Senior Design II

OUC SOLAR SCULPTURE

COLLEGE OF ENGINEERING & COMPUTER SCIENCE

Group 9 – Spring 2018
Sponsored by OUC

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1. **Executive Summary**

Solar energy derived from photovoltaics is a sustainable energy source that has recently become cost-efficient on-par with conventional energy sources, but without the carbon emissions that contribute to global warming. However, one of the disadvantages of using photovoltaics is the perceived notion that the resulting object will be ugly or lack aesthetic appeal. Photovoltaic panels may be used to express art while advocating for clean technology. In places like the Austrian town Gleisdorf and Chinese city Dezhou, photovoltaic structures are altering the landscape. These structures, from street lighting to solar trees, are meant to encourage environment-friendly energy sources that aid the main grid as well as being aesthetically pleasing.

Photovoltaic structures placed in highly populated locations is a start towards normalizing green energy. These structures would be symbols of humanity's initiative to care for mother nature. Being that photovoltaic technology can be considered modern/futuristic, customers will support a progressive entity investing in these structures while probably receiving governmental aid such as state or federal tax credits. Structures that share the same objective and goal as our project, that demonstrate a physical definition of our project description, are becoming more and more popular.

Project OUC Solar Sculpture was designed with the goal of combining beauty in an artistic sense and energy-efficient/saving technology (solar power) while maintaining an appealing visual to promote more people to the idea of switching to energy-efficient/saving structures as well as feeding green energy into the main grid. The prototype was designed to be a scaled model of a sculpture that could compete with other models and be put on display in the Orlando City Soccer Club (OCSC) stadium. The prototype was able to survive the Central Florida environment, was oriented for efficient solar angle/orientation, provided a visual display (via UI or some form) of the estimated solar energy produced, and abided by the Florida Building and Electric Codes.

The OUC Solar Sculpture project lasted two semesters starting in the Fall of 2017 and ending in the Spring of 2018. The first semester was dedicated to research of PV panels, electric components, structure design, and art design. In the first semester, students from three different departments from UCF (ECE, MAE, ARTs) worked together to design a 1/8 replica of a feasible design that will be installed in front of the OCSC stadium. Once the design was set, the OUC group bought all the components by the end of the first semester. The second semester was used to further define the design and create a PCB design that would control the electrical components in the sculpture. At the end of the second semester, OUC engineers chose the best design based on aesthetics and electrical integration that would then be built. The end goal was to build a solar sculpture that met the satisfaction and delight of the stake holders.

2. Project Description

The project was sponsored by OUC and part of the interdisciplinary senior design program at UCF. This meant that the OUC group worked alongside students from the UCF School of Visual Arts and Design and students from the UCF Department of Mechanical and Aerospace Engineering. The students from the visual arts department oversaw the aesthetics and overall artistic design of the project, the mechanical and aerospace students oversaw the structure and feasibility of implementing into a real-life structure, and the electrical and computer engineers oversaw the electric components needed for the system interactivity and for converting solar energy into AC power and sending it to the grid. The OUC team was advised by Dr. Lei Wei, Dr. Samuel Ritchie, Dr. Mark Steiner, Dr. Felix Soto Toro and OUC engineers.

The OUC group worked with the art and mechanical students to create a solar structure to replace a generator at the Orlando City Soccer stadium with the requirement of producing a net value of 850 kWh yearly. With the goal to make the system interactive for foot traffic the OUC group implemented motion sensors into the design that once triggered, set off a set of LED patterns provided by the art students to make the solar sculpture light up.

2.1 Project Motivation & Goals

The project that was selected was the OUC sponsored solar structure. This project was taken up by two EE and two CE students that were eager to apply their engineering knowledge they had gained throughout their undergraduate career. Unlike other sponsored projects offered for senior design, the OUC sponsored project was multidisciplinary. This meant that other engineering and disciplinary departments teamed up to complete this project from across UCF. Multiple mechanical engineering teams in combination with art design teams from the Graphics Art and Design School worked together for a truly unique senior design project experience. This gave the project a more realistic feeling of how an engineering project would be carried out after we graduated from UCF. Once we are in our professional careers we will be working with individuals that have different backgrounds and all bring different skills to the plate. We worked side by side with senior level engineers that have years of experience in the field. Our professors took the roles of our bosses and will judged us as such. This was a great learning experience before going into our respective fields. When combining all the different disciplines together into a cohesive system, a better outcome was produced.

All the different members of the EE and the CE team had different motivations for taking on this project. One motivation that we all shared was that we were all very passionate about doing our part towards saving and restoring the environment. This showed in our enthusiasm to work with new and up and coming renewable energy technology that will produce clean energy for years to come. We originally wanted to work with solar panels for our senior design project and when we heard about a utilities company that is so well respected within the community like OUC, we couldn't wait to get started. We were given guidelines to follow by OUC which gave us a good direction to head towards.

The overall goal for this project was to change the general public's perception on photovoltaic technology and solar systems. In an effort to mainstream renewable energy technology that will potentially stabilize climate change, the solar structure will be elegant and environmentally beneficial. If our project design is selected by OUC, the structure will be built in the heart of downtown Orlando as a public tourist display. It would be a great honor for all the members of the team to know they have contributed to a greater cause as well as make UCF proud knowing it was UCF alumni who contributed to the sculpture.

Each team individual gained a substantial amount of knowledge that can be applied in their respected fields in the future. We were thankful for this opportunity because we collectively learned about technology applications that otherwise would have never been taught to us in any class. With this useful information we can implement our knowledge to building solar energy systems of our own. Whether that be in our homes to save money on our electrical bills, to charge batteries, or for future projects. Also, this will look great on our resumes when applying for jobs after graduation. Since renewable technology careers are in the up and coming, this project will give us an upper edge in the related field. Different fields that we can potentially be hired for with this experience in our resume would be utility energy, controls, conservation, design and environmental to name a few opportunities. We looked forward to working with our senior design professors, OUC, mechanical engineering and art students.

2.2 Similar Products

With the push towards renewable energy growing stronger by the day, more and more photovoltaic panels are popping up and being implemented as much as possible. This gave us a better range of products and projects to research and analyze. This gave us a better idea of how to go about creating the solar sculpture while learning from the mistakes and correct use of PV panels. For example, we learned the correct way to mount the panels, how to take into consideration the surrounding environment, and what directions and angles to set the panels for better efficiency.

2.2.1 Lockheed Martin Solar Parking

The first existing solar product that was looked at was the solar panel structure located at the Lockheed Martin RMS office in Orlando. The structure is built on top of a parking to provide shade for the cars of the Lockheed Martin employees as well as serve its function to make renewable energy. This structure is the "largest private, non-utility solar project in the state, and will allow Lockheed Martin to cut facility energy costs by up to 60 percent." [20] The fact that the structure acts as a shade in the hot Florida weather is an extra advantage to way this structure is built. Engineering requirements that the OUC project needed to follow can also be seen in this structure. To begin, the structure has no moving parts which allows for easier maintenance and no energy waste in the powering of the movements. The structure is also placed in a spot where most of the sculpture is not near any trees and far enough and tall enough to not receive any form of shade from the main Lockheed Martin building itself. This helps have no drop off in efficiency at any point in the day. Being far away from the trees also greatly reduces the chances of debris such as leaves and birds landing on the PV panels. All the panels are also placed at a slight angle to get the maximum efficiency from the suns energy. The 7,260-solar module structure will produce approximately 3.33 million kilowatt hours of electricity per year for 25 years, resulting in annual savings of over $300,000 and slashing greenhouse gas emissions by 35% and energy use by 25% by the year 2020[20]. This solar structure was built and implemented meeting good engineering requirements and is a good example showing how PV panels and renewable energy can be used.

Fig. 1. Solar Panels at Lockheed Martin Parking Lot

2.2.2 Traffic Signs Solar LEDs

The next product that was studied was the PV panels placed on top of traffic signs such as STOP signs and people crossing signs. The goal of these PV panels is to power lights such as LEDs to help oncoming traffic see the signs better. There is one PV panel placed on top of or alongside the sign to use the sun's energy to power the LEDs. The circuits in the signs use PCB technology like the OUC project does, and the LEDs are powered for 24 hours. The main function of the sign is to power LEDs to help the oncoming traffic. For this reason, there is a battery connected to the signs for when the solar power is not enough, and sometimes there are small wind turbines installed as well to produce energy [28]. These PV panels are installed at an angle of 45° to 65° depending on region. [34] This idea of placing solar panels on stop signs is a good one because there are not a lot of cables needed to connect to the power source, the LEDs are low powered which, even though the PV panels are small, they can produce enough energy to power the LEDs, and because the PV panels are small they are low cost but high reward. The problem with these PV panels is that they must be on traffic signs and there are some traffic signs that are located underneath trees and therefore do not get a lot of sunshine. This causes the signs to use the battery power more than the power produced from the sun, which is not what they were designed to do. Another fault in this product is the direction that some signs, and therefore solar panels, are placed. The optimum direction for a PV panel is to be facing either South or West to be the most efficient [30]. This means that the signs that are facing either North or East are not receiving the maximum amount of solar energy to use. The pros of this product outweigh the cons which is the reason why so many urban and rural areas are using these types of PV panels.

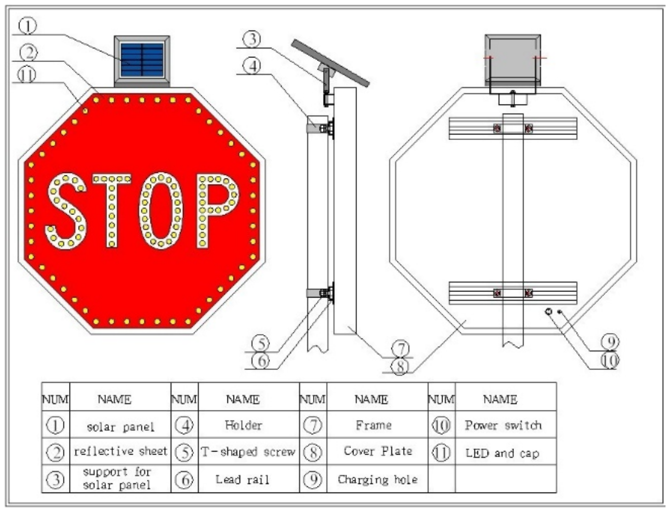


Fig. 2. Stop sign using solar panels

2.2.3 UCF Charging Station

The next product that was studied was the UCF Charging Station. The energy produced from this charging station is being used to charge electric cars hooked up to its batteries. The difference between this and other solar powered structures is that the UCF Charging Station does not convert the energy received into AC voltage, instead it leaves it as DC and stores it in a battery. This method allows for less loss in the conversion of energy received from the usual 10% loss to a 5% loss [38]. The charging station faces SE to account for the busy mornings at the UCF campus. This panel orientation makes it so that the charging station is more effective in the morning [38]. Like the Lockheed Martin parking structure, this charging station provides shade for parked cars although on a much smaller scale it is perfect for students with electric cars. With a simple structure and nothing too complex the station needs very little maintenance, which is a very important requirement for any PV panel installment. The biggest problem seen with this structure is the location of it. On a normal day, the location of the charging station, which was placed right alongside the UCF Memory Mall, would not be a problem but during the UCF football season it is located close to the tailgating and this could cause concern. There is a lot foot traffic in this area with a lot of college students being under the influence of alcohol. These students have easy access to the structure and can manage to cause damage to either the batteries or the PV panels themselves. These three different structures provided real world examples of PV panel implementation. The first one converted the solar energy and sent it straight back into the grid, the second one converted the energy and put back straight away to power LEDS and the third structure stored the energy gained into batteries to be used to power electrical vehicles.

