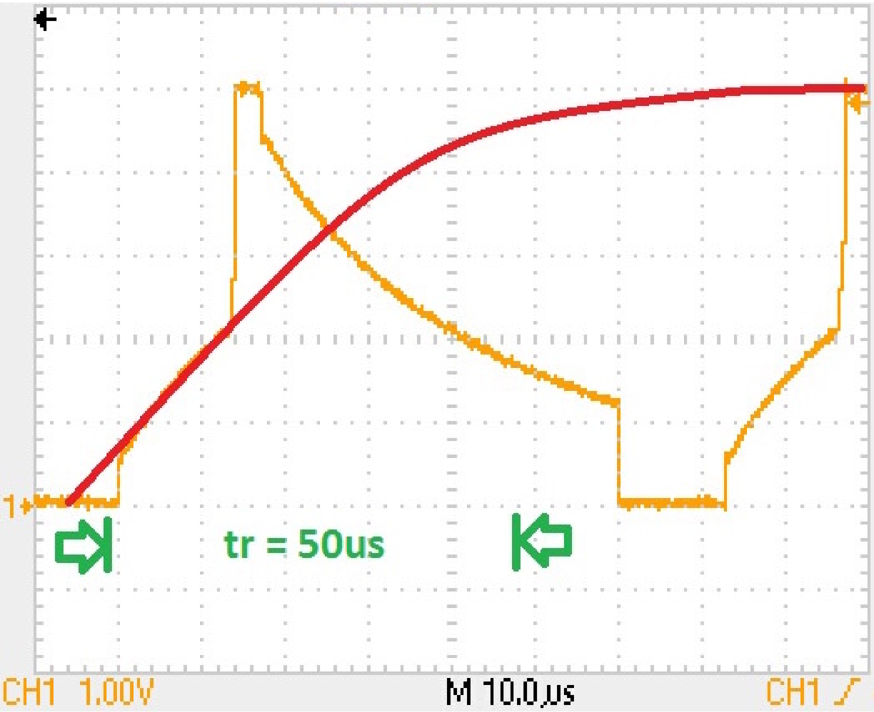


Figure 53: Extrapolating Risetime from Receiving Pin

After investigating both approaches for the capacitive touch sensor this approach was decided upon for the following reasons:

1. Simple straightforward design
2. Requires no external interrupts
3. Requires no additional hardware or integrated circuits
4. Quickly cycles through each capacitive pad
5. Arduino library available for programming through this method

5.1.6 Final PCB Design

With the optimal touch pad design determined in Section 5.1.3 above, the final capacitive touch pad PCB was designed with self capacitance style pads. Intuitive operation of the Power Panel is critical, making a simple and symbol-based button layout the focus. Since the touch pad is the only user input to the Power Panel, it must be able to control every aspect of the menu and programs within. Four directional arrows with a central select pad were considered a necessity for basic navigation of the menu. A back pad (top left) and menu pad (top right) were added for jumping between levels in the user programs. Finally, to aid in future expansion of the Power Panel software, two unassigned pads were added with a triangle and square label to allow the most flexibility when assigning an operation to them. With nine pads, a square layout was used, as it was most space space efficient. The maximum size allowed by the PCB manufacturer is 60 square inches, making PCB area a limitation. The final size is 8.25 inches by 7.25 inches and is shown below in Figure 54:

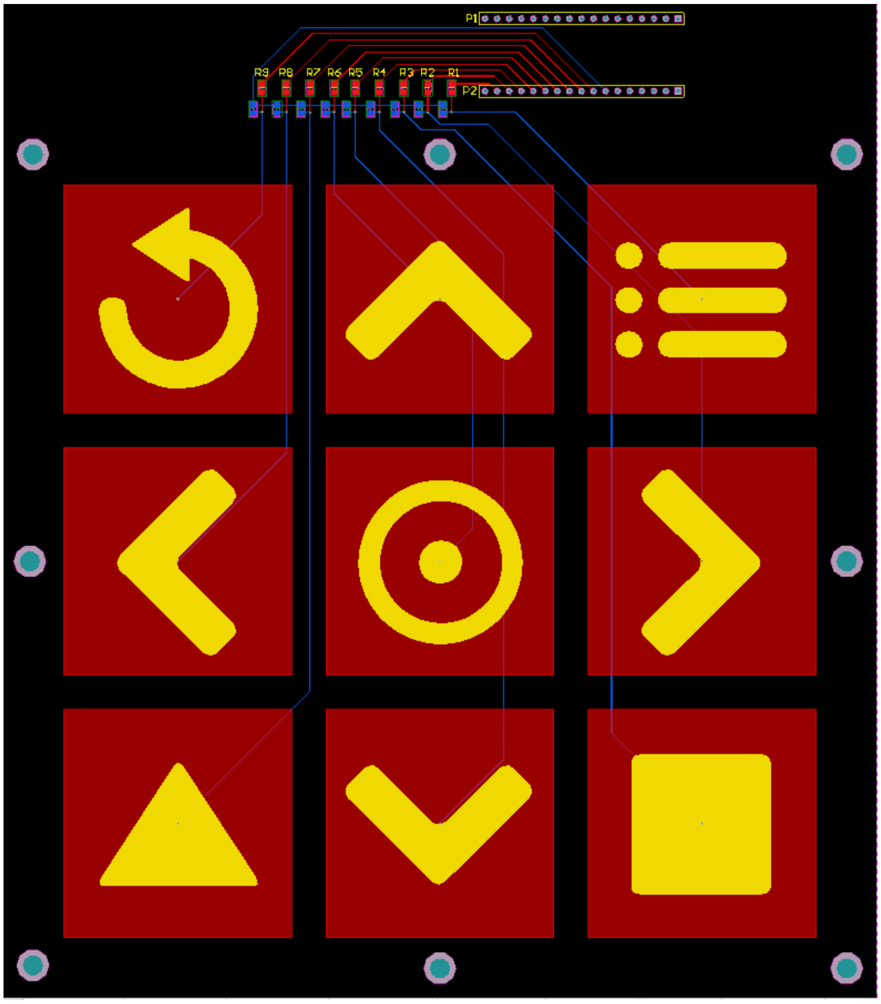


Figure 54: Final PCB layout. Red is top layer, blue is bottom layer, yellow is top overlay.

The PCB is a simple 2 layer board with the required sending and receiving pin resistors in surface mount form. The Arduino Micro is soldered directly to the PCB, making the only cable connecting the capacitive touch pad to the ODRIOD XU4 a micro USB cable carrying power and data. The top inch of the board is to be covered by a piece of aluminum preventing users from touching the exposed Arduino Micro pins or resistors. In order to further prevent users from triggering unwanted touches, only the pads themselves are on the top layer. All traces leading back to the Arduino Micro are on the bottom layer and are as small as possible (10 mil) to reduce their parasitic capacitance. Figure 55 shows the final PCB:

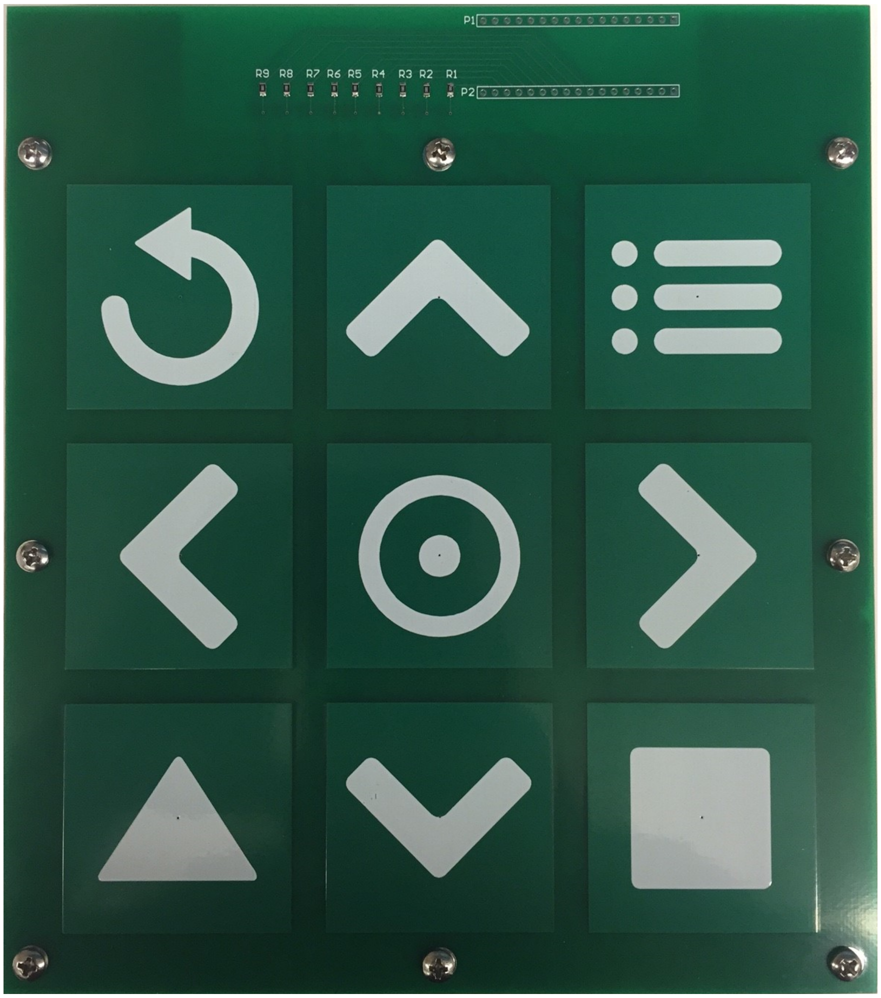


Figure 55: Final PCB with Components Installed

The PCB is 0.062 inches thick and is mounted to a wooden board to increase rigidity. There is a cutout in the top middle where the Arduino Micro protrudes and has its USB jack. The nine touch pads are clearly distinguished from the rest of the PCB by a slightly different shade of green.

5.2 Power and Wiring

In order to design the optimal solution with regard to power and wiring for the Power Panel, several options were considered. This section discusses the test results and theory that were considered while making design decisions. Two power supply configurations were considered with 5 V and 36 V rails. For the 36 V rails to provide the necessary 5 V to each individual panel, a DC/DC converter was tested and results are included in this section. Overall, because of the multiple displays as a result of the Main Display and Auxiliary Panels, the complexity and cost of powering the Power Panel was a large focus of design.

5.2.1 DC/DC Converter Testing

Before making a decision on any other power and wiring configurations, the DC/DC converter was tested to ensure it met its specifications. Due to the especially low price of the converters, there was concern that it might not meet its specifications due to poor quality control, small safety margins, or other cost cutting measures. Using an electronic load and monitoring both input and output voltages and current, the DC/DC converter was load tested. Two different input voltages of ≈34.5 V (slightly below the maximum of 36 V) and ≈24 V were used in the test. The converter was set to a 5.00 V output using the trim potentiometer when at no load and was not adjusted throughout testing. The electronic load was set to constant current mode, and measurements were taken at 0.5 A intervals from 0 A to the maximum continuously rated 5 A. Test results can be viewed in 11 where shaded rows represent results with a junction temperature above the maximum of 125°C assuming 25°C ambient temperature and a thermal resistance of 30°C/W.

Input Voltage [V]	Input Current [A]	Input Power [W]	Output Voltage [V]	Output Current [A]	Output Power [W]	Efficiency [%]	Power Dissipated by Converter [W]	Junction Temperature Above Ambient [°C]
34.5	0.09	3.11	5.00	0.5	2.50	80.52	0.61	18.15
34.5	0.18	6.21	5.00	1.0	5.00	80.52	1.21	36.30
34.5	0.26	8.97	4.99	1.5	7.49	83.44	1.49	44.55
34.5	0.34	11.73	4.99	2.0	9.98	85.08	1.75	52.50
34.5	0.43	14.84	4.98	2.5	12.45	83.92	2.39	71.55
34.5	0.51	17.60	4.98	3.0	14.94	84.91	2.66	79.65
34.5	0.60	20.70	4.99	3.5	17.47	84.37	3.24	97.05
34.5	0.69	23.81	4.99	4.0	19.96	83.85	3.85	115.35
34.5	0.78	26.91	4.99	4.5	22.46	83.44	4.46	133.65
34.5	0.88	30.36	4.98	5.0	24.90	82.02	5.46	163.80
23.9	0.12	2.87	4.99	0.5	2.50	86.99	0.37	11.19
23.9	0.24	5.74	4.99	1.0	4.99	86.99	0.75	22.38
23.9	0.36	8.60	4.99	1.5	7.49	86.99	1.12	33.57
23.9	0.48	11.47	4.99	2.0	9.98	86.99	1.49	44.76
23.9	0.60	14.34	4.99	2.5	12.48	86.99	1.87	55.95
23.9	0.73	17.45	5.00	3.0	15.00	85.97	2.45	73.41
23.9	0.86	20.55	5.01	3.5	17.54	85.31	3.02	90.57
23.9	0.99	23.66	5.02	4.0	20.08	84.87	3.58	107.43
23.7	1.12	26.54	5.02	4.5	22.59	85.10	3.95	118.62
23.7	1.25	29.63	5.01	5.0	25.05	84.56	4.58	137.25

Table 11: Load Testing of XL4015 DC/DC Converter Board

The DC/DC converter proved to be able to produce a 5 V output at loads up to 5 A. It's efficiency remained in the 80% range as expected. However, at currents above ≈3 A, both the IC and the output inductor increased in temperature so much that the test was only run for a few seconds at these higher currents. Although a small heat sink was attached to the IC with an adhesive, the thermal pad of the IC was soldered directly to the PCB, limiting the effectiveness of the heat sink. Although the converter board was marketed at being able to supply 5 A, clearly this value was only possible with a heat sink with an appropriate power dissipation, not a simple PCB heat sink. Unfortunately, the XL4015 with board was the only DC/DC converter within budget, making the option of using higher voltage rails unfeasible. The following power supply analysis was started prior to testing of the XL4015 DC/DC converter, and therefore assumes it works as specified. Although the DC/DC converter was often the ideal option, its inability to perform as needed forced the choice of a 5 V option.

5.2.2 Power Supply Configurations

Two power supply options are analyzed in this section. The first option is to power the panels with 5 VDC directly from the AC/DC converters. This simplifies the power system by avoiding the need of additional DC/DC step down converters. However, the relatively low voltage delivering high power results in higher current, forcing the use of lower gauge wire and increasing voltage drop. Adding individual DC/DC step down converters to each panel opens up the possibility of running higher voltage DC to the panels, resulting in lower current in the relatively long power supply wires.

5 Volt Supply Rails Since the LED panels run off of 5 VDC, one option is to power the panels with 120 VAC to 5 VDC switching converters. Figure 56 shows the equivalent circuit of a single 120 VAC to 5 VDC power supply delivering 5 V directly to a panel, including wire resistances.

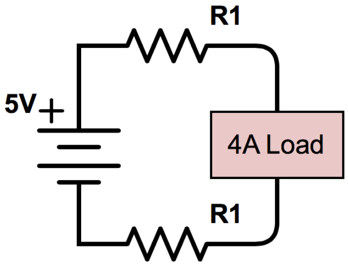


Figure 56: Equivalent Circuit for a Single Panel Connected to a 5 V Power Supply with Wire Resistances R1.

For a single panel, the voltage drop is calculated as follows:

$$V_{load} = V_{supply} - (I_{load} * 2R_1) \tag{12}$$

When multiple panels are connected to a single power supply output, they will be wired in parallel as shown in Figure 57.

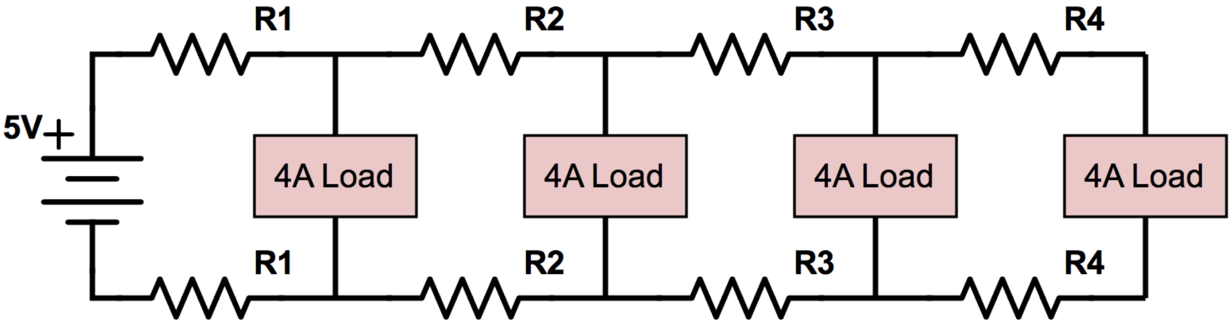


Figure 57: Equivalent Circuit for Four Panels Connected in Parallel to a 5 V Power Supply with Wire Resistances R1, R2, R3, and R4.

With four panels connected in parallel, the fourth panel is the limiting factor, as it will always experience the largest voltage drop. Therefore, for the following calculation, where

N is the number of panels in parallel, the voltage drop can be defined as the voltage drop at the last panel wired in parallel. See Appendix E for the full derivation.

$$V_{load} = V_{supply} - I_{load} * R_{\frac{\Omega}{Foot}} * 1000 * 12 * l * \frac{N(N+1)}{2} \tag{13}$$

$$V_{supply} = V_{supply} * I_{load} * N \tag{14}$$

36 Volt Supply Rails Another option for powering the panels is to run higher voltage DC rails and step down that high voltage DC to 5 VDC at each panel with a separate DC/DC buck converter. Since the DC/DC converter chosen has a maximum input voltage of 36 VDC, 36 V power supplies were used in the following calculations through Equation 13 where V_{load}=$V_{DC/DC}$.

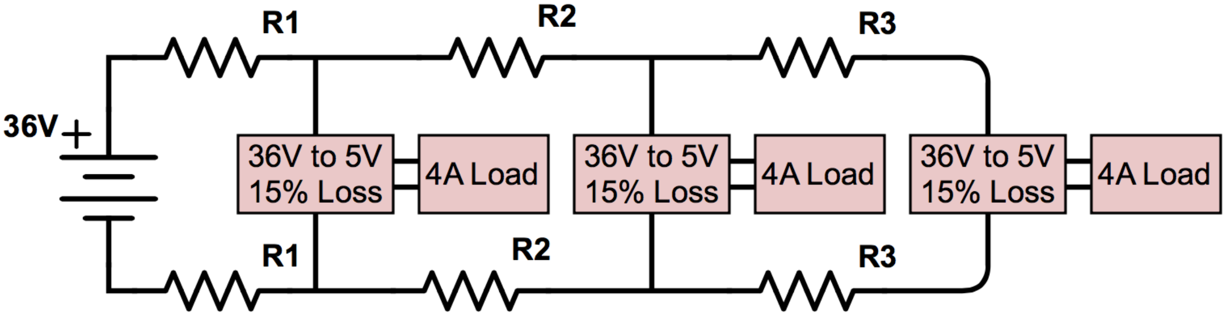


Figure 58: Equivalent Circuit for Four Panels Connected in Parallel to a 36 V Power Supply with Wire Resistances R1, R2, R3, and R4, and DC/DC Step Down Converters Directly Powering LED Panels.

The voltage for each panel is regulated by the DC/DC buck converter to 5 V. Although the DC/DC converters solve the problem of too low of a voltage to the LED panels, they are not 100% efficient, and therefore require more total power. Figure 58 shows an efficiency of 85% at a 4 A load when stepping down from 36 V to 5 V. With this 15% loss of power in each DC/DC converter, the power supply requirement can be calculated as seen in the equation below (see Appendix E for full derivation).

$$P_{supply} = 23.529 * N \tag{15}$$

5.2.3 LED Display Wiring Configurations

In determining the optimal wiring scheme for all displays in the Power Panel, the overall layout of the displays was considered. Some groups of displays have the potential to be powered individually or together with nearby displays.

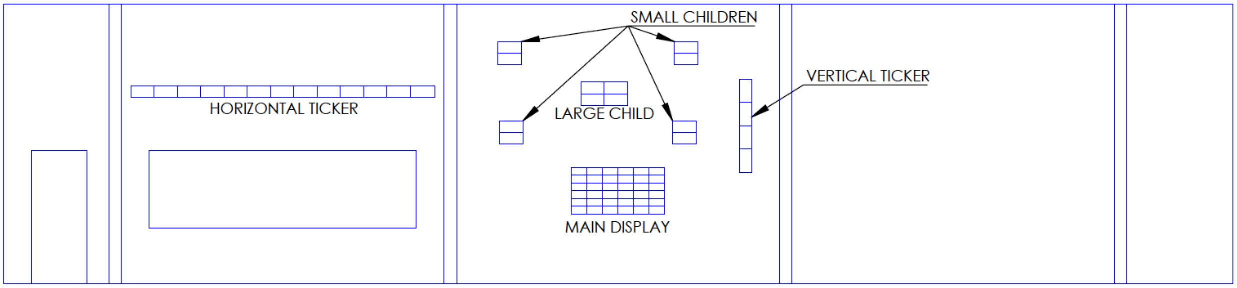


Figure 59: General Placement of All Displays on Wall of Atwater Kent Pumpkin Lounge

A few of the displays - the Main Display and the Horizontal Ticker - were large enough to warrant their own power supplies. However, the cluster of Children Displays have the option to be all powered by a central unit, as is explored later in this section. Table 12 summarizes the multiple options for power and wiring configurations, where shaded rows indicate selected options. Each of the configurations are described throughout the remainder of this section.

Display(s)	Configuration	Number of Panels	Total Power Required	Number of Power Supplies	Power Required Per Power Supply [W]	Power of Selected Power Supply [W]	Margin of safety [%]	Maximum Current of Panels in Parallel [A]	Smallest Acceptable Wire Gauge	Voltage at last panel in parallel [V]	Total Cost [$]
Main Display	Multiple 5V Supplies	36	720	3	240	300	20	12	10	4.98	126.89
Main Display	Multiple 36V Supplies	36	847.05	3	282.35	349.2	19.14	1.96	18	35.98	180.45
Horizontal Ticker	Single 5V Supply	12	240	1	240	300	20	24	8	4.92	70.83
Horizontal Ticker	Multiple 5V Supplies	12	240	3	80	110	27.27	8	12	4.97	90.9
Horizontal Ticker	Single 36V Supply	12	282.35	1	282.35	349.2	19.14	3.92	14	35.95	73.35
Vertical Ticker	Single 5V Supply	4	80	1	80	110	27.27	8	12	4.97	29.6
Vertical Ticker	Single 36V Supply	4	94.11	1	94.11	110	14.43	1.30	18	35.98	38.54
Large Child	Single 5V Supply	4	80	1	80	110	27.27	4	14	4.98	104.1
Small Children (x4)	Individual 5V Supplies	2	40	1	40	50	20	4	14	4.98	
Large and Small Children	Central 5V Supply	12	240	1	240	300	20	8	12	4.92	57.23
Large and Small Children	Central 36V Supply	12	282.35	1	282.35	349.2	19.14	1.30	18	35.94	70.15

Table 12: Summary of Power and Wiring Configurations. Shaded Rows Indicate the Chosen Options.

Main Display The Main Display uses 36 4 mm pixel pitch LED panels in a six panel wide by six panel high grid as shown in Figure 60 where each small rectangle represents an individual LED panel.

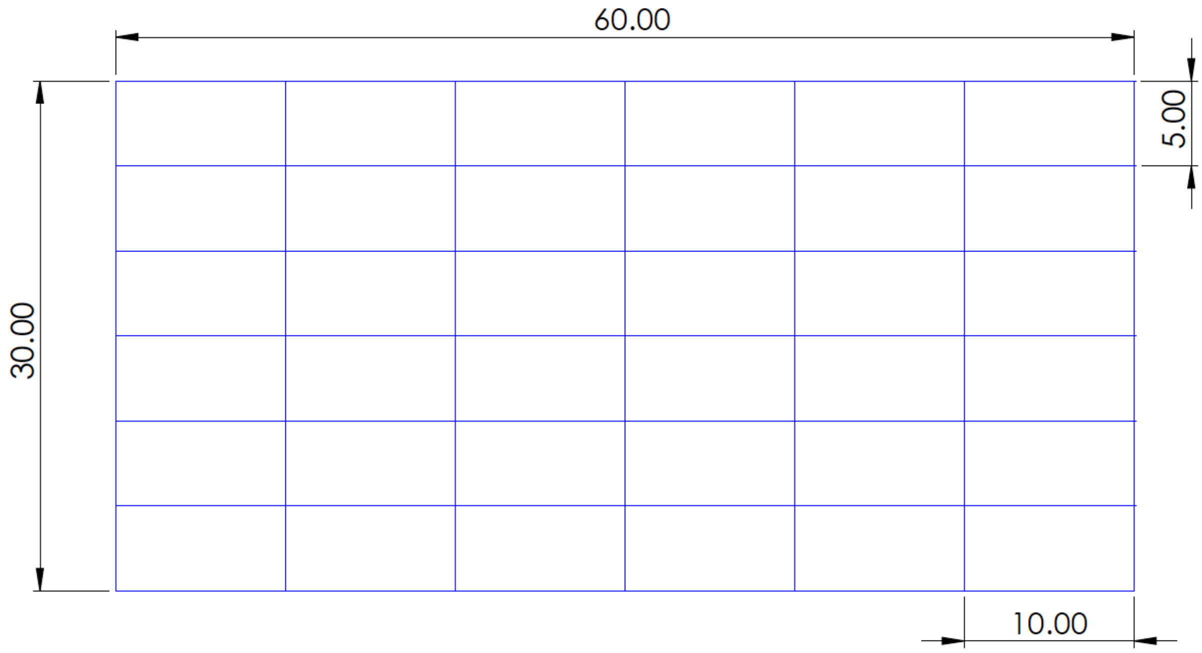


Figure 60: Dimensions of Main Display in Inches

The total power draw of the Main Display is 720 W. Because the most powerful 5 V LRS series power supply is 300 W, at minimum three separate power supplies are required to power the Main Display. The 36 panels can be broken into three groups of 12 panels with each group drawing 240 W, with an adequate margin of safety of 20%.