Fig. 3. Solar panels at UCF parking lot

All the structures placed their PV panels in different orientations to be most effective for their engineering requirements. For the OUC group, the Lockheed Martin solar panel parking was the best to look at. The Lockheed Martin PV panels produce a big amount of solar energy which was one of the engineering requirements in the OUC group, needing to have an average output of 850 kWh annual output. The three examples also helped understand how to consider the angle and placement of the PV panels, showing what to do and what not to do when implementing in the structure. The OUC structure will be placed in front of the soccer stadium and the OUC group will place the structure itself and will angle the PV panels based on the months of operation between March and December. These are months of operation that are considered because that is when the Major League Soccer (MLS) campaign starts, which is the league that Orlando City Lions partake in.

2.3 House of Quality Analysis

The house of quality is used as a tool to help visually analyze the correlation between engineering requirements and market requirements. Additionally, the house of quality also compares the relation of engineering requirements among themselves which their positive and negative correlations are shown in the roof of the house from the house of quality table. In Fig. 4, we see our engineering requirements and the market requirements are assigned to the row and columns respectively.

From these requirements we can draw correlations between the two and analyze and weigh them as a positive or negative correlation. An example of how to read a correlation between a row and column would be as the amount of power output generated increases then the cost will exponentially rise. This results into a negative correlation where if we want to generate more power then we need more PV panels which requires more money to be invested.

The market requirements were generally the requirements placed on the project with regards to the investors. Basically, the qualities we expected to meet and demonstrate that the project achieved these requirements to please the investors.

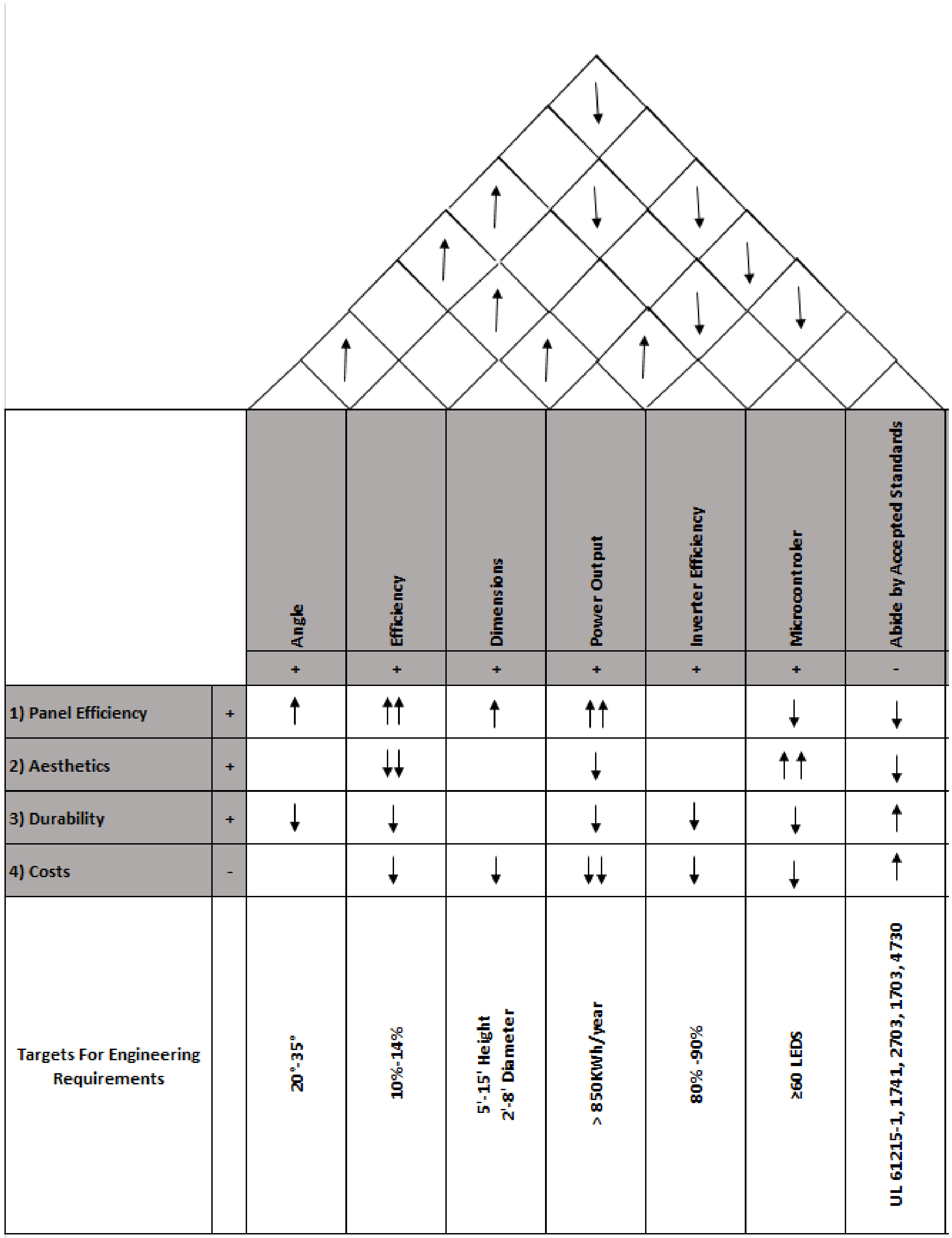


Fig. 4. House of Quality

2.3.1 Panel Efficiency

Panel Efficiency was something that we could influence based on the design of how we wanted to meet our annual energy gained. This value was considered while we were researching and looking for the correct PV panel to buy for the project. How it correlated to angle was that depending on the orientation of the PV panel to the sun, it was obviously more efficient if the panel was facing in the optimal angle. In this case it was positively correlated together as if the angle was closer to the optimal the higher efficiency we could achieve per panel. The dimensions of the Solar Sculpture, or the size, positively correlated with panel efficiency because if there was more surface area for us to work with then we had more options or ways to obtain a higher efficiency either through larger, or more expensive/efficient PV panels.

The relationship between panel efficiency and power output generated was very positive because if we had more efficiency then we could generate more power effectively and vice versa, where if we had lower efficiency we would generate much less. There was no correlation between the panel's efficiency and our inverters efficiency because the inverter just converts the DC power generated from the panel into AC for appliances and the value of either did not affect the other. Our microcontroller and its components such as LEDs, displays, and sensors had a negative correlation with the PV efficiency. This was due to the more components used or the amount of power required to power all of these potentially resulting in requiring higher quality solar panels with greater efficiency to meet the extra power used. Lastly, the relationship between accepted standards was kind of negative because for instance there were standards for mounting, safety, and building codes that needed to be obliged which may or may not have affect the maximum efficiency we could achieve.

2.3.2 Aesthetics

Aesthetics were important for this project. The goal of the Solar Sculpture was to promote renewable energy such as photovoltaics and show that they could also be beautiful while doing great things for the world. However, it was a tradeoff between artistic look and how efficient the sculpture will actually generate. So, this resulted in a negative correlation because we had to balance keeping the artistic design while aiming to reach the required energy gained. Therefore, it was possible to gain higher efficiency or net annual energy gained, but at a severe cost of aesthetic appeal which we had to avoid. However, this was not an issue in relation to our microcontroller because with a better and more powerful microcontroller, we could create light shows with LEDs, use a larger display that was visible to people, or be interactive utilizing sensors. Abiding by standards is usually only detrimental towards the artistic appeal because building and safety codes might be violated depending on if the sculpture is in a crazy shape or could be a hazard of some sort and would have to modified to not violate these standards.

2.3.3 Durability

The durability, or sustainability of the sculpture and its component's life time will depend on materials/products used or positioning of the sculpture with regards to its location. The angle of the PV panels results in a negative correlation with regards to the durability because depending on the angle and how the orientation is positioned may result in more maintenance or possibility to be damaged under Central Florida environment. The efficiency of the solar sculpture, inverter efficiency, and power output in relation with durability is also a negative correlation because assuming increased efficiency with the sculpture is due to expanding the amount of solar panels (generating more power) or the effective orientation of the sculpture results in a lower durability and requires more maintenance. Our microcontroller has a negative correlation with the maintenance and lifetime before maintenance is required because the components like LEDs, displays, etc. are more prone to failure and may need to be replaced more often, especially since these will be in an outdoors environment. Lastly, following and abiding by standards and regulations will results in a positive outcome because following all of the building codes and regulations and safety standards should improve the durability and maintainability of the sculpture.

2.3.4 Cost

The factor of cost almost always has negative correlation with other requirements. Whenever you improve one factor, this usually costs money and high cost is always a big negative for investors. Therefore, balance must be considered, and compromise should be used whenever applicable to reduce cost while maintaining requirements. This is especially true with all the electrical components such as PV panels, inverters, microcontrollers, LEDs, sensors, and displays. Overall, the cost is usually measured against the budget given for the project and finding ways to reduce cost and stay within that budget is key.

2.3.5 Engineering Requirements

The engineering requirements can be compared amongst themselves. The angle of the solar panels has a positive relationship with the efficiency as the more optimal angle in the orientation of the sun's position results in better efficiency and ultimately more power generated from the photovoltaic system. However, the microcontroller and its additional components result in a loss in the net gain requirement of annual energy and must be subtracted from the total. The dimensions of the sculpture results in more surface area to work with and gives potential for more energy but may suffer from building standards and regulations. Overall, to meet the engineering requirements it largely revolves around meeting and surpassing the net gain of annually estimated power (due to microcontroller, LEDs, displays, sensors consuming power) and utilizing solar panels efficiently either by angle or surface area with more panels.