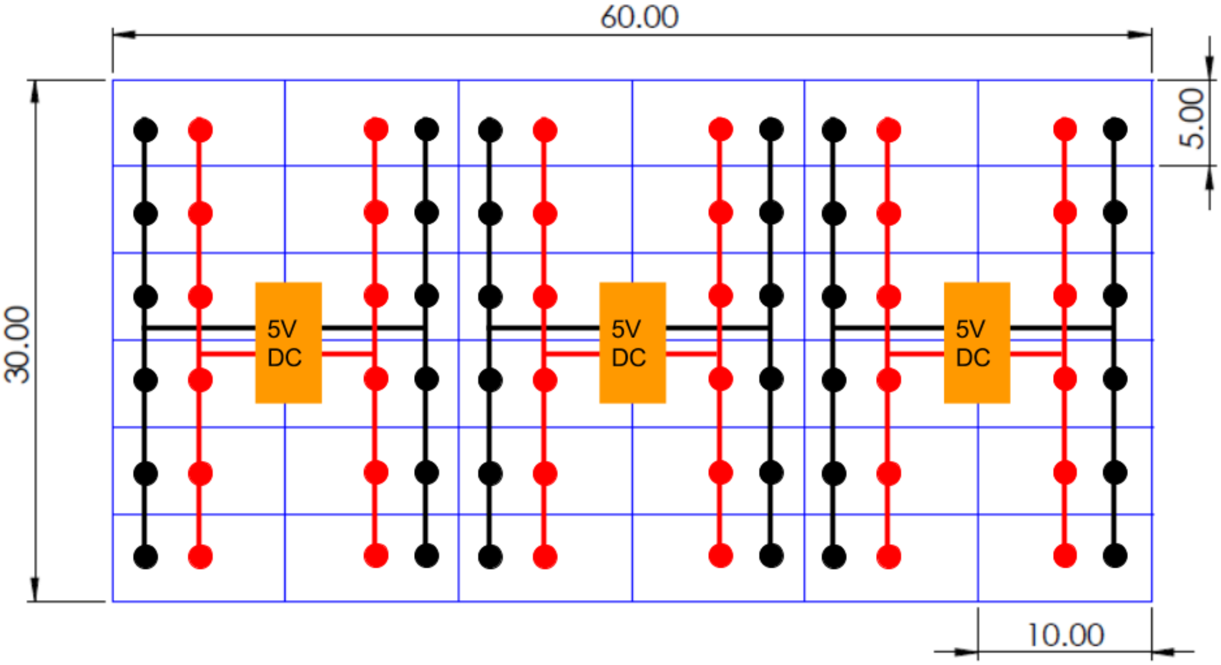


Figure 61: Main Display Power Supply and Wiring Configuration Using Three 5 V Power Supplies

In order to reduce the wire lengths from the power supplies to the panels, the power supplies will be centered on each group of 12 panels. Each power supply will power four groups of three panels wired in parallel. This wiring configuration will minimize the current through the wires to a maximum of 12 A. The 12 A of current requires 10 AWG wire according to Table 7. Accounting for the resistance of 10 AWG wire, the voltage delivered to the third panel wired in parallel is 4.99 V which is well within the 10% voltage drop range. The total cost of this scheme including the three 300W power supplies and 10 AWG wire is $126.89.

Using 36 V power supplies with individual DC/DC step down converters results in a similar wiring layout, with only the addition of the converters at each panel. The higher voltage buses allow for a much smaller wire, in this case 18 AWG to carry the maximum of 1.96 A. The smaller gauge wire is easier to work with and less expensive, but the addition of DC/DC converters adds complication and cost. The total cost of the 36 V setup, including power supplies, wiring, and DC/DC converters is $180.45.

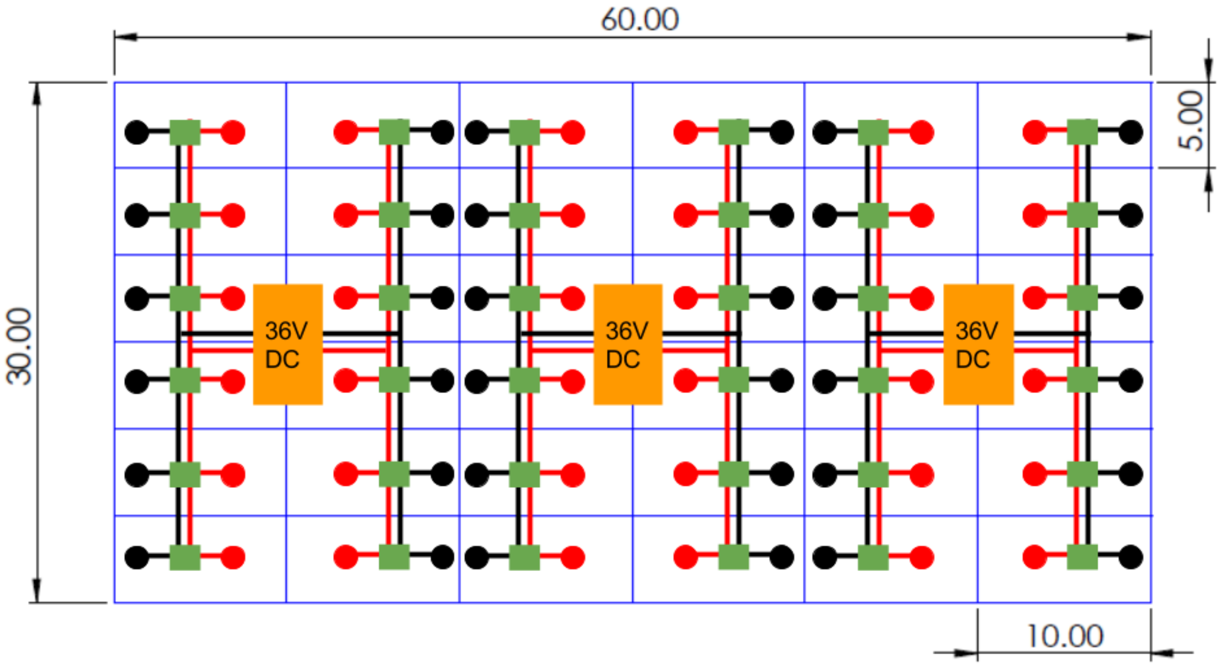


Figure 62: Main Display Power Supply and Wiring Configuration Using Three 36 V Power Supplies (Green Boxes Indicate DC/DC Converters)

Due to the minimal benefits of the 36 V power scheme over the 5 V one, the Main Display will be powered directly with 5 VDC using the lower gauge wire.

Horizontal Ticker The Horizontal Ticker uses 12 6 mm pixel pitch LED panels in a single twelve panel wide row. Figure 63 shows the dimensions of the Horizontal Ticker, where each small rectangle represents an individual LED panel.

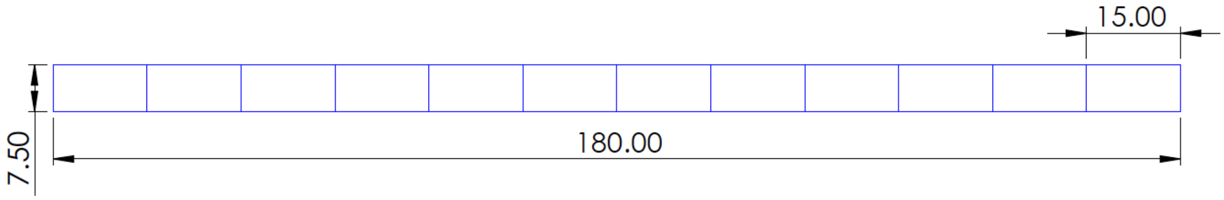


Figure 63: Dimensions of Horizontal Ticker in Inches

The 12 panels in the Horizontal Ticker essentially make it one third of the Main Display. However, due to the linear layout, the panel grouping is not possible with the Horizontal Ticker as it was with the Main Display. Because the maximum power required by the Horizontal Ticker is 240 W, it can be powered by a single 300 W 5 V power supply with a 20% safety margin. The linear layout forces six panels to be wired in parallel where the power supply is placed in the middle. This wiring configuration results in a maximum of 24 A, requiring 8 AWG wire. The longer wire run results in a larger voltage drop, causing the sixth panel in parallel to receive 4.93 V. Despite the low gauge wire, this configuration costs the least, at $70.83, due to only using one power supply.

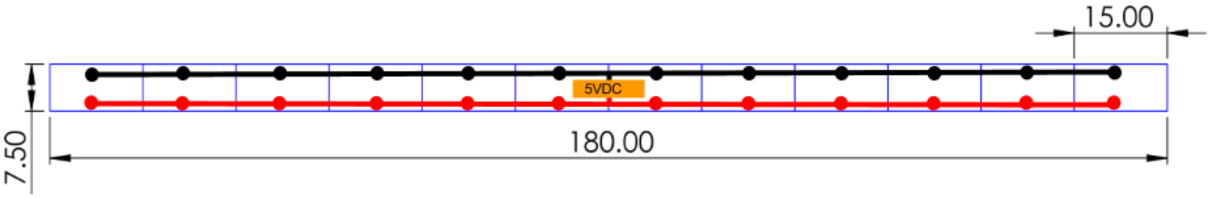


Figure 64: Power Supply and Wiring Configuration Using a Single 5 V Power Supply

To reduce the maximum current, thereby increasing the required wire gauge, the 12 panels could be split into three groups of four. With one power supply mounted in the center of each group of four panels, only two panels would need to be wired in parallel. Four panels require 80 W, so 110 W 5 V power supplies can be used with a 27% percent margin of safety. The two panels in parallel draw 8 A maximum, requiring 12 AWG wire. Voltage drop is minimal, with 4.93 V supplies to the second panel in parallel. The total cost of this configuration with three power supplies is $90.90.

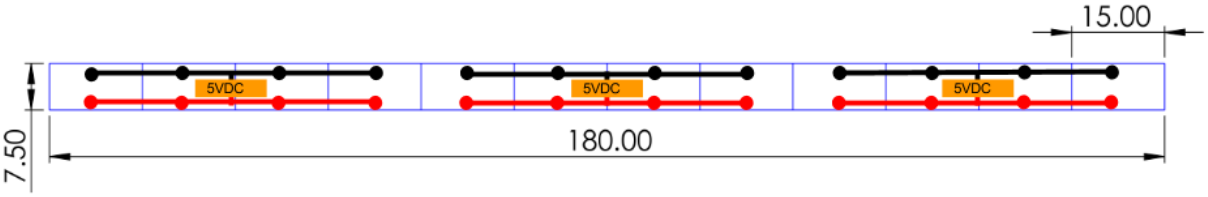


Figure 65: Power Supply and Wiring Configuration Using Three 5 V Power Supplies

If using a higher voltage 36 V rail, then only a single power supply configuration should be considered, as the voltage drop and wire gauge is not as much of a concern. Smaller 14 AWG wire is required due to the maximum 3.92 A current draw. The cost of the 36 V version is $73.35, higher than the 5 V version due to the addition of the DC/DC converters.