2.4 Block Diagrams

2.4.1 Software Flow Diagram

Our project contained a system to read input from sensors and generate output to LEDs and LCD screens. The heart of this system was our microcontroller which took all the inputs and generated outputs based on how we programed it. We created a software flow we envisioned for our system in Fig. 7. When the system started it should have perform a quick self-test to check if it was functioning properly. If that test were to fail, it should have saved a log of what it checked and what went wrong so that a technician could get information about the problem to help them fix it. Upon successful completion of the self-test, the microcontroller should have started executing a code that would make the LEDs follow a prescribed base pattern. Then the microcontroller would listen for interrupts in the background always. When an interrupt was received, different code would execute depending on which interrupt was received. When interrupts came from the sound sensors or the light sensors, code that alters what the LEDs are doing would be generated.

We hoped to create a very robust code that would be able to generate many different patterns depending upon which specific light sensors had sent interrupts, and what the nature of the interrupt was, e.g. was it fast, was it constant, was the interrupt periodic, etc. We believed this would make for a more interactive and interesting sculpture. It would be tricky to make the system work as envisioned as the system would be receiving constant interrupts from the sensors which could make the LEDs act in unintended ways, therefore thoughtful programming was necessary.

The other interrupt the system would listen for was from the inverter. Inverters usually come with the ability to generate information about the power they are producing. Our program took that information from the inverter and fed it into an algorithm that used it to make calculations about power being produced right now, power produced so far, how much money the solar panels are saving, and other messages to promote the benefits of solar energy. The output of that algorithm will be sent to the LCD for the public to view.
Our system was not designed to be shut off. Ideally, it would be on forever but there will be times it must be shut down, say for maintenance, or will lose power due to an outage or fault. Therefore, the program flow doesn't have a termination, instead after any code executes, the system goes back to waiting for interrupts. A termination is anytime the system loses power, or there is an error that cannot be recovered from, and therefore the system must be shutdown. After a power loss event, the system simply restarts once power is returned.

2.4.2 Outline of system (Hardware Flow Diagram)

In Senior Design 2, we changed a few things in our hardware and software. These changes are reflected in Fig. 5 and 6. Specifically, we added an external current sensor board and a voltage divider circuit to the main PCB. The voltage divider uses a 100 kΩ resistor in parallel with a 25 kΩ resistor. The output of the voltage divider is calculated using (1). The resistors chosen ensure that the output voltage falls within the 5 V working limit of the ATMega 2560. The solar panel we used has a maximum output of 24 V. We simply reworked this equation in the software to get V_{in} and then multiplied it by the output of the current sensor to show the Watts the solar panel was producing.

The software flow was changed to handle some issues we uncovered during testing. We changed our interrupt driven approach to the software design because the Adafruit Neopixel LEDs do not work well with interrupts. Instead, we changed to a flow where the current inputs are read after an LED pattern finishes running. In this way, we do not build a stack of sensor inputs and attempt to handle all of them. We just see which sensors are being triggered after each LED pattern finishes, then use the first input recorded after an LED pattern ends to decide which LED pattern will go next. The updated software flow can be seen in Fig. 6.

$$Vout = Vin * R2/(R1 + R2) \quad (1)$$

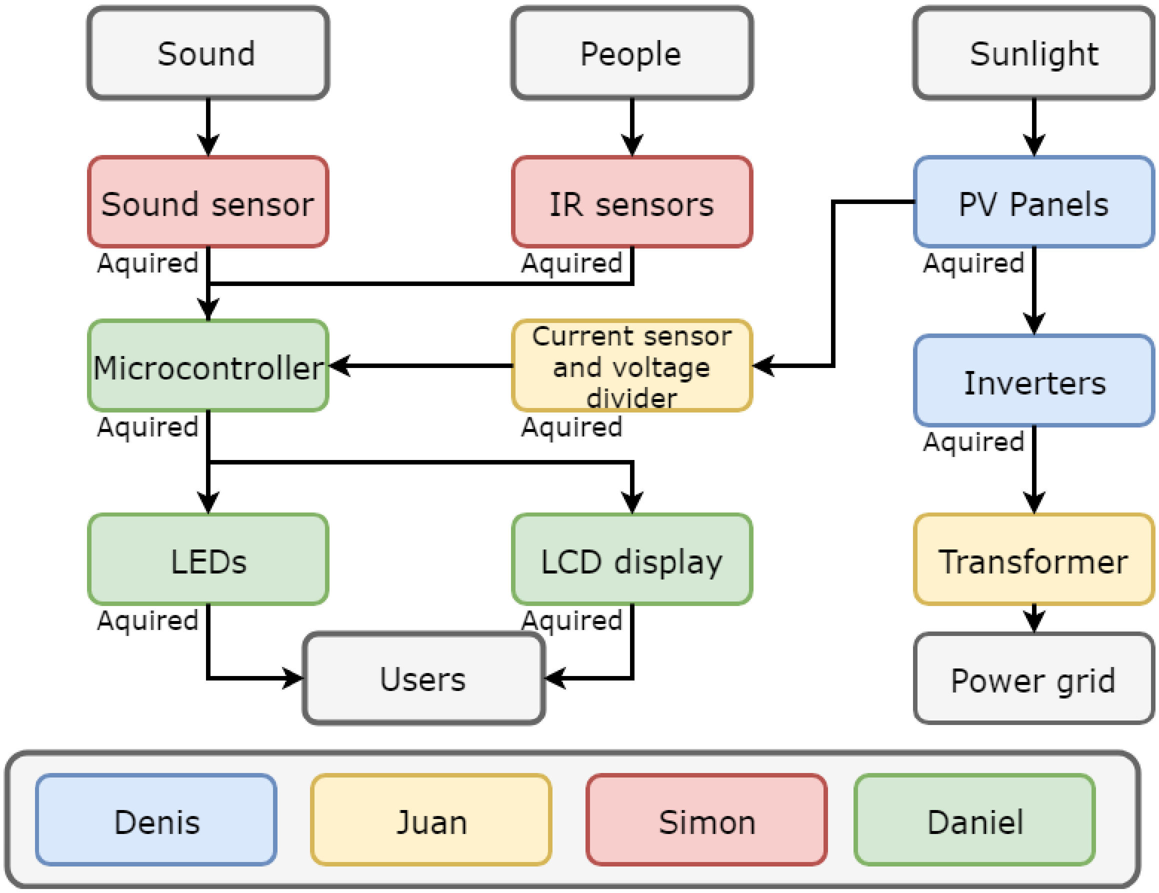


Fig. 5. Updated hardware flow diagram. A current sensor and voltage divider were added to the design to read the power output directly from the solar panel. The maintenance display was removed.

Our project could be broken down into many sub tasks and our concept of how to break it down is shown in Fig. 8. The system was divided into two large parts. The first part was the functional, energy production part. This part was composed of solar panels, inverters, circuitry to condition the electricity produced, and a device to feed the power produced into the grid. The concept we had for this side of the system was that the sunlight would activate the solar panel, the solar panel would generate DC power, the inverter would convert the DC power to AC power, the circuitry would convert this to power suitable to be injected into the grid, and OUC would handle the actual connection to the grid. Most of the parts of this side of the project were purchased and not created by us. The other side of this project was composed of sensors (light and sound), LEDs, a microcontroller, and two screens, one for displaying messages to the public and one to be used by technicians.

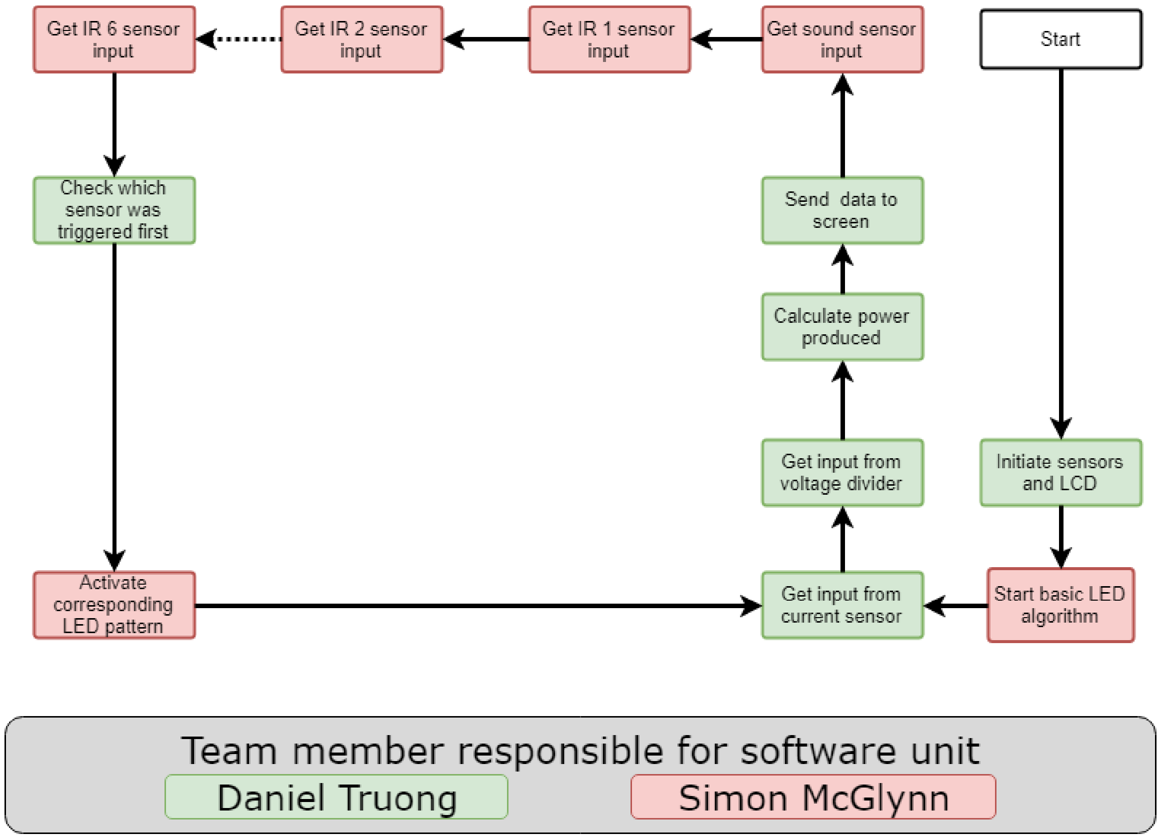


Fig. 6. Updated software flow diagram. The algorithm completes every time and does not get interrupted. The interrupts were dropped due to their lack of usability with the Adafruit Neopixel LEDs.

Our concept for how this side of the project should flow was that light sensors should pick up on changes in ambient light, as well as sudden dips in light, and relay that data to the microcontroller. Similarly, the sound sensors should pick up in changes in ambient sound levels, as well as sudden spikes in sound, and send that data to the microcontroller. The microcontroller would use this data to make decisions about what code to execute to control the LEDs. Our objective was to use the data from the sensors to detect different situations, such as whether it is day or night, if someone is nearby, if there is a large crowd present, if no one is around, etc. The purpose of knowing these situations was that we wished to use different LED displays and lighting levels depending on the situation.