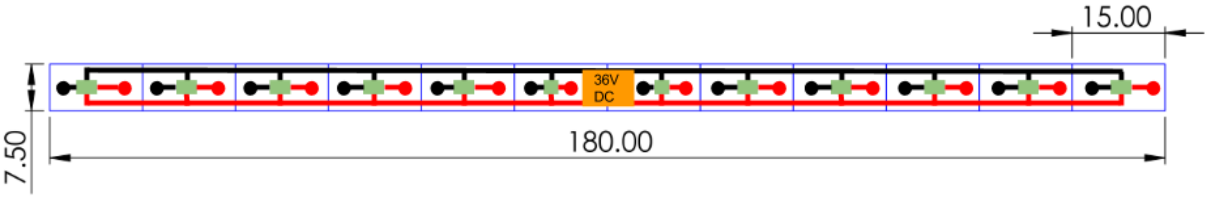


Figure 66: Power Supply and Wiring Configuration Using a Single 36 V Power Supply (Green Boxes Indicate DC/DC Converters)

Unlike the Main Display, the Horizontal Ticker benefits from the reduced current of 3.92 A in the 36 V rail design. Instead of needing 8 AWG or 12 AWG wire, smaller 14 AWG wire would be used. The additional cost of the DC/DC converters is nearly offset by the smaller wire needed. However, as discovered in Section 5.2.1, the DC/DC converter did not meet specification and could not continuously supply 4 A at 5 V. Therefore, the 36 V configuration is not a possibility. Of the two 5 V supply options, the three supply version was chosen over the single supply version due to the significantly lower current involved - 8 A versus 24 A. Although 8 AWG wire would be sufficient for carrying the 24 A, high DC currents were avoided due to safety, and 8 AWG crimp terminals are much less common than 10 AWG or higher crimp terminals.

Vertical Ticker The Vertical Ticker uses 4 6 mm pixel pitch LED panels in a single four panel high column as seen in Figure 67 below where each small rectangle represents an individual LED panel.

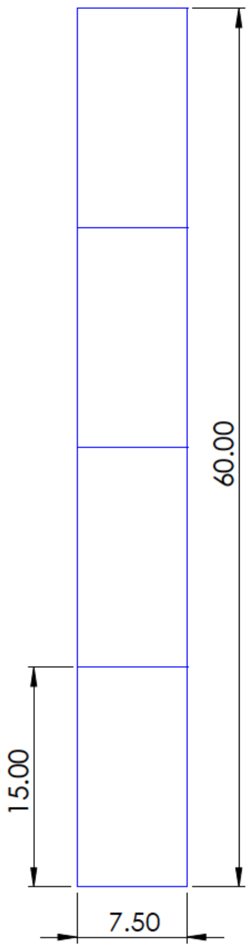


Figure 67: Dimensions of Vertical Ticker in Inches

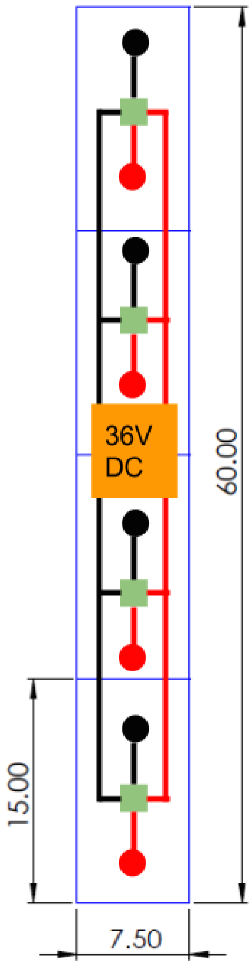


Figure 68: Power Supply and Wiring Configuration Using a Single 36 V Power Supply (Green Boxes Indicate DC/DC Converters)

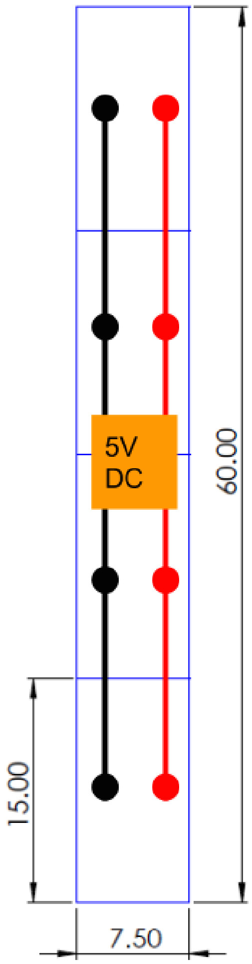


Figure 69: Power Supply and Wiring Configuration Using a Single 5 V Power Supply

Since the Vertical Ticker is one third of the Horizontal Ticker, the reasoning behind the Horizontal Ticker's 5 V three power supply configuration applies directly to the Vertical Ticker. Only the cost differs, being one third of the Horizontal Ticker, or $29.60. 12 AWG wire would still be required given the maximum current of 8 A.

A 36 V rail configuration shown in Figure 68 can be used with the Vertical Ticker as well, however due to the shorter length compared to the Horizontal Ticker, the benefits are less pronounced. The maximum current would be 1.30 A, requiring 18 AWG wire. Including power supplies, wire, and DC/DC converters, the 36 V configuration would cost $38.54. The minimal benefit of the 36 V option again makes the 5 V configuration the primary choice for the Vertical Ticker.

Children Displays The Children Displays use 6 mm pixel pitch LED panels in either a one panel wide by two panel high square (2 panels) or a two panel wide by two panel high rectangle (4 panels). Figure 70 shows the dimensions of the Small and Large Children where each small rectangle represents an individual LED panel.

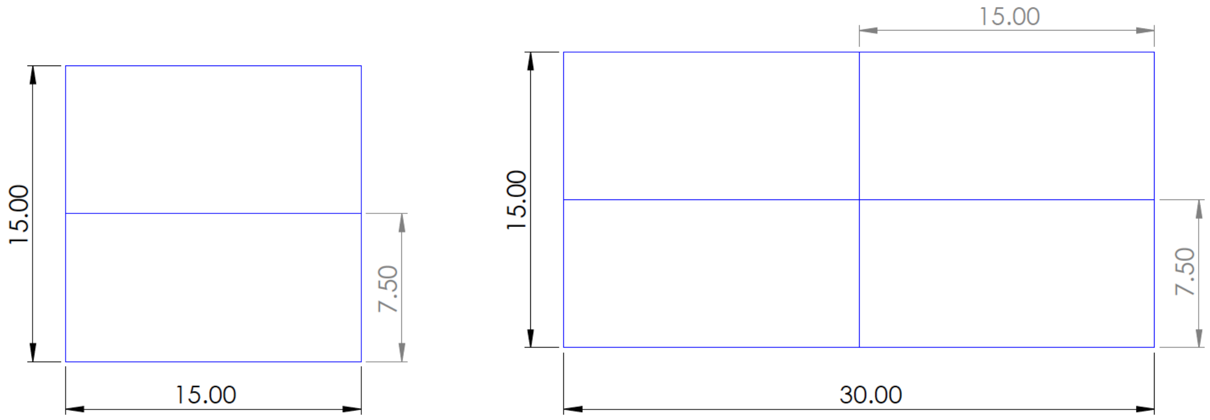


Figure 70: Dimensions of Small Children (Left) and Large Child (Right) in Inches

Due to the proximity of the Children Panels, there is the possibility of powering all of them with a central power supply located at the Large Child, in addition to the option of individually powering each Child.

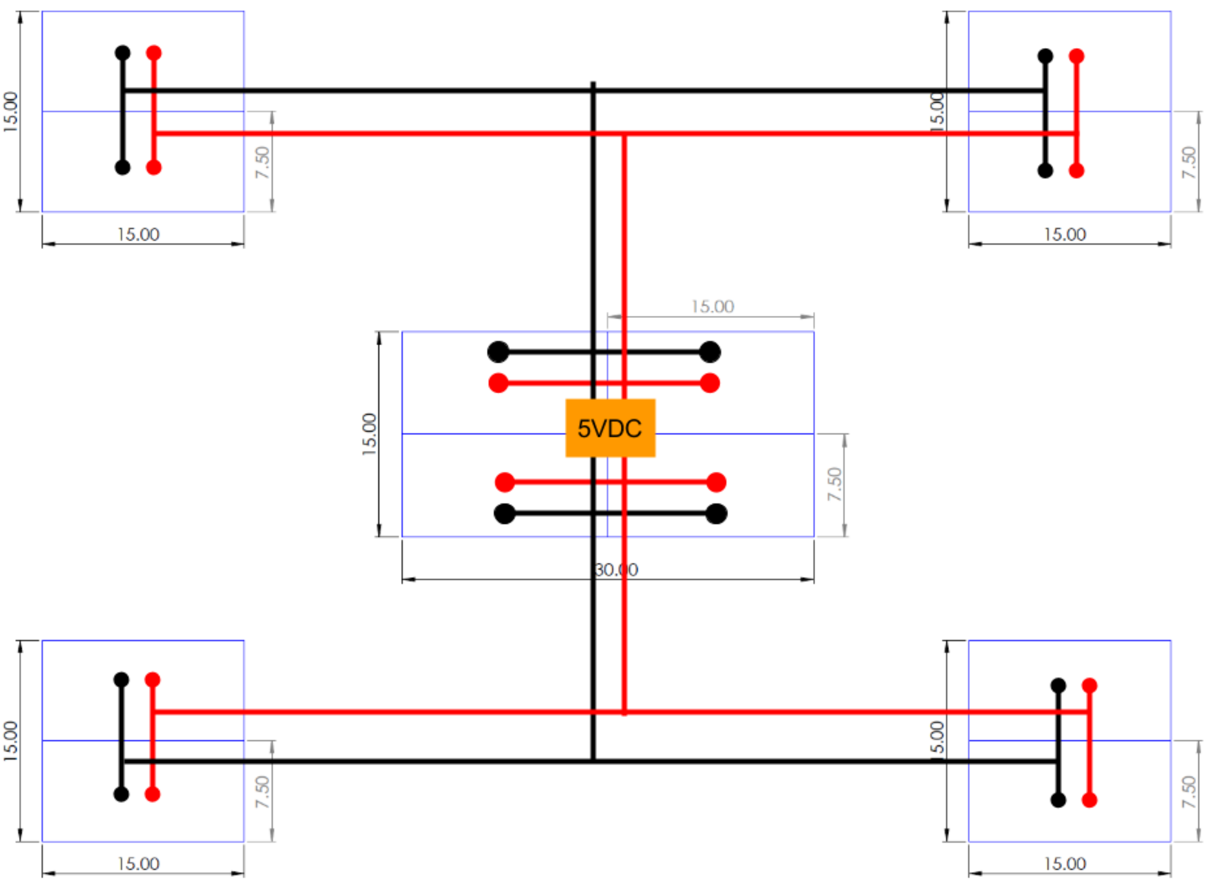


Figure 71: Power Supply and Wiring Configuration Using a Single 5 V Power Supply for all Children Displays.

The central 5 V power supply option reduces component count and therefore cost. However, the long power wires from the Large Child to the Small Children incur significant voltage loss. Because the Small Children only draw a maximum of 8 A at 5 V, the long power wires do not have to be excessively thick. 12 AWG wire would be required between the Large Child and each of the Small Children displays. The total cost of this configuration is $57.23.

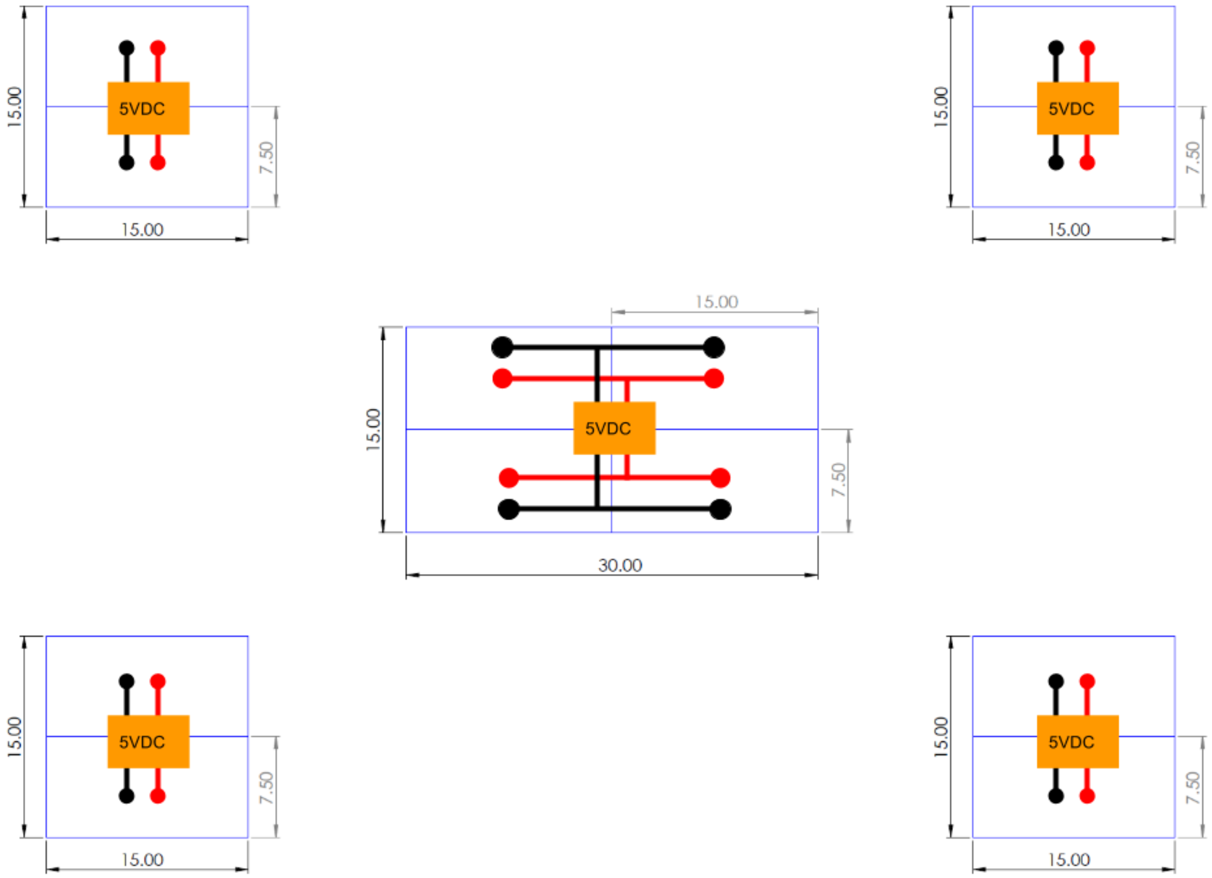


Figure 72: Power Supply and Wiring Configuration Using Individual 5 V Power Supplies for Each Children Display.

Having each Child Display use its own 120 VAC to 5 VDC power supply eliminates the DC power wires connecting each of the Children Panels together but costs significantly more at $104.10. Wire gauge can be reduced to 14 AWG because each panel would be wired directly to the power supply with no paralleling.

Finally, a 36 V wiring configuration is also a possibility, with the 36 V power supply still centrally located at the Large Child. The 36 V rails reduce the current and wire gauge requirement to 1.31 A and 18 AWG respectively. This configuration would cost $70.15, right between the two 5 V options. The combination of low cost and small current and wire requirements make the 36 V power supply option ideal for the Children Displays. However, as mentioned above with the Horizontal Ticker, the 36 VDC to 5 VDC converters were found to be unable to sustain a 5 A load without overheating.

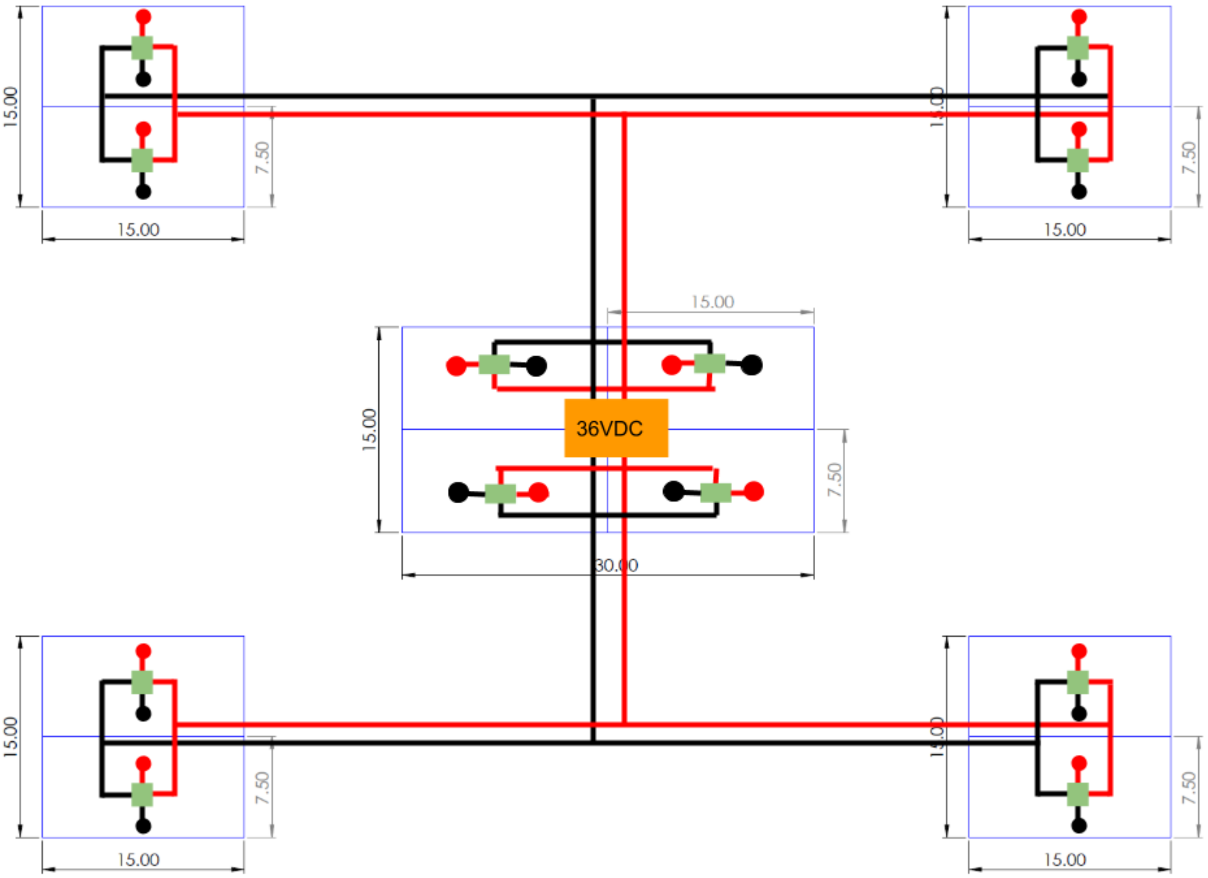


Figure 73: Power Supply and Wiring Configuration Using a Single 36 V Power Supply for All Children Displays (Green Boxes Indicate DC/DC Converters)

Of the two 5 V power configurations, the individual 5 V scheme was chosen due to the reduction in length of high current DC wiring, and less reliance on single power supply.

5.3 Frame Design

All of the display designs involve combining two or more LED panels into a seamless surface. Due to the custom shapes and orientations of the displays, an equally custom frame was required for each display. All of the panels have six M3 threaded inserts on the back as seen in Figures 19 and 21. Additionally, each panel shipped with four M3 screws terminated in a neodymium magnet, making it possible to attach the panel to any magnetic surface. Several types of frames were considered in the initial design process:

- Wooden board with cutouts for power and data connections. The panels would be mounted directly to the wood using M3 screws though the wood into the threaded inserts.
- Sheet metal backed wooden board or steel grid that the panels could be magnetically attached to using the included magnetic screws.

- Steel angle grid that panels would be mounted directly to using M3 screws.
- Aluminum angle grid that panels would be mounted directly to using M3 screws.

Each option has inherent benefits and drawbacks that are discussed in Table 13 below.

Pros	**Cons**
Wooden Board	
• Inexpensive • Single piece that requires no additional assembly	• Would require large CNC router • Would need to be thick for strength
Magnetically Attached Steel	
• Alignment is not critical • Easy to remove panels for maintenance	• Panels could come out of alignment easily • Panels are easily stolen • Heavy
Steel Grid	
• Secure mounting of panels • Very stiff • Cheaper than aluminum	• Heavier than aluminum • Needs to be precisely aligned • Difficult to machine
Aluminum Grid	
• Secure mounting of panels • Lighter than steel • Easy to machine	• Needs to be precisely aligned • Not very stiff • More expensive than steel

Table 13: Comparison of LED Panel Frame Options

Since security and permanent mounting are primary concerns, magnetically mounting the panels, although convenient, is not a viable option. In order for the wooden board method to be successful, all of the holes would have to be drilled by a CNC machine. While this method may work for some of the smaller Auxiliary Displays, the Main Display and both Tickers are too large to fit in the beds of the CNC mills available in WPI's machine shops. The design of the remaining two options, steel and aluminum grids, are both very similar. Steel was initially considered due its lower cost compared to aluminum. However, the strength and weight of steel was determined to be unnecessary for the purpose of the frames. Aluminum's easy machinability and light weight made it the ideal choice for the panel frames.

The entire frame is constructed from 6063 aluminum angle. The extruded angle aluminum has the stiffness of a much heavier and more expensive solid bar while remaining light weight and easy to machine. 6063 aluminum is not as strong as some other grades of aluminum but is considered architectural aluminum, therefore all angles are sharp 90 degree corners instead of rounded edges. Figure 74 shows a model of the frame (red and blue) used to support the LED panels (green) for the Main Display.

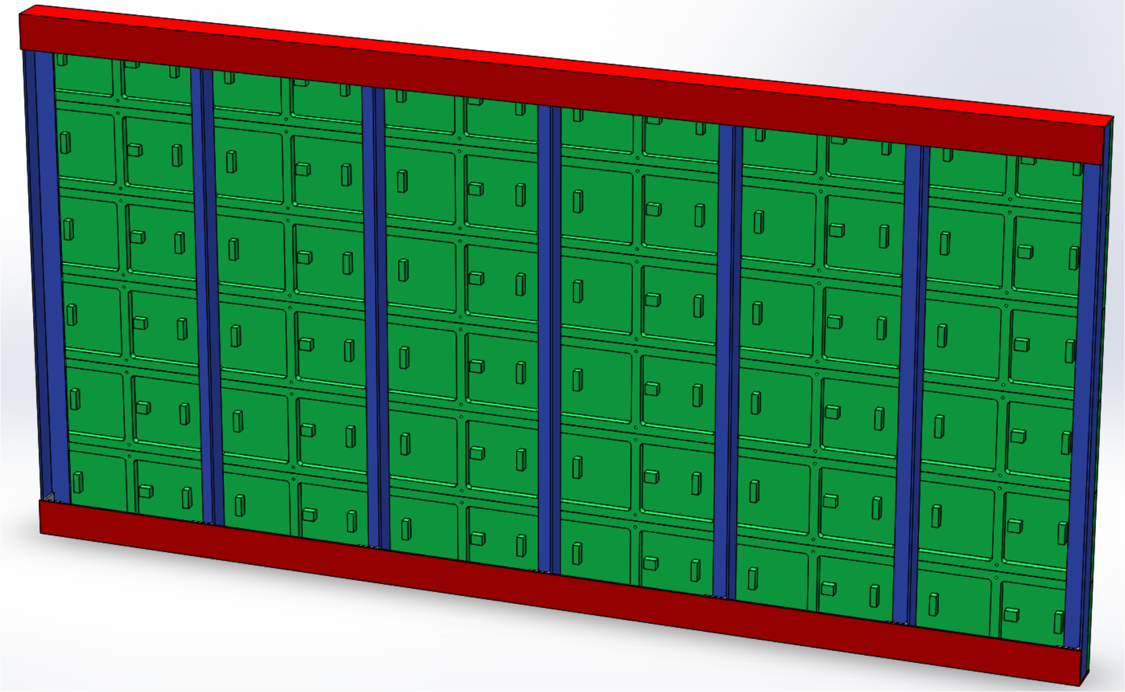


Figure 74: Aluminum Frame (Red and Blue Components) Used for Main Display with LED Panels (Green Components)- Back View

The aluminum shown in red is 2 inch by 1/8 inch angle, and the aluminum shown in blue is 1.25 inch by 1/8 inch angle. The approximate wight of the aluminum alone is 10 pounds, making the Main Display weigh approximately 35 pounds, which includes the LED panels and the power supplies. All other Auxiliary Displays use a similar frame design to reduce construction and assembly time. Figure 75 below shows the Main Display fully assembled.