The microcontroller will also send information to the screens to display messages to either the public or a technician. Usually it will be messages to the public, unless a technician is currently using the system. The messages to the public will be about how much energy the panels are producing, how much money that translates to, how much carbon dioxide would be produced to create this amount of energy in a fossil fuel plant, etc. We may be able to get information about the power produced from the inverters.

The power for the LEDs, sensors, and screens will be taken from the grid, we will create the circuitry necessary to output the appropriate power to each device.

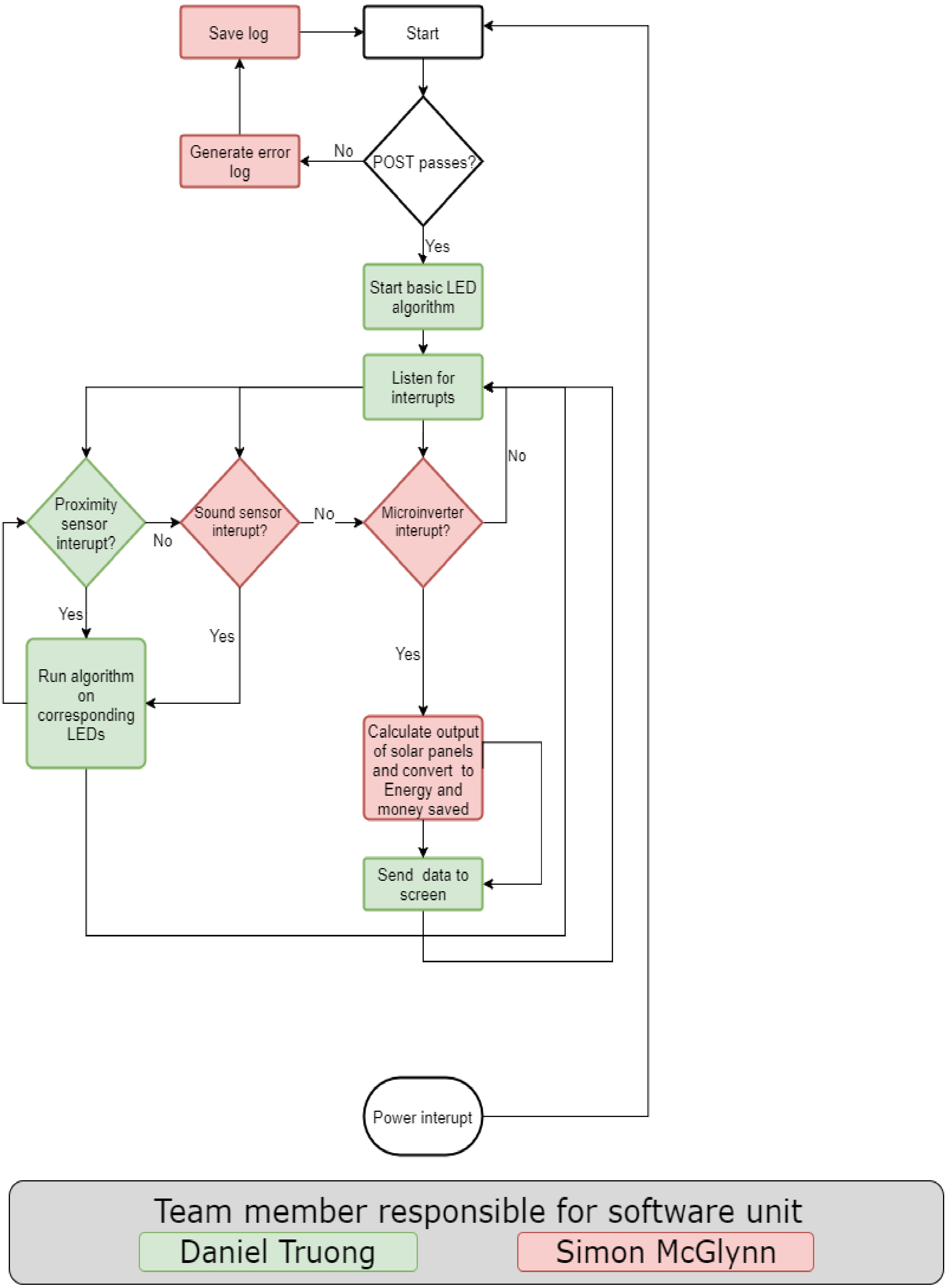


Fig. 7. Software flow diagram for the MCU to control the LEDs and sensors on the sculpture

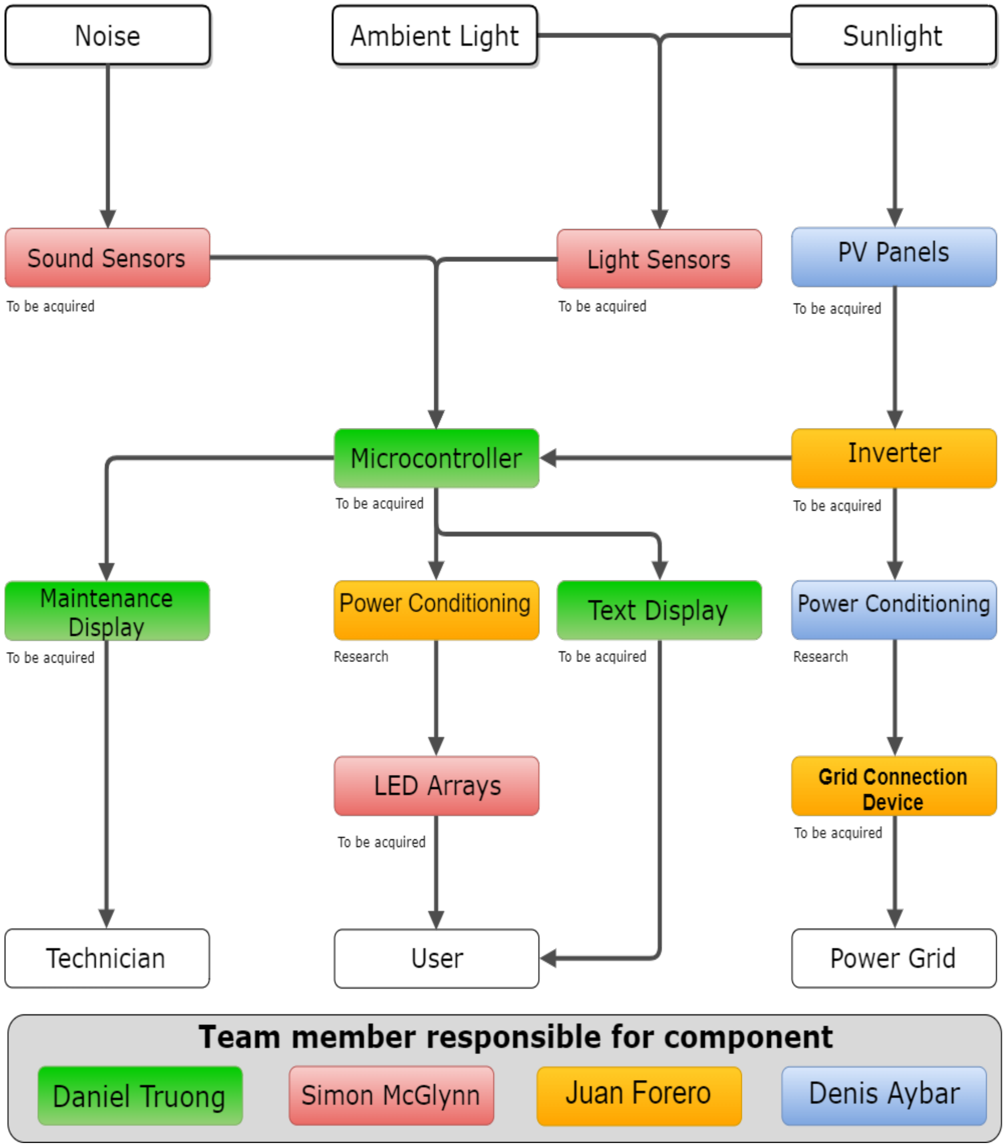


Fig. 8. An outline of the system to be designed for the solar sculpture

2.5 Engineering Requirement Specifications

For the life cycle of any engineering project there are certain required specifications that the engineers must keep in mind throughout. Engineers are bound by these given specifications, which are put in place for various reasons, to get the best and most effective system needed. These specifications will drive the analysis, design, and implementation of any system and any engineering project. The specifications set the ground floor of the project and it is the engineer's job to follow the specs as well as develop and roll out an effective, feasible, and workable project. The required specifications can be introduced by anyone ranging from stakeholders to customers to company requirements.

The OUC Solar Sculpture group was included in the engineering groups that needed to follow certain specifications. Since this UCF project was an interdisciplinary one, the final design that came from the OUC electrical and computer science team was also affected by the required specifications of the mechanical and art teams. Although this did affect our design and what technology and PV panels we could use, we still followed our required specifications, let them be known to the mechanical and art students, and ultimately ended up with a design that met all the required specifications for the three groups.

For the ECE group there were two sets of requirements that were given for us to follow. The first set of requirements came from the Orlando Utilities Commission and the second set of requirements came from the UCF senior design requirements. The OUC requirements gave us certain guidelines which helped us figure out exactly what they wanted, how they wanted us to implement them, how big the structure could be, and how much power was needed to be converted. Following those guidelines helped us keep the customer (Orlando City Soccer Club) and sponsor (Orlando Utilities Commission) happy. The UCF requirements put into place were for us to show what we had learned throughout our years at UCF and be able to demonstrate those skills learned by the end of our undergraduate careers. Following those requirements helped keep our professors happy.
The ECE OUC group kept all requirements in mind while completing senior design I and senior design II to have a workable design that met all requirements. Those requirements were the driving factor to every decision made.

2.5.1 OUC Requirements

The Orlando Utilities Commission was the company that helped sponsor the ECE and MAE groups and worked alongside the customer to make the design exactly how they wanted. At the beginning of the semester the OUC group was given a list of engineering requirements set forth by OUC. The requirements were as follows:

1. Minimum 850 kWh annual output
2. Between 5 to 15 feet tall and 2 to 8 feet in diameter.
3. Withstand Central Florida environment
4. Grid interconnectivity
5. Provide visual display of estimated solar energy production, given varying orientation, inverter efficiencies, shading considerations, etc.