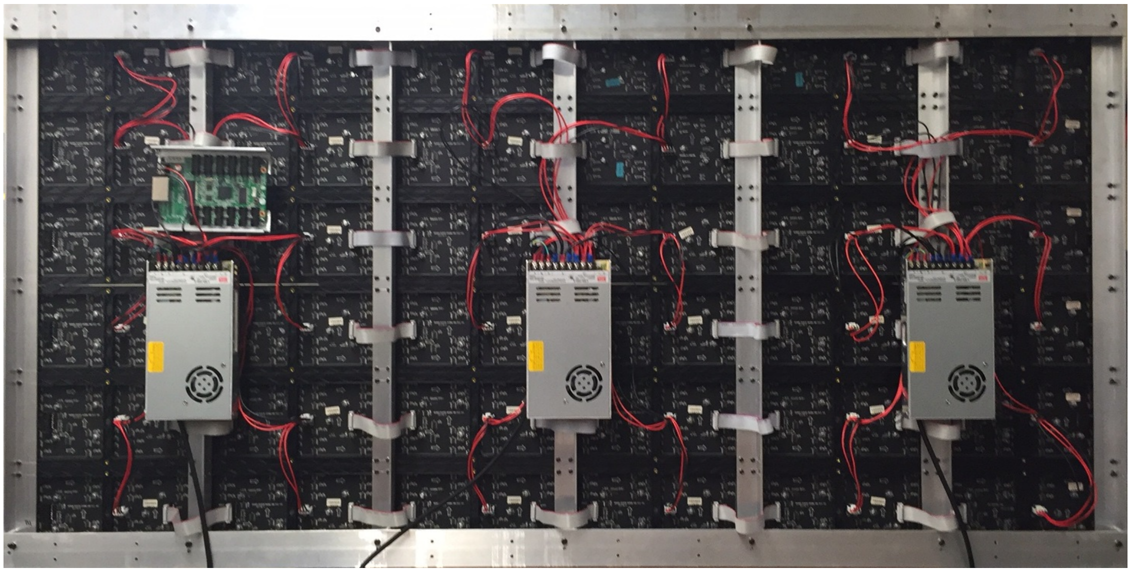


Figure 75: Fully Assembled Main Display - Back View

The visible portions of the frame on the top, bottom, and sides were treated with an abrasive bristle brush creating a visually appealing look.

5.4 Wireless Solar Panel Data Transfer

One of the goals of the Power Panel is to create a display for the power produced by solar panels on the roof of Atwater Kent. The cable carrying power from the panels currently enters the building through the ceiling in AK317. In order to prevent having to route this cable from the access point on the third floor to the Pumpkin Lounge, located on the first floor, a reliable wireless transmission system was established using XBee modules. Other options such as Bluetooth and WiFi/Ethernet connectivity were also considered. Bluetooth, however, has a limited range of connectivity between two points and therefore would not be able to transmit data successfully. Connecting to WPI's WiFi is restricted by strict security requirements of the institution's network. XBee modules are low power embedded systems that use the Zigbee wireless data transmission protocol to establish reliable transmission. Figure 76 shows the two XBee modules used. One was used with an Arduino Uno while the other was used with an adapter dongle allowing the XBee to communicate with a computer via USB.

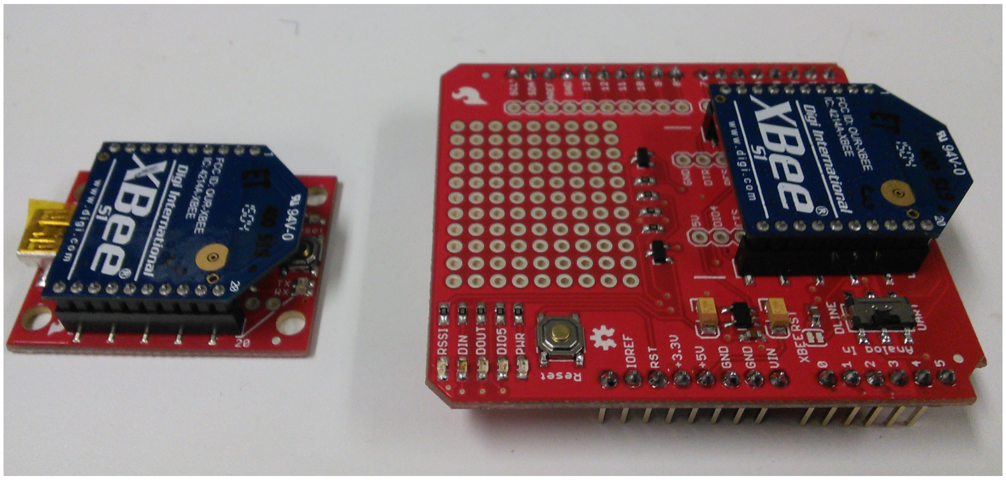


Figure 76: XBee Modules Used for Wireless Communication

These XBee modules will be used in conjunction with one of the previous MQP's, "The Grid Independent Solar Charging Display." An Arduino Uno will be fed voltage data directly from the solar panel and current data from one of the Hall Effect sensors available. This data will then be transmitted directly from AK317 to the Pumpkin Lounge using the Xbee modules. Code was written in Arduino and Processing to ensure communication and proper data display.

5.5 Component Product Certifications

Many of the components used in the Power Panel meet one or more internationally recognized certifications. These standards ensure that the product is guaranteed to perform under specified conditions and was crucial for use in the Panel. Below Table 14 summarizes the certifications met by the components used in this project.

Component	Standards	RoHS Complaiant
64x32 P4 and P6 LED Matrix Panels	CE; CCC; Back of Panel: IP40; Front of Panel: IP50	Yes
LED Display Sending/Receiving Cards	CE	Yes
Mean Well LRS AC/DC Power Supplies	UL60950-1; IEC/EN60335-1(PD3); IEC/EN61558-1, -2 -16; EN55022; EN55014	Yes
XL4015 DC/DC Converter	N/A	N/A
Capacitive Touch PCB	IPC Class II	No
ODRIOD XU4	EN 55022:2010/AC:2011; EN 55024:2010; EN 61000-3-2:2014; EN 61000-3-3:2013	N/A
XBee RF Module	CE; Part 15 FCC, IEEE 802.15.4	Yes
Arduino Micro	N/A	N/A
10 AWG Wire	UL 1581	N/A
AC Power Cords	UL; cUL	Yes
18 AWG Ring Terminal	UL; ASTM B-152; ASTM B-545	Yes
10 AWG Ring Terminal	N/A	Yes
10 AWG Butt Splice	1-UL Listed; CSA Listed	N/A
Ribbon Cable	2005/95/EC	Yes
IDC Connectors	UL	Yes
0805 Resistors	AEC-Q200; UL; EN 60115-1; EN 140400; EN 140401-802; IEC 60068-2-x	Yes
6063 Aluminum Angle	ISO 9001:2008; AMS-QQ-A 200/8; ASTM B308	Yes
Hammond Watertight ABS Enclosure	IP 66; NEMA 4, 4X, 12 & 13; UL94 HB	Yes
Hammond Cord Grip	NEMA 4; IP68 UL94-V2; UL; CSA; VDE	Yes

Table 14: Certifications and RoHS Compliance of All Components Used in the Power Panel

6 Results and Installation

Following the completion of detailed design, the Power Panel was installed into the Atwater Kent Pumpkin Lounge. Wall mounting methods including types of hardware used had to be considered. Wiring schemes were also decided upon before installation in order to satisfy safety margins. Finally, images of the finished installation are included.

6.1 Wall Mounting

To secure the Power Panel to the wall of the Pumpkin Lounge, multiple types of anchors and clips were researched. Interlocking hangers were found online which would allow the various displays to mount flush to the wall. The hangers were ordered in two types: locking and non-locking. These hangers are shown in Figure 77.

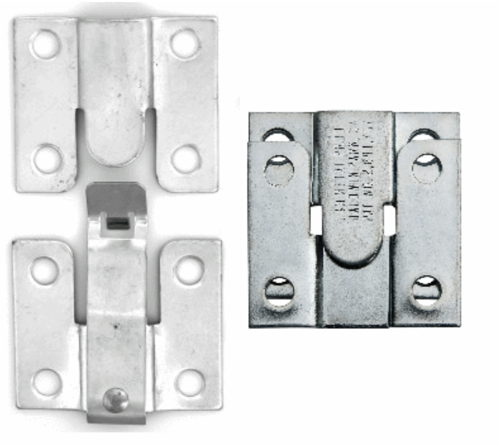


Figure 77: Locking and Non-Locking Hangers for Installation

The locking hangers were used on the tops of each of the displays to protect against easy removal. The locking hangers do not permanently affix the displays to the wall, as they will unlock using a small tool, however this does require more force than the non-locking hangers. These interlocking types of hangers were chosen for easy mounting ability as well as easy removal in the case of repair or maintenance. The Large Child and all four Small Children are attached with two locking hangers. The Horizontal Ticker, Main Display, and Vertical Ticker each respectively have four, three, and one locking hangers. The Main Display, Vertical Ticker, and the lowest Small Child each also have non-locking hangers on the bottom of the displays. This is to prevent students and visitors from being able to pull the displays away from the wall.

Hollow wall anchors were decided upon for the final installation. These anchors provide a machine screw thread that remains on the wall after removing the mounting screws, which made them more viable than other options such as toggle bolts. These anchors were properly sized for the 5/8 inch thickness of the Pumpkin Lounge drywall. Each hanger was attached to the wall using two anchors. Based on analysis of the hangers and the mounting hardware, this method provided sufficient force to hold the displays of the Power Panel on the wall.

In order to mount the Panel to the wall, the whiteboards had to be removed. In doing so, the team uncovered a series of holes drilled previously for attempted wall anchor placement. It became clear that encountering studs wasn't considered by past groups working on this surface. The team purchased a stud finder and mapped out studs for all locations that would need to be drilled. This allowed for on the spot adjustment and minimal time wasted drilling holes where anchors couldn't be placed. Multiple panels were affected by the stud locations and were shifted a few inches to avoid issues, however the layout of the Power Panel remained as close to the planned dimensions as possible.

6.2 Wiring and Distribution

To determine the wire gauges necessary to carry power to each of the panels from the main wall supply, the UL Circuit Ampacity charts were referenced. UL guidelines as shown in Table 15 were followed to ensure that the Power Panel is up to code and is safe for use in a public space. All cables were sized to ensure that the current required did not exceed 80% of the current rating.

Wire Gauge [AWG]	Maximum Ampacity [A]
18	7
16	10
14	15
12	20

Table 15: UL Wire Gauge and Maximum Ampacity (1)

In order to determine appropriate wire gauges, an optimal wire routing was created. The ampacity necessary to carry through each of the wires is based on the maximum power needed for the various displays. The maximum current for the Power Panel is 12.9 A. The 12.9 A is carried through a 12 AWG wire to a distribution block located behind the Main Display. From there, it's divided between the 7.2 A needed for the Main Display and 5.7 A needed to run the auxiliary displays. A 14 AWG wire runs from the distribution block to the Main Display and a 16 AWG goes to the auxiliary panels. Each of the displays after this step draw less than 2.8 A and therefore 18 AWG was used for the remainder of the Power Panel.

Mounted behind the Main Display and Large Child are two distribution blocks. These allow for power distribution to multiple panels and allow for convenient wiring routes. Because of the large span of the Power Panel, it was important to minimize wire distances as much as possible. The distribution blocks also helped to create a power connection which was easy during installation. Connection to each of the power supplies is via screw terminal however the distribution blocks use 0.25 inch Quick Connects. This allows more convenient connections for the power cables while the displays are mounted. The distribution block behind the Main Display connects the main power source from AK113 to the Main Display, distribution block behind the Large Child, as well as to the two Small Children and Vertical Ticker on the right side of the array. The distribution block behind the Large Child distributes power to the Large Child, Horizontal Ticker, and to the two remaining Children Panels on the left side of the array.

6.3 Finished Installation

The Power Panel has been installed into the Pumpkin Lounge of Atwater Kent and images of the installed Panel are included in this section. The Power Panel is operational although the displays are turned off in each of the following images. Figure 78 shows the Main Display, 5 Children Panels, and Vertical Ticker. The Horizontal Ticker is the only display not featured in this image. The power and data wiring connecting the displays is contained in 1.5 inch by 0.75 inch black raceway.

Figure 78: Main and Nearby Children Panels

Figures 79 and 80 show views of the Power Panel from both sides of the Pumpkin Lounge.

Figure 79: Power Panel in Pumpkin Lounge

Figure 80: Power Panel in Pumpkin Lounge

Figure 81 shows a closeup of one of the capacitive touch controls located on the door frame of the wall opposing the Power Panel. Figure 82 shows the door frame with both capacitive touch controls. The wiring for the controls is concealed using 0.75 inch by 0.5 inch white raceway. The junction box located just above the door frame includes a 2 port USB hub and a USB over CAT5 adapter to send data from the controls to the ODRIOD.