These requirements all shared different importance to the overall and final design that the OUC group ended up with. The first requirement of having an annual output of 850 kWh was one of the most important requirements given. This was what the whole idea of having renewable energy introduced was based on. The aesthetically pleasing structure with an annual output of 850 kWh would replace a generator with the same amount of annual output. Having this requirement gave us freedom on what features we could use to have the structure interactive and also gave us the freedom of deciding what PV panels we would place on the structure. The OUC engineers told us that as long as we had a net gain of 850 kWh, we could implement any electrical components we wanted. The restriction we would have would be with the mechanical teams on the PV panel sizing but because we could choose the PV panel we could alter the design a little and still get the net output of 850 kWh.

The second and third requirements were where it was visible that this was an interdisciplinary project. These requirements were more for the mechanical and art students to keep in mind while coming up with designs and critiquing them to make sure they were stable. This did not mean that the OUC ECE did not have to worry about those requirements. We had to pick products that could withstand the Florida heat that is present for around nine of the twelve months of the year. We also had to pick components that were waterproof and that were sturdy enough to withstand Florida environmental factors such as hurricane-force winds.

The last three requirements all fell in a similar category. They were not requirements of a measured value, but mostly they were requirements of what the structure needed to have or must follow. The grid interconnectivity helped us choose what to do with the solar energy converted. The display made us narrow down what we could have on the structure, ultimately deciding on displaying the information via an LCD screen mounted on the structure.

2.5.2 UCF Requirements

The requirements that UCF placed upon us were not that many. We were given the freedom of choosing what project we would want to do over the course of the two semesters and having a successful finished product. A requirement given was turning in the correct documentation during the senior design I phase and having a minimum report of our project of 120 pages. The only hardware requirement that UCF gave to use was that one way or another we had to design and implement some sort of PCB design into our project. It was noted that there were exceptions to the PCB requirement, but these exceptions were few and far in between.

3. Project Research and Part Selection

3.1 Photovoltaic Systems

To understand what type of hardware we should select for the project to meet the specification requirements by OUC and UCF, first the understanding of the overall solar system needed to be considered. Different components would be put together and research on how they would interact with each other was important when making the final decision of which specific hardware components we would select. As complicated as a solar energy system sounds, a simple break down of all the components is displayed in Fig. 9.

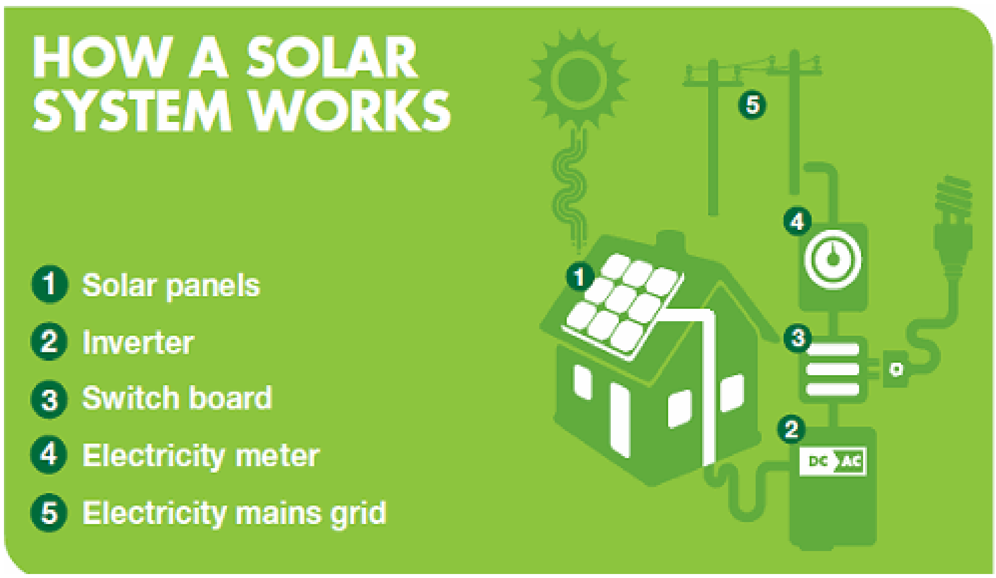


Fig. 9. Basic solar system.

Solar panels or photovoltaic panels, are the source of electricity production. These panels, supplied with the suns, transfer the solar energy to direct current (DC) energy. Output power from the solar panel is dependent on its specific efficiency and area of coverage. Inverters convert DC energy created form the solar panel to alternating current (AC) which is the type of current that runs through electrical grids all through the USA and what OUC is requesting. Inverters can also transfer DC to DC to power devices attached to the solar system. Switch boards direct the energy created and inverted by the solar panel to smaller devices attached to the solar system as well as directing the electricity to the main grid. Switch boards can also provide current protection in case of a fault or short happening in the system. Electric meter acts as a measurement device calculating Voltage, current, power (watts), frequency and so forth. Electric main grid is ultimately supplied by the solar power excess production of electricity. Main grid is integrated with other loads which the solar panel can provide electricity to with a small footprint impact to the environment.
Calculating the system size is based on the area available and the panel's efficiency or from the number of panels and panel nameplate size.

System Size (kW) = Panel Surface Area (m^2) × 1 kW/m^2 × Panel Efficiency (%)

Panel Efficiency (%) = coefficient differs depending on the panel and is calculated by measuring the difference between the suns input kW and the panels output kW

Panel Surface Area (m^2) = the panels array surface area facing the sun

Or

System Size (kW) = Panel Nameplate Size (W) × Number of Panels ÷ 1,000 W/kW

Number of panels = total number of panels used in the system

Panel Nameplate Size (W) = photovoltaic panel power is the result of the maximum power point voltage times the maximum power point current

There are 3 different solar panel system categories across residential and commercial installations:

- Grid-tie system
- Grid-tie with battery backup
- Off-grid system

Most common photovoltaic system being the grid-tie system in which the solar panels and the inverter is tied to the residential or commercial electrical system. Grid-tie simply offsets the energy usage from the utility companies electrical grid. Grid-tie systems are the most economically viable, quickest return on investment and excess power generated is sold back into the grid. This system not only saves the consumer money but also lower the dependency from the utility company. Con against grid-tie systems is that it does not provide any sort of protection against a power outage, causing the grid-tie system to shut down.

Second system would be the grid-tie with battery backup. This system powers during an outage by using the electricity stored in the batteries as well as share the pros of a grid-tie system. Grid-tie with battery backup is best suitable for personnel where power is unreliable or where there is important machinery. Con to grid-tie with battery backup would be the extra investment in battery equipment.
Third system, the off-grid system, is completely independent of utility companies power grid. Off-grid systems are perfect for location where there is no grid power available or it is too expensive to bring in the power grid. Issues with off-grid systems is that the batteries will wear out faster since they are being cycled every day.

3.1.1 PV Functionality

How Photovoltaic panels generate electricity from the sun is through two semi-conductor silicon layers. These two silicon layers are separated by a neural layer but wire together. One layer facing the sun and another facing the opposite side. When sunlight shines over photovoltaic panels, electrons are excited which causes them to break apart from their associated atoms. Once separated by the sunrays photons, the electrons on the silicon layer facing the sun travel through the connecting wire to the separated second silicon layer. When the electrons travel through the wire an electrical current is produced. Photovoltaic cells are wire in series, which in series creates an output voltage. Typical voltage outputs range around 12, 18 and 24 volts DC. Output wattage or power is directly dependent on the efficiency of the panel as well as square foot coverage. [3]

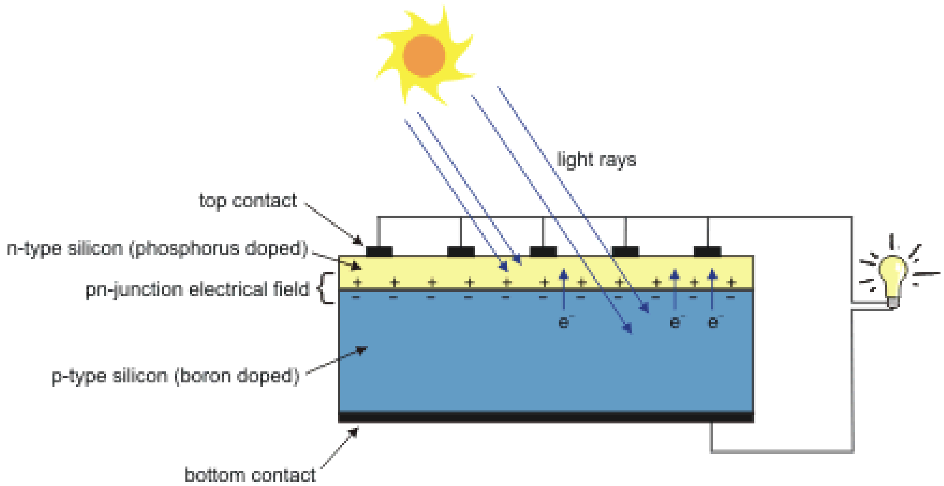


Fig. 10. PV functionality.

Calculating how good photovoltaic panels are is measured by its solar cell efficiency which refers to the amount of sunlight energy that is converted into electricity. Non-mechanical factors that affect the solar cell efficiency are the angled position and the climate around the location of the photovoltaic panel. Both combine to determine the annual energy output. Technical aspects affecting a photovoltaics efficiency would be its reflectivity efficiency, thermodynamic efficiency, charge carrier separation and conduction values. Measurement unit's quantum efficiency, V_{oc} ratio and fill factor are used to calculate the difficult parameters.

3.1.2 Technical Aspects Affecting PV Efficiency

3.1.2.1 Reflectivity

One of the function of the photovoltaic panels is to absorb the photons form the sun. Any light that is reflected off the surface of the panel is considered a loss or uncaptured energy. To combat reflection loss, different antireflection schemes have been developing to increase efficiency of solar cells. Different anti-reflecting coatings such as quarter-wavelength and high quality. Other methods to increase solar efficiency is by integrating nano and microstructures with broadband light-trapping capability to suppress surface reflection. [12]

Light reflection is reduced by adding texture to the silicon surface and applying anti-reflection coating. Anti-reflection coating "consist of a thin layer of dielectric material, with a specially chosen thickness that interference effects in the coating cause the wave reflected from the anti-reflection coating top surface to be out of phase with the wave reflected from the semiconductor surfaces. These out-of-phase reflected waves destructively interfere with one another, resulting in zero net reflected energy." [13]

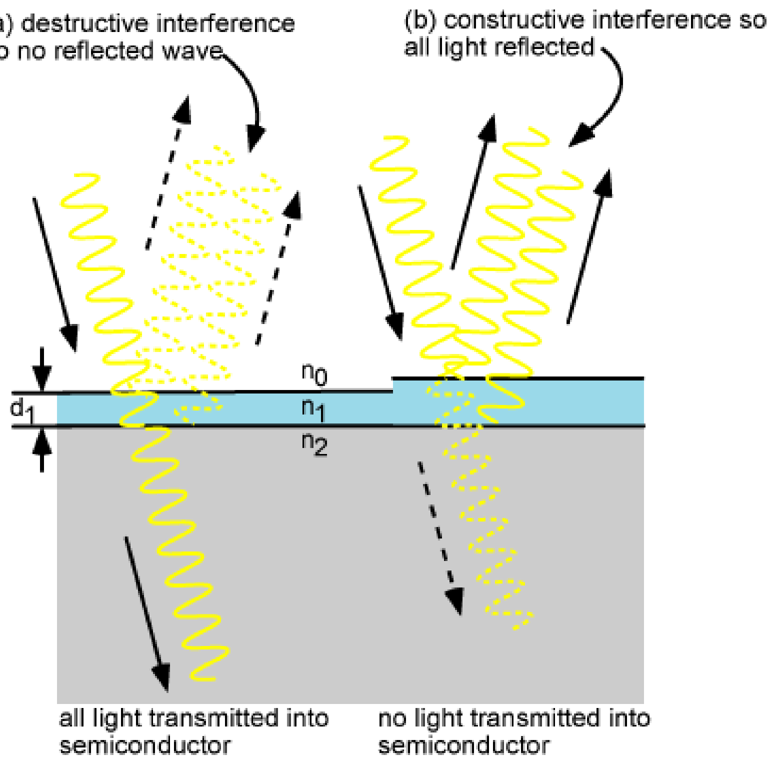


Fig. 11. Light reflection.

For the anti-reflection coating to work adequately and cancel out the reflected light, a proper thickness has to be chosen for optimal anti-reflection. Calculating coating thickness is determined by equation

$$d_1 = \frac{\lambda_0}{4\eta_1}$$
$$d_1 = thickness$$
$$\lambda_0 = incoming\ lights\ wave\ length$$
$$\eta_1 = refractive\ index\ of\ anti - refelction\ layer$$

Anti-reflection index seems like a difficult value to calculate but is calculated by the geometric mean of the refractive index of the semiconductor and refractive index of the material covering the semiconductor whether that be glass and or air. Although these equations theoretically cause zero reflection, this only occurs at a single wavelength. The wavelength of 0.6µm is the peak power of the solar spectrum and is chosen when calculating refractive index and thickness.

3.1.2.2 Layering

DLARC or double layer anti-reflection coating refers to adding two or multiple coating layers for an even better light reflection cost.

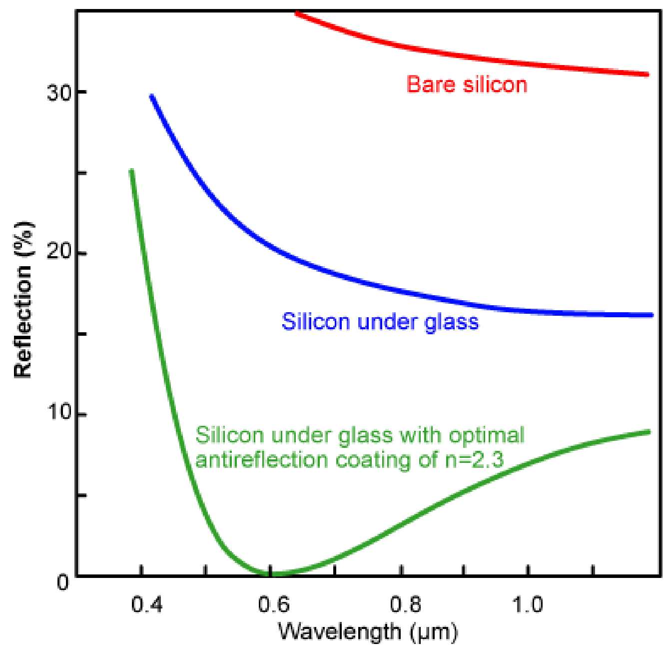


Fig. 12. Panels with anti-reflective coating graph.

Only issue with DLARC is the expense that comes along with the technology making DLARC not cost effective. Formulas that come along with calculating the reflectivity of DLARC are much more complicated and "performance benefits of multiple layers are marginal." [13]

3.1.2.3 Texture

Adding a textured pattern to the surface of the silicone surface in combination with anti-reflection coating minimizes reflectivity on photovoltaic panels. By ingraining textured patterns into the surface of the silicon layer facing the sunlight, light that is reflected has a better chance to bounce on to the surface of the silicone instead of away back towards the air. Patterns shown below display the type of patterns ingrained via laser on to the silicone surface.

Temperature limits the efficiency of the solar panel which in Florida temperature can vary depending on the season. Average temperature for summer being 84º F and 61º F during winter in the state of Florida. When capturing sunlight, solar cells have a limit of operation due to their sensitivity to have a limit of operation due to their sensitivity to temperature. The limitation causes solar energy to not convert to electricity after a certain point for causing stress on the photovoltaic panel. This is a con for reducing the reflectivity of the panel through adding texture or coating the surface.

Light consumed by other materials surrounding the solar cells also contributes to total heat generated by photovoltaic panels which also lowers efficiency. Engineering breakthroughs are making solar cells convert heat into electricity which can potentially triple the efficiency of the photovoltaic panels.

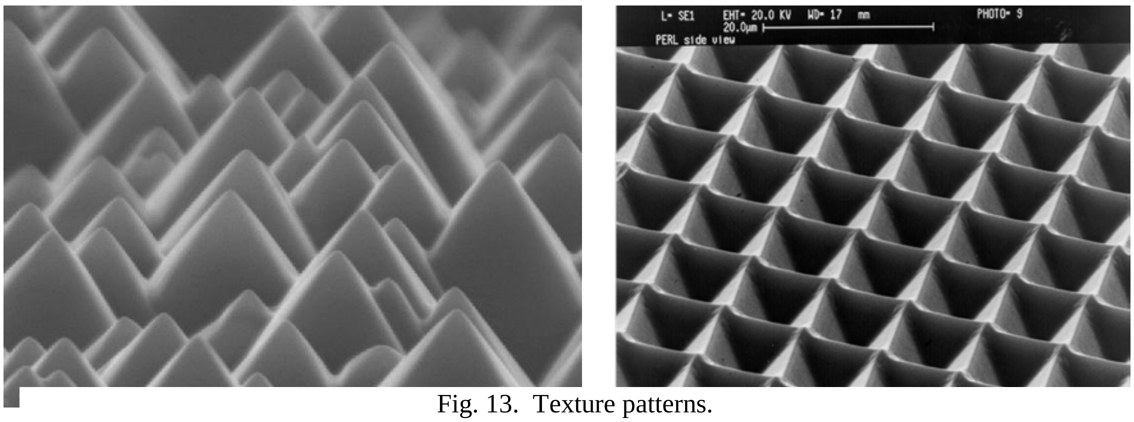


Fig. 13. Texture patterns.

3.1.3 Physical Aspects Affecting PV Efficiency

3.1.3.1 Angle

Altitude, location, position and angle of the photovoltaic panel in combination, exponentially affect the power output. Certain atmospheric effects decrease the efficiency of photovoltaic panels. These atmospheric effects are constant with a small percentage of variation in the city of Orlando including humidity, clouds and air pollution. The suns trajectory in the specific location of the solar sculpture decides what is the ultimate angle and position of the photovoltaic panel for maximum power output. To pick an ideal angle and location, the specific latitude, longitude and average of year-round solar time. Location has been given by the OUC team overseeing the project. Solar sculpture will be in the main entrance at approximately latitude 28.55° N and longitude 81.33° W. With the given information an angle of incidence can be calculated which is the angle between the ground surface and rays impacting the surface of the photovoltaic panel. It is important to consider the season or more specifically the month of the year when calculating the angle. The sun will be lower in the sky during the winter time and higher during the summer time, hence why there is not an ideal fixed angle year-round. During winter time the panel should be more vertical while in the summer the panel flatter. A feature that can be implemented into the solar structure to optimize performance from the solar system is to make the photovoltaic panels adjustable. That way a set angle can be set in the mounting structure depending on the season and a simple manual adjustment can be done to maximize power output. To calculate the optimal angle depending on the season for the solar panel and produce the maximum power output at the location presented by OUC the equations in Table 1 are considered.

In relation to what direction to face the panels, whether it be south, west or east, is not that important in the sunshine state Florida. Between west/east and south there is a 10% difference where south is 10% more efficient.

TABLE I
ANGLE CALCULATIONS

Season	Equation	Latitude	Answer
Winter	$(\theta_w) = (\theta_{latitude}*0.9)+29°$	28.55°	54.68699°
Summer	$(\theta_s) = (\theta_{latitude}*0.9)-23.5°$	28.55°	2.18699°
Spring and Fall	$(\theta_{s\&f}) = \theta_{latitude}-2.5°$	28.55°	23.18699°

Average angle year round = 26.68699°

The lack of importance is due to Florida having a lower altitude and being closer to sea level. For maximum output results “Solar panels should always face true south if you are in the northern hemisphere.” [17]

3.1.3.2 Humidity

From the 100% energy from the sun, around 30% of the sunlight is absorbed by clouds, land and oceans. Florida humidity levels range between 65% to 80% which results in a small layer of water vapor between the sun and photovoltaic panel surface. This humidity factor declines the percentage of utilization from solar energy by an additional 10-15% in addition to the 30% absorbed by clouds, land and oceans. Light absorbed by the ocean generates more humidity to the atmosphere which Florida is surrounded by. “humidity drastically effects the performance of the Solar Panel and proves out to decrease the Power produced from the Solar Panels up to 15-30% if subjected to environment where in the Humidity level remains high.” [1]

3.1.4 Types of PV

Photovoltaic panels can split into multiple different types. Many new photovoltaic technologies are emerging currently or in the near future due to the abundant amount of research going into renewable energy. USA is estimated to invest $5 billion annually into energy research. Out of the $5 billion only 30%, $1.5 billion, goes to renewable energy. More directly, $188 million of the USA renewable energy budget is directed towards R&D solar technology. This is a small contribution in comparison to China, Japan and Korea. Although there is a variety of photovoltaic panel technology, the market is dominated by crystalline silicone technology. [5]

TABLE II
EFFECT OF HUMIDITY ON PV PANELS

Temperature(K)	Humidity (%)	Voltage (DC)	Current Amps(DC)	Powers(watts)
305	25	17.10	2.78	47.538
305	30	16.72	2.63	43.973
305	35	16.53	2.42	40.002
305	40	16.45	2.3	37.605
305	45	16.41	2.14	35.117
305	50	16.33	2.04	33.313
305	55	16.32	1.88	30.681