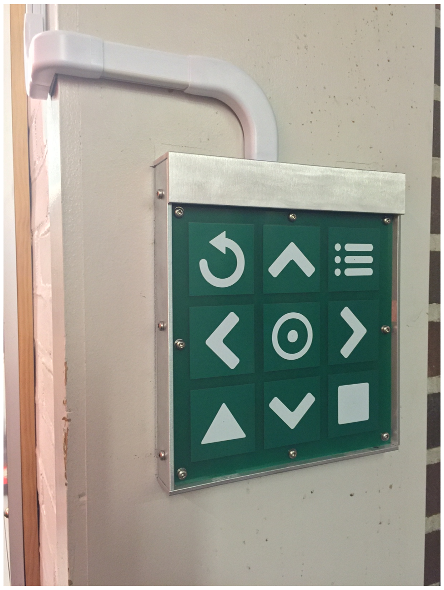


Figure 81: Capacitive Touch Controls

Figure 82: Capacitive Touch in Doorway

The decision to mount the ODRIOD and sending card in AK113 allows for ease of maintenance and use by future groups. These components are contained in a watertight box, along with additional components including a power supply to power the ODRIOD, sending card, XBee, and USB hub. The box also contains an XBee for communication with the XBee located in the AK317 lab which receives data from the solar panels. The box additionally includes two switches, one which controls the components in the box, and one which controls the Power Panel displays. The box has one single power cord entering, which is protected from being unplugged by a custom made cover. The box also has one ethernet cable entering which is an input to the Odroid. A hole was drilled behind the Main Display to feed power cables and data cables from the components in the Pumpkin Lounge to those in AK113. Figure 83 shows the inside of the box. This view does not include the Odroid or sending card however. Figure 84 shows the box closed.

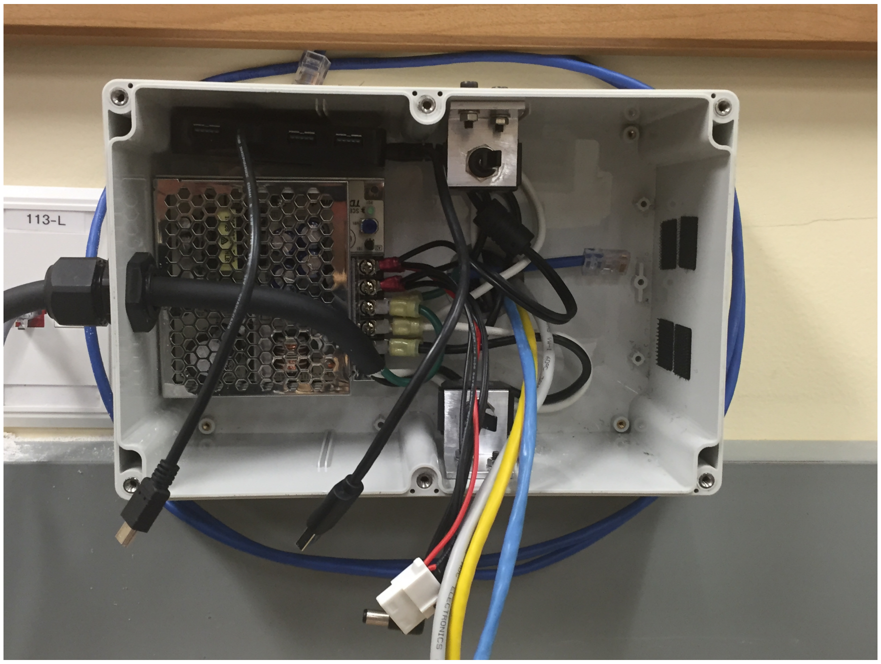


Figure 83: Inside of Box in AK113

Figure 84: Installed Box in AK113

7 Future Work and Recommendations

Overall, this project has made significant progress in establishing a sustainable Power Panel for the Atwater Kent Pumpkin Lounge. Sufficient work has been completed with regard to the physical setup and user interface, in addition to display functions through Processing.

Future teams can expand upon the Power Panel to help it reach a larger audience and functionality. The Power Panel currently has a wide range of feature sets for display however there are many additions that can be made. Progress was made in obtaining power demand data yet future teams can work toward obtaining live demand data for the Panel. This will involve using the buildings with the newly installed meters and working with the WPI IT department to obtain a secure path for this information. Another feature of the Power Panel which was considered this year however not completed due to time constraints is the lab occupancy monitor. The monitor would be an ideal component for display on the Panel and would prove useful for students in Atwater Kent. Of course, the Panel will also benefit from adding more games and features which students would be interested in using.

The Power Panel can be improved upon with additional user inputs as well. By providing a means for students to text or email the Panel, more activities and events can be advertised. Another source of input to the Panel includes additional sensors. By implementing motion sensors, gesture recognition, cameras, and/or pressure sensors, a new range of feature sets become possible. Games such as Dance Dance Revolution can be added to increase the interactive experience.

The Panel has been greatly expanded upon from its original design with the addition of Children Panels, Horizontal Ticker, and Vertical Ticker. There is the possibility to add more LED matrices to the Panel if desired and budget permits. Initially, the idea was to connect the Children Panels together with LED strings. Although it did not prove reasonable for the Power Panel this year due to time and budget constraints, there is a possibility to add to the Panel for increased aesthetics.

Overall, there are various areas which future teams can add to the Power Panel in order to increase usability by the Atwater Kent community. Expansion of the feature sets and hardware components will be most useful in building upon the work already completed.

8 Conclusion

The objective of this project was to design and assemble a 21st Century Power Panel to display relevant information to students and visitors of the Atwater Kent Pumpkin Lounge. The Panel serves to inform about energy consumption and usage in AK, as inspired by multiple previous projects. This display serves as a source of information to students including campus wide events and countdowns however will provide an artistic atmosphere through LED inspired pixel art and interactive games.

For this project, the team was able to finalize many design decisions that contribute to a working Power Panel. Numerous LED matrix panels were implemented and configured to Processing sketches which run multiple features as desired by the team. During the development of this system the team was able to resolve many of the issues that were encountered. In cases where a solution was not easily resolved alternative approaches were easily identified and implemented, such as with the capacitive touch sensor. A working capacitive touch system was designed and tested using various methods to provide the optimal experience for user interaction. Finally, the exploration of power and wiring, along with assembly options, brought the Power Panel together for final installation.

Due to the scale of this project and limited time frame, there is room for additional growth and improvements which can provide an increasingly informative display.It is expected that professors and students will take advantage of the groundwork left by this project to reflect the impressive and creative work that WPI students are capable of.

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Appendices

A Value Analysis Criteria Description

Visibility (Weight = 5)

Weight	How easy it is to read messages and information
0	Cannot read anything
1	Messages and information can be seen but difficult to interpret
2	With effort messages and information can be interpreted
3	Messages and information can be read at a quick glance

Feasibility (Weight = 4)

Weight	How likely is it that the team completes the design by the end of C-term
0	Very unlikely
1	Implemented but with very limited functionality
2	Implemented with a majority of all proposed features
3	Completed and installed with all expected features incorporated

Interactivity (Weight = 3)

Weight	How likely will this design encourage use
0	Encourages little to no use from the public
1	Encourages a fair amount of use from the public
2	Encourages regular use from the public
3	Encourages a lot of use from the public

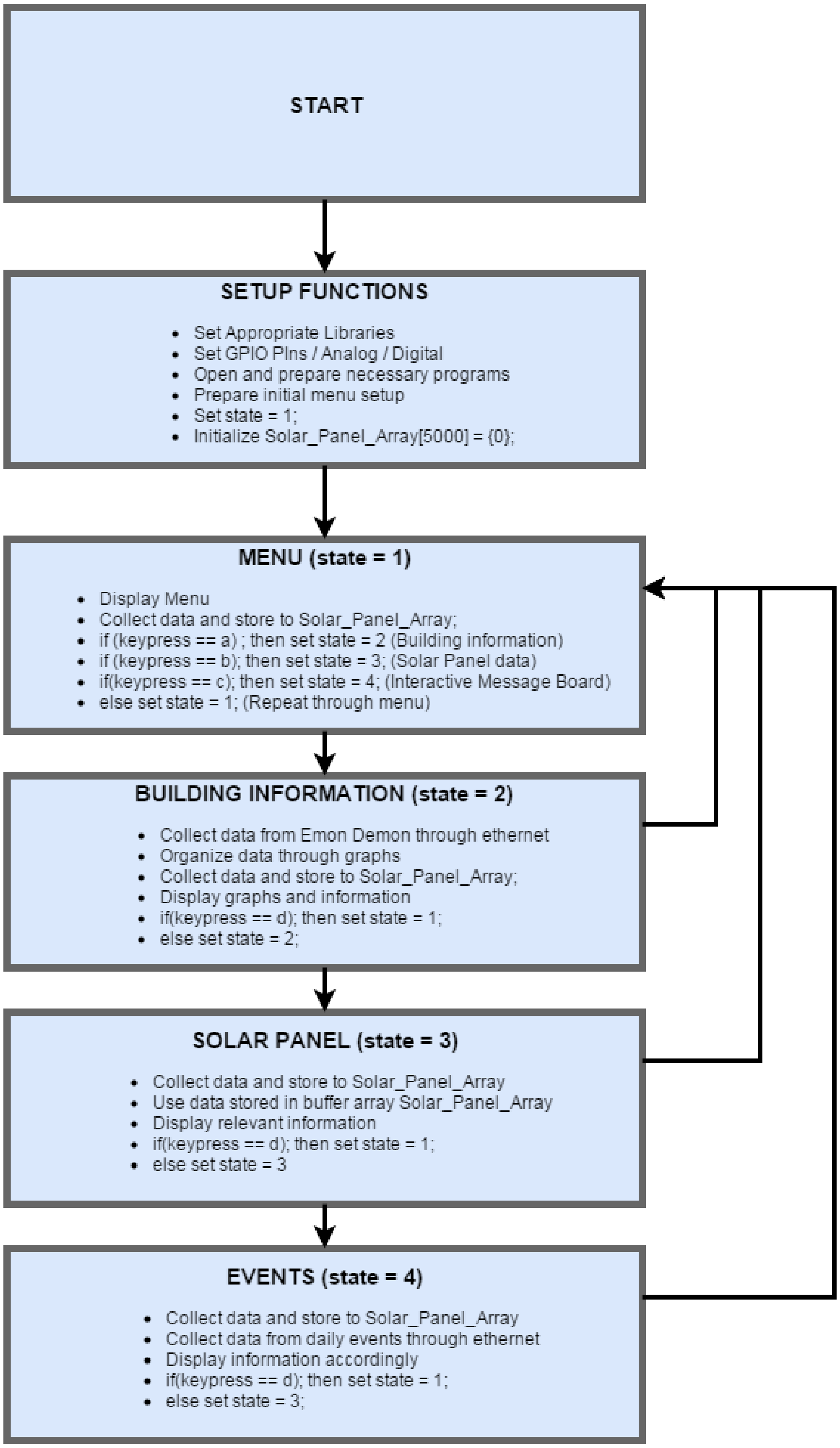
Cost (Weight = 2)

Weight	Potential cost of the product
0	$1500+
1	$1250-1500
2	$1000-1250
3	Less than $1000

Creativity (Weight = 1)

Weight	How interesting, attractive, creative and unconventional the project is
0	Interesting
1	Interesting and attractive
2	Interesting, attractive, and creative
3	Interesting, attractive, creative and unconventional

B High Level Programming Diagram for Main Display



C Capacitive Touch Sensor Measuremnets

TouchPad	Touch	Risetime [uS]	Capacitance w/Parasitic [pF]	Capacitance w/o Parasitic [pF]	Ratio Tap/Cover to None
Parasitic	None	3.40	15.49	0.00	
	None	4.60	20.96	5.46	
CS1	Tap	17.00	77.46	61.96	11.35
	Cover	32.60	148.54	133.04	24.37
	None	4.30	19.59	4.09	
CS2	Tap	19.60	89.31	73.81	18.03
	Cover	30.60	139.43	123.93	30.28
	None	4.00	18.23	2.73	
CS3	Tap	11.10	50.58	35.08	12.87
	Cover	23.20	105.71	90.21	33.10
	None	33.60	153.09	137.59	
CS4	Tap	43.20	196.84	181.34	1.32
	Cover	174.00	792.81	777.31	5.65
	None	10.80	49.21	33.71	
CS5	Tap	18.60	84.75	69.25	2.05
	Cover	50.80	231.46	215.96	6.41
	None	6.40	29.16	13.66	
CS6	Tap	10.20	46.48	30.98	2.27
	Cover	17.80	81.10	65.60	4.80
	None	17.80	81.10	65.60	
CS7	Tap	27.20	123.93	108.43	1.65
	Cover	113.00	514.87	499.37	7.61
	None	7.20	32.81	17.31	
CS8	Tap	11.70	53.31	37.81	2.18
	Cover	34.40	156.74	141.24	8.16
	None	4.80	21.87	6.37	
CS9	Tap	7.80	35.54	20.04	3.15
	Cover	44.00	200.48	184.98	29.04
	None	12.60	57.41	41.91	
CS10	Tap	16.20	73.81	58.31	1.39
	Cover	73.20	333.53	318.03	7.59
	None	5.80	26.43	10.93	
CS11	Tap	11.00	50.12	34.62	3.17
	Cover	27.20	123.93	108.43	9.92
	None	9.80	44.65	29.15	
CS12	Tap	12.80	58.32	42.82	1.47
	Cover	52.80	240.58	225.08	7.72