Photovoltaic types split into 3 main categories. Different type of photovoltaic panels works best for different regions depending on the weather conditions. Currently in the market the most efficient panel is the monocrystalline panel. Monocrystalline panel is made up of a single solid silicone panel and tend to have a black or dark blue look. On average the monocrystalline absorbs around 18% of sunlight and works in low light conditions. Monocrystalline panels also happen to be the most expensive panels in the market. Polycrystalline panels are considered to be a lower quality than monocrystalline. Polycrystalline is made up of small silicone crystals smashed together and tend to have a blue or blue chip look. Average absorption of sunlight rages around 15%. Amorphous panel or thin-film is the cheapest and lightest panel in the market. Monocrystalline and polycrystalline panels have a large power output for a smaller area in comparison to thin-film panel per area as well as a longer life span. Absorption average ranges around 10% of sunlight best suitable for regions with intense sunlight. Another advantage other than price for thin-film is they are sunlight tolerant. This means if the thin-film panel is partially covered by shade the thin-film panel will have a proportional power hit. Example being if 50% of the thin-film panel is covered by shade, the panel will lose around 50% of the power that it could potentially generate. Covering 0.5% of a polycrystalline and monocrystalline panel can result in a 20% power loss. Also, thin-film panels are made of a malleable material adding a flexibility aspect that monocrystalline and polycrystalline panels lack. [33]

3.1.4.1 Monocrystalline vs Polycrystalline

Monocrystalline or single crystalline panels and polycrystalline or multicrystalline panels are very similar in comparison with little difference in performance. Appearance wise the solar cells for monocrystalline panels are black or dark blue as mentioned earlier because of its manufacturing process. Monocrystalline silicone materials are cut into wafers from a conical silicon ingot that is grown in a lab. How the ingot is formed is due to silicon rocks melted at 2500 degrees Fahrenheit followed by a seed crystal lowered to a melted slush. As the seed crystal is lowered, it is slowly pulled upwards while rotating. Due to the ingot being a round shape, there is a lot of material that is waster when cut into solar cell square shape. Hence why monocrystalline panels have rounded edges to minimize waste. Older monocrystalline panels are made up of round cells.

Polycrystalline panels manufacturing process is significantly different than monocrystalline panels. For polycrystalline panels, roughly 1300 pounds of silicone rocks are placed in a 3x3 foot base and placed in a 2500 degrees Fahrenheit furnace. The reason why polycrystalline panels have a blue spotted pattern is due to the melted silicon when cooled down and hardened because the silicon crystallizes. When the polycrystalline silicon is cut into wafers there is much less waste material from the square ingot than the round monocrystalline ingot, making polycrystalline manufacturing process cheaper. Manufacturing process directly affect the cost of solar panels leaving monocrystalline to be more slightly more expensive than polycrystalline. Price differences between monocrystalline panels and polycrystalline panels are small due to high efficiencies in manufacturing processes. [2]

Performance wise, monocrystalline panels tend to be more efficient than polycrystalline. As stated above on average efficiency for monocrystalline is around 18% and 15% for polycrystalline meaning monocrystalline are only 2-3% more efficient than polycrystalline. Monocrystalline produces slightly more power for the same amount of surface area. Example:

TABLE III
SOLARLAND SOLAR PANELS

Type	Monocrystalline	Polycrystalline
Size	59x26.5x1.5 inches	59x26.5x1.5 inches
Price	$324.80	$326.25
Power output	160 watts	150 watts
Current	8.8 amps	8.11 amps
Voltage	12 VDC	12 VDC
Model	SLP160 Silver	SLP150 Silver
Same output	15(panels)*160(W)=2400(W)	16(panels)*150(W)=2400(W)
Weight	26.46 lbs.	26.68 lbs.
Temperature Coefficient	± 0.05%	± 0.05%

Comparing a polycrystalline panel and a monocrystalline panel with the same size from the same company, the differences are noticeable. To get the panels to produce the same power output it would require 15 monocrystalline panels and 16 polycrystalline panels, 1 more polycrystalline panel which in turn involves more space, racking and more hardware components like more wires, micro-inverters or power optimizers.

Although for the examples displayed above the temperature coefficient is the same for both panels, for the most part monocrystalline panels tend to have a better temperature coefficient. Monocrystalline panels handle the hotter temperatures slightly better than polycrystalline panels. The difference is only one hundredths of a difference in power output. In extreme temperature conditions, a desert, the difference would matter but for our location in front of the Orlando City Stadium is a very small difference factor.

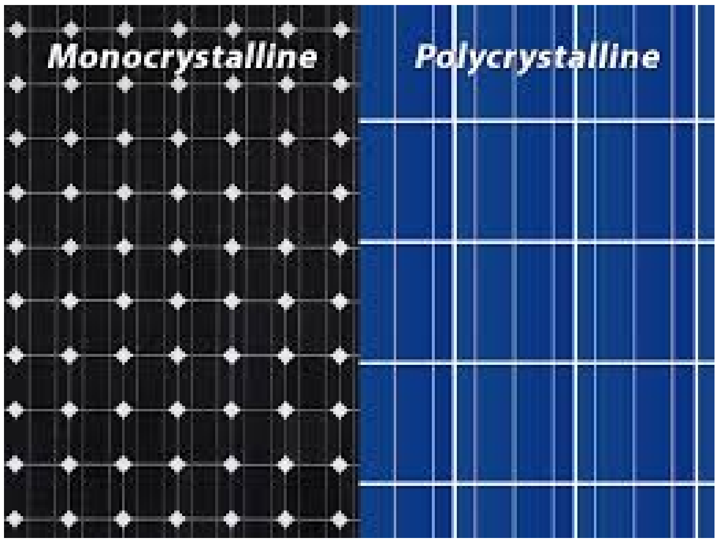


Fig. 14. Monocrystalline vs. Polycrystalline panel.

3.1.4.2 Thin Film

Amorphous or thin-film panels, though not as efficient as monocrystalline and polycrystalline, has its advantages like being cheaper, lighter, flexible and solar tolerant. Thin-film panels use far less semiconductor materials to convert sunlight into electricity making thin-film technology to have lower manufacturing price and lighter on the boards. Thin-film panels are made up of a different material from polycrystalline and monocrystalline panels. While polycrystalline and monocrystalline panels are composed of silicon, thin-film panels are made from either:

- Amorphous silicon
- Cadmium telluride
- Copper indium gallium selenide
- Dye-sensitized solar cell

These new technologies are still young in comparison to silicon technology. Thin-film technology is projected to improve its efficiency to 16% from 10% within the upcoming 10 years. Temperature coefficients are far lower from thin-film than polycrystalline and monocrystalline meaning high temperatures have “less impact on solar panel performance.” [33] Thin-film panels also do not require racking equipment because of its peel and stick application lowering the overall cost.

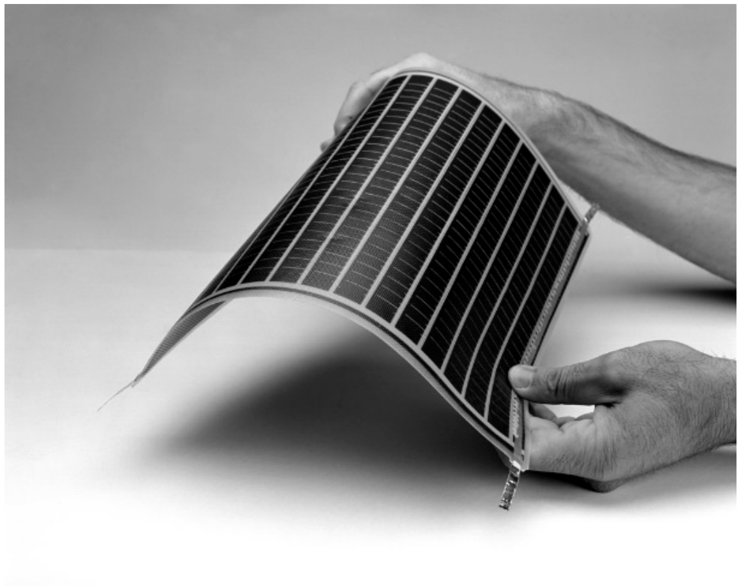


Fig. 15. Thin-film panel. Reprinted with permission from Explain That Stuff

3.1.4.3 PV Comparison

Table 4 compares three different solar panels from different companies. Not all companies stated the efficiency of their panels on their website, which made them an unlikely fit for our needs. Whichever panel we would choose needed to have all its pertinent data available to us so we could design a safe and effective sculpture.

3.1.4.4 SLP190S-24 vs AS-6P 340W vs CS6X-340M-FG

Table 4 compares three different photovoltaic panels that could be purchased from the company Solar Land, Amerisolar and Canadian Solar. The SLP190S-24 and the CS6X-340M-FG had a clear advantage over the AS-6P 340W being made from monocrystalline silicon compared to the AS-6P 340W that is made from polycrystalline silicone. The advantage of the monocrystalline was that photovoltaic panels made from this material generally have better efficiency than polycrystalline. The SLP190S-24 has smaller dimensions and weighs less than the other two PV panels. This was ideal in the OUC group situation because the photovoltaic panels were not being placed on the ground but on artistic structures. This smaller dimension and smaller weight allowed for more placement opportunities and gave less limitations to the design. Although this was good, there was a clear trade off in the power output of the photovoltaic panels. From Table 4 it can be seen that both the AS-6P 340W and the CS6X-340M-FG produce a higher power output compared to the SLP190S-24, with the photovoltaic panels producing 340W annually respectively, compared to the 190W from the SLP190S-24. Although the AS-6P 340W has the same nameplate power output as the CS6X-340M-FG, AS-6P 340W is made up of polycrystalline cells which are lower quality than the monocrystalline cells the CS6X-340M-FG is composed of. The maximum voltage and maximum current are dependent on the maximum input values for whichever inverter is selected.

From the three photovoltaic panels listed above the best one studied was the CS6X-340M-FG. Even though the CS6X-340M-FG has bigger dimensions and weighs more than the SLP190S-24, it produces a higher power output. Nameplate power output was the most important variable for the OUC group. It was noted that the AS-6P 340W also had the same high power output, but due to the fact that it is made from polycrystalline the CS6X-340M-FG had a clear advantage in material quality. For these reasons, the CS6X-340M-FG was chosen as the best photovoltaic panel from the 3 panels listed on the PV comparison Table 4.