Table 16: Measured Capacitance Values from RC Circuit

TouchPad	Touch	Frequency (R$_A$ + $2R_B =$ $10K\Omega$) [kHz]	Frequency (R$_A$ + $2R_B =$ $50k\Omega$) [kHz]	Frequency (R$_A$ + $2R_B =$ $100k\Omega$) [kHz]	Frequency (R$_A$ + $2R_B =$ $200k\Omega$) [kHz]	Frequency (R$_A$ + $2R_B =$ $300k\Omega$) [kHz]	Frequency (R$_A$ + $2R_B =$ $500K\Omega$) [kHz]	Frequency (R$_A$ + $2R_B =$ $1M\Omega$) [kHz]	Frequency (R$_A$ + $2_RB =$ $5M\Omega$ [kHz]
CS1	None	26,426	5,285	2,643	1,321	881	529	264	53
	Tap	2,328	466	233	116	78	47	23	5
	Cover	1,084	217	108	54	36	22	11	2
CS2	None	35,252	7,050	3,525	1,763	1,175	705	353	71
	Tap	1,955	391	195	98	65	39	20	4
	Cover	1,164	233	116	58	39	23	12	2
CS3	None	52,932	10,586	5,293	2,647	1,764	1,059	529	106
	Tap	4,113	823	411	206	137	82	41	8
	Cover	1,599	320	160	80	53	32	16	3
CS4	None	1,049	210	105	52	z	21	10	2
	Tap	796	159	80	40	27	16	8	2
	Cover	186	37	19	9	6	4	2	1
CS5	None	4,280	856	428	214	143	86	43	9
	Tap	2,083	417	208	104	69	42	21	4
	Cover	668	134	67	33	22	13	7	1
CS6	None	10,561	2,112	1,056	528	352	211	106	21
	Tap	4,658	932	466	233	155	93	47	9
	Cover	2,199	440	220	110	73	44	22	4
CS7	None	2,199	440	220	110	73	44	22	4
	Tap	1,330	266	133	67	44	27	13	3
	Cover	289	58	29	14	10	6	3	1
CS8	None	8,336	1,667	834	417	278	167	83	17
	Tap	3,816	763	382	191	127	76	38	8
	Cover	1,021	204	102	51	34	20	10	2
CS9	None	22,646	4,529	2,265	1,132	755	453	226	45
	Tap	7,199	1,440	720	360	240	144	72	14
	Cover	780	156	78	39	26	16	8	2
CS10	None	3,442	688	344	172	115	69	34	7
	Tap	2,474	495	247	124	82	49	25	5
	Cover	454	91	45	23	15	9	5	1
CS11	None	13,203	2,641	1,320	660	440	264	132	26
	Tap	4,167	833	417	208	139	83	42	8
	Cover	1,330	266	133	67	44	27	13	3
CS12	None	4,949	990	495	247	165	99	49	10
	Tap	3,369	674	337	168	112	67	34	7
	Cover	641	128	64	32	21	13	6	1

Table 17: Calculated Frequencies From 555 Timer Using Different Resistor Combinations

D 555 Timer Derivation

D.1 Charging of Capacitor

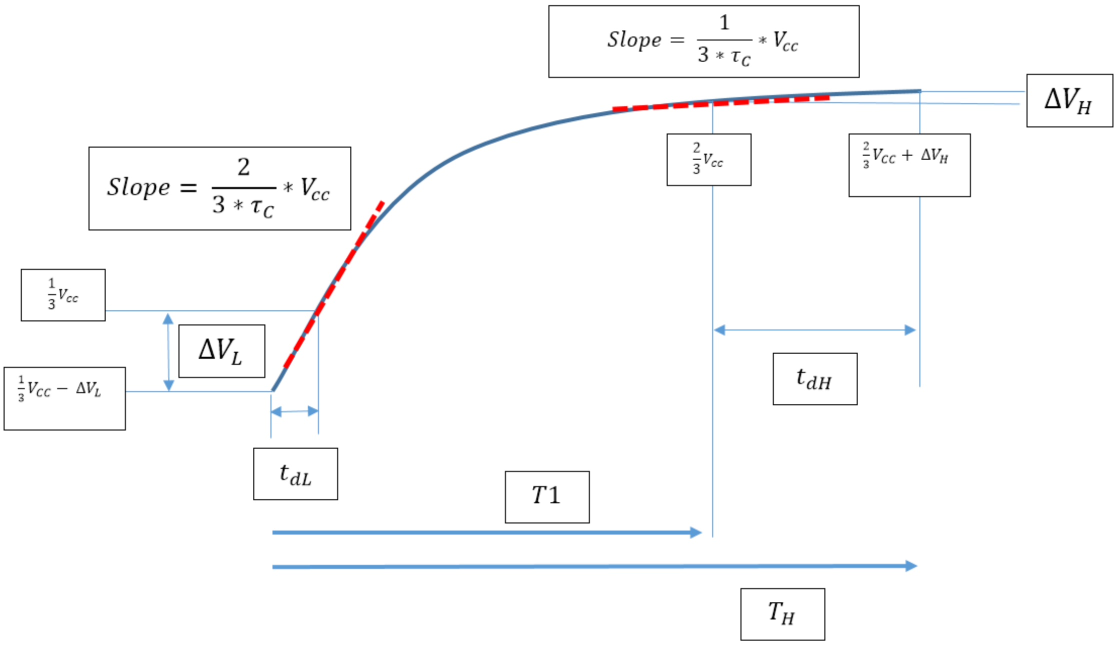


Figure 85: Diagram of Charging Capacitor

$$V_{out} = V_F - (V_F - V_I) * e^{\frac{-t}{\tau}} \tag{16}$$

$$V_F = V_{CC} \tag{17}$$

$$V_I = \frac{1}{3} * V_{CC} - \Delta * V_L \tag{18}$$

$$T_H = T_1 + t_{dH} \tag{19}$$

$$\Delta * V_L = \frac{2}{3} * \frac{V_{CC} * t_{dL}}{\tau_C} \tag{20}$$

$$\Delta * V_H = \frac{1}{3} * \frac{V_{CC} * t_{dH}}{\tau_C} \tag{21}$$

$$\frac{2}{3} * V_{CC} = V_{CC} - (V_{CC} - (\frac{1}{3} * V_{CC} - \Delta * V_L)) * e^{\frac{-T_1}{\tau_C}} \tag{22}$$

$$T1 = ln(2(1 + \frac{t_{dL}}{\tau_C})) * \tau_C \tag{23}$$

$$T_H = ln(2(1 + \frac{t_{dL}}{\tau_C})) * \tau_C + t_{dH} \tag{24}$$

D.2 Discharging of Capacitor

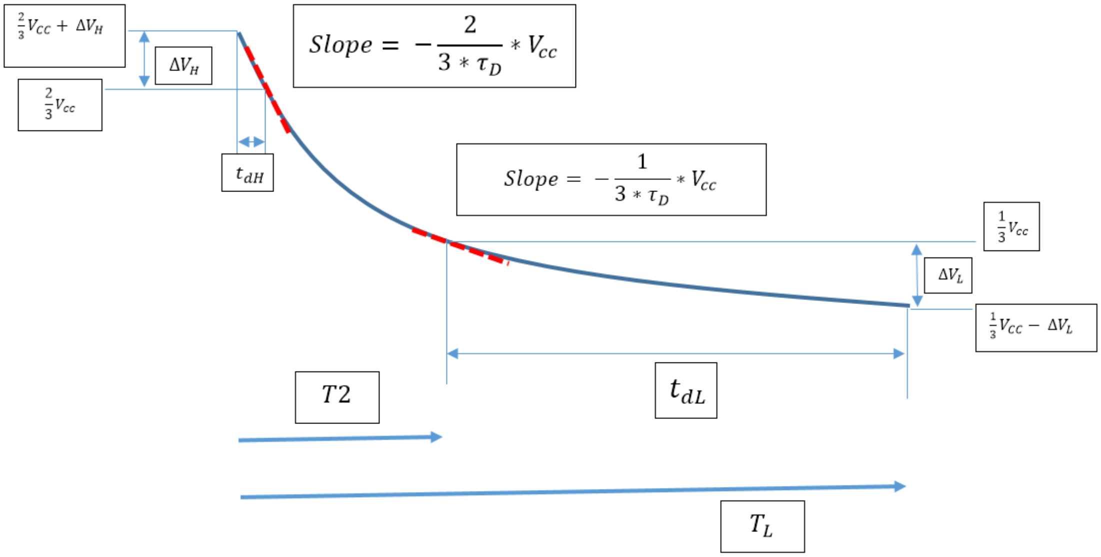


Figure 86: Diagram of Discharing Capacitor

$$V_F = 0V \tag{25}$$

$$V_{OUT} = \frac{1}{3} * V_{CC} \tag{26}$$

$$V_I = \frac{2}{3} * V_{CC} + \Delta * V_H \tag{27}$$

$$T_L = T_2 + t_{dL} \tag{28}$$

$$\Delta V_L = \frac{1}{3} * \frac{V_{CC} * t_{dL}}{\tau_D} \tag{29}$$

$$\Delta V_H = \frac{2}{3} * \frac{V_{CC} * t_{dH}}{\tau_D} \tag{30}$$

$$\frac{1}{3}V_{CC} = 0V - (0V - (\frac{2}{3}V_{CC} + \Delta V_L))e^{\frac{-T2}{\tau_D}} \tag{31}$$

$$\frac{1}{3}V_{CC} = 0V - (0V - (\frac{2}{3}V_{CC} + \frac{2}{3} * \frac{V_{CC} * t_{dH}}{\tau_D}))e^{\frac{-T2}{\tau_D}} \tag{32}$$

$$T2 = ln(2(1 + \frac{t_{dH}}{\tau_D})) * \tau_D \tag{33}$$

$$T_L = ln(2(1 + \frac{t_{dH}}{\tau_D})) * \tau_D + t_{dL} \tag{34}$$

D.3 Full Derivation

$$DutyCycle = \frac{T_H}{T_H + T_L} = \frac{ln(2(1+\frac{t_{dL}}{\tau_C})) * \tau_C + t_{dH}}{ln(2(1+\frac{t_{dH}}{\tau_D})) * \tau_D + t_{dL} + ln(2(1+\frac{t_{dL}}{\tau_C})) * \tau_C + t_{dH}} \tag{35}$$

$$Period = T_H + T_L = ln(2(1+\frac{t_{dH}}{\tau_D})) * \tau_D + t_{dL} + ln(2(1+\frac{t_{dL}}{\tau_C})) * \tau_C + t_{dH} \tag{36}$$

$$Frequency = \frac{1}{T_H + T_L} = \frac{1}{ln(2(1+\frac{t_{dH}}{\tau_D})) * \tau_D + t_{dL} + ln(2(1+\frac{t_{dL}}{\tau_C})) * \tau_C + t_{dH}} \tag{37}$$

E Power and Wiring Calculations

The voltage at the fourth panel wired in parallel is as follows:

$$V_{load} = V_{supply} - [(4 * I_{load} * 2R_1) + (3 * I_{load} * 2R_2) + (2 * I_{load} * 2R_3) + (I_{load} * 2R_4)] \tag{38}$$

Assuming all wires between panels are same length ($R_1 = R_2 = R_3 = R_4$) simplifies the expression to the following:

$$V_{load} = V_{supply} - [(4 * I_{load} * 2R) + (3 * I_{load} * 2R) + (2 * I_{load} * 2R) + (I_{load} * 2R)] \tag{39}$$

Combining like terms results in the simplified equation below:

$$V_{load} = V_{supply} - I_{load} * 2R(4+3+2+1) = 5 - I_{load} * R(4+3+2+1) \tag{40}$$

For N number of panels connected in parallel:

$$V_{load} = V_{supply} - I_{load} * R * \frac{N(N+1)}{2} \tag{41}$$

Converting resistance into resistance per inch, and introducing a length variable in inches between the panels gives Equation 1 below:

$$V_{load} = V_{supply} - I_{load} * R_{\frac{Ohm}{Foot}} * 1000 * 12 * l * \frac{N(N+1)}{2} \tag{42}$$

The power required to run N panels in parallel using the DC/DC converters takes into consideration the 85% efficiency of the converters:

$$P_{DC/DC} = \frac{P_{panel}}{0.85} = \frac{4*5}{0.85} = 23.529W \tag{43}$$

$$P_{supply} = 23.529 * N \tag{44}$$