TABLE IV
PV COMPARISON

Model type	SLP190S-24 Silver Monocrystalline	Amerisolar AS-6P 340W Polycrystalline	Canadian Solar CS6X-340M-FG (340W) Monocrystalline
Size	62.2×31.8×1.38 in	77 × 39.1 × 2 in	77.6 × 39.2 × 0.2 in
Cost	$245.00	$212.00	n/a
Weight	41.9 lbs	50.7 lbs	60.6 lbs
Efficiency	n/a	17.52%	17.31%
Power Output	190W	340W	340W
Current	5.16A	9.07A	8.97A
Voltage	24VDC	37.5VDC	37.9VDC
Temperature Constraints	-(0.5±0.05)%/ °C	-0.41%/K	-0.41%/K
Annual output	267 kWh/Year	478 kWh/Year	478 kWh/Year

3.1.4.5 LG NeON R vs LG NeON 2 72cell 18.8% vs LG NeON 2 72cell 19.3%

Table 5 compares three different photovoltaic panels that could be purchased from the LG company. The LG PV Comparison table above list the top LG photovoltaic panel options. Unlike the Solar Land, Canadian Solar and Amerisolar company where there were 2 monocrystalline panels and 1 polycrystalline, for the LG company all the panels offered on their site were monocrystalline which tend to be the best type of photovoltaic panels in the market. Both the LG NeON 2 72cell 18.8% and the LG NeON 2 72cell 19.3% panels had a clear advantage over the LG NeON R 60cell 20.3% panel being that the LG NeON R 60cell 20.3% panel was an older model. The advantage of the newer models is that they are made out of newer and more modern technology making the solar cells more adaptable to modern inverters. LG NeON R 60cell 20.3% has smaller dimensions and weighs less than the other two more modern photovoltaic panels and happens to have a highest panel efficiency. This was ideal in the OUC group situation because the photovoltaic panels were not being placed on the ground level but instead on artistic structures being displayed approximately 15 to 20 feet high. These smaller dimension and smaller weight cause less stress on the sculptures infrastructure and allow for more placement liberty giving less limitations to the design. Also noticeable from the older LG NeON R 60cell 20.3% panel is the lower temperature constraint value but it is only a one one hundredth of a difference which will not greatly affect the total power output. Although these were positive attributes, there was a clear trade off in the power output with the newer photovoltaic panel models. From Table 5 it can be seen that both the LG NeON 2 72cell 18.8% and the LG NeON 2 72cell 19.3% produced a higher power output compared to the LG LG NeON R 60cell 20.3%, with the photovoltaic panels producing 390W and 400W respectively, compared to the 365W from the LG NeON R 60cell 20.3%. Both of the newer models were identical in physical attributes but differed in power output and price. The maximum voltage and maximum current were dependent on the maximum input values for whichever inverter was selected.

TABLE V
LG PV COMPARISON

Model type	**LG NeON R 60cell 20.3%**	**LG NeON 2 72cell 18.8%**	**LG NeON 2 72cell 19.3%**
Size	66.93 x 40.0 x 1.57 inch	79.69 x 40.31 x 1.57 inch	79.69 x 40.31 x 1.57 inch
Weight	40.78	47.84 lbs	47.84 lbs
Efficiency	20.3%	18.8%	19.3%
Power Output	350	390	400
Current	9.62	9.81	9.86
Voltage	36.4	39.8	40.6
Temperature Constraints	-0.30 %/°C	-0.36%/°C	-0.36%/°C
Annual output	492 kWh/Year	548 kWh/Year	562 kWh/Year

From the three LG photovoltaic panels the best one studied was the LG NeON 2 72cell 18.8%. Even though the LG NeON 2 72cell 19.3% had a bigger power output than the LG NeON 2 72cell 18.8%, it produced enough power output to meet the minimal OUC requirement and comfortably power any other attached devices while taking into account the overall system loss. Annual output was the most important variable for the OUC sponsor group. It was noted that the LG NeON R 60cell 20.3% also had a high power output, but due to the fact that it was an outdated technology the LG NeON 2 72cell 18.8% had a clear advantage. For those reasons, the NeON 2 72cell 18.8% was chosen as the best PV panel from LG.

3.1.4.6 Overall Best PV Panel

Comparing the best photovoltaic panel from the Solar Land, Amerisolar, Canadian Solar and LG to then pick the overall best fit panel for our system was an easy option. To meet OUC minimal annual power output this would take 3 panels from Solar Land, Amerisolar and Canadian Solar not only meet but also comfortably power any attached devices. On the other hand, for LG to meet the minimal OUC annual power output and comfortably power any attached devices to the structure, only 2 panels would be required. Although when taking price into account the Solar Land, Amerisolar and Canadian Solar even after buying 3 panels comes out to be cheaper than 2 panels from LG. Still the quality of technology as well as smaller surface area coverage on the structure made the LG NeON 2 72cell 18.8% more advantageous. Overall the best photovoltaic panel from the selections listed above was the NeON 2 72cell 18.8%.

3.2 Inverters

Solar panels generate a direct current (DC) which only flows in one direction. OUC required the solar sculpture to be tied into their commercial grid and no battery component to be attached to the solar sculpture. OUCs commercial grid runs on alternating current (AC), which changes direction periodically as well as the voltage producing a negative and positive voltage in relation to the direction of the current. Since the solar panel produces electricity not only for the attached components but the grid as well, a device called an inverter was introduced to convert the DC produced from the panel to AC for attached components and commercial grid.

The DC electricity that is generated by the solar panels is fed to a DC/AC converter. The AC electricity is then used to power electronics (LEDs, pumps, etc.) attached to the sculpture and the surplus is fed to the local power network. Inverters can be referenced as the brain of the solar system. Modern inverters can display how the system is performing as well as identifying problems along the system. These features “help improve grid stability and efficiency.” [44] For a solar energy system with battery components the inverter can act as battery management.

3.2.1 String Inverters

For solar farms or when multiple solar panels are installed side by side, they are referred to as a string or row. Depending on the capacity of the inverter, one string inverter can be installed and multiple panels can be connected to a single string inverter. This makes for the investment of a single inverter the cheapest option. Though string inverters are a trusted technology it does come with its flaws. If shading occurs on a single panel out of the X number of panels attached, to the string inverter, the output power of energy panel on the string is reduced to the struggling panels output. Also all panels must face the same direction and produce the same output. If one panel is facing south and another east the panel facing east will reduce the power output of the panel facing south and vice versa. New technology that can be installed to each panel alongside a string inverter is a power optimizer. Power optimizers diminish the shading effects on solar panels by converting DC to DC, maximizing the power harvested by the photovoltaic panel before reaching the inverter.

3.2.2 Micro-inverters

Micro-inverters are smaller than string inverters and in contrast to string inverters there is a micro-inverter for every photovoltaic panel. They are high performance inverters more applicable for complex systems. Micro-inverters are also directly connected to the photovoltaic panel converting DC to AC at panel level. This causes each panel to act individually. Unlike string inverters, if a panel is being shaded or facing a different direction the overall production will not be affected. Also, micro-inverters make individual panel performance check easier, eliminating the trouble shooting process. Overall micro-inverters make the solar system more efficient. Issue with micro-inverters is the higher cost associated with buying an inverter for each panel instead of a single string central inverter. Another negative of micro-inverters is the maintenance of each micro-inverter is more work since there is multiple inverters and they are located at panel level.

3.2.3 Battery Based Inverter

Battery based inverters can operate as off-grid, grid tied and grid interactive. These inverters, apart from converting DC to AC power, charges batteries while selecting power from different sources. A battery charger component is included within the inverter. This charges batteries from different power sources, like a commercial power grid, other than the sun rays in case of a rainy day and/or high loads. A complex controlling system functions when the grid system is down. A load shed setting is activated to disconnect noncritical loads, which in turn minimizes the damage taken by the batteries is battery voltage drops below a certain point. The battery energy is conserved to power essential loads. This setting can also be applied when the batteries are running low in charge to signal the systems owner. Main purpose of battery-based inverter is monitoring the status and regulating how batteries acquire charge while managing energy between solar panels and the grid. This type of inverter was not in consideration when selecting the final inverter for the solar sculpture since OUC did not want a battery component attached to the solar sculpture.

3.2.4 Power Optimizers

Basic functionality of power optimizers is to maximize the power output of each individual solar panel it is attached to. This is completed by having the power optimizer converting the generated DC to the maximum DC level possible through maximum power point tracking at each solar panel. Power optimizers device work alongside string inverters and have similar properties to micro-inverters in terms of isolating the panels from each other in a string inverter system. Isolating the panels from each other is a string inverter leads to better system performance since each panel is individually tuned to optimal performance. Being that power optimizers are attached to each individual panel, they can be bought and installed separately or be purchased in a panel and power optimizer package were the power optimizer is already installed. Panels not producing the same amount of power output is a string inverter system is eliminated since each panel operates at each panel's optimal current and voltage, independently of other panels in the system.

Power optimizers on average improve the photovoltaic system with a 25% energy increase. Most power optimizers include their own real-time performance data for each solar panel. These performance monitoring is made visible through the power optimizers companies applications. The applications functionalities include data charts, panel layout and system management. These functionalities can alert the owner if the system is underperformance and make trouble shooting more efficient reducing maintenance cost and time ensuring optimal system output. Power optimizers also make photovoltaic systems safer by automatically shutting down the systems current and voltage in case of the inverter or grid turning off. The inclusion of power optimizers makes photovoltaic systems safer than traditional systems as well as provide hardware protection meeting local safety standards. Traditional design constraints for string inverter systems are eliminated allowing for different orientations and tilts. [31]

3.2.5 Inverter Comparison

TABLE VI
INVERTER COMPARISON

Type	**Micro inverter**	**Micro Inverter**	**String inverter**	**String inverter**
Model	IQ6PLUS-72-2-US	MICRO-0.3HV-I-OUTD	SMA Sunny Boy SB 6.0-US	SE11400A-US
Efficiency	97.0 %	96.5%	97.6 %	98%
Input DC power	400 W	360W	6300 W	15350W
Max voltage input	62 V	79V	600 V	500V
Max current input	15 A	10.5A	10 A	34.5A
Cost	$135.90	$99.00	$1,190.00	$1,853.60
Size	8.62x7.52x 1.5in	10.5x9.7x1.37in	21.1x28.5x7.8in	30.5x12.5x10.5in
Weight	3.3 lbs	< 3.5lb	57 lbs	88.4 lbs

When selecting an inverter for the overall system many factors needed to be taken into consideration. The first and most important factor when selecting hardware was the artistic design that was going to hold the photovoltaic system. Other factors being how many panels would be needed to meet the minimal annual output as well as where the panels would be located. If the photovoltaic panels were located far away from each other, then a micro-inverter was to be taken into account since this required less traveling wires into a junction box. If there were multiple photovoltaic panels that happened to be located near each other and facing the same direction, then a string inverter would be best suited. A string inverter could also be used if the panels were not facing the same direction, but additional hardware power optimizers were highly recommended to be integrated alongside the string inverters which was an additional cost. If a string inverter or micro-inverter was best suited then input power, max input voltage and current values had to be present when seeing photovoltaic panel output. Taking into account the best suited solar panel mentioned above and cost of all the devices that were to be purchased the micro-inverter IQ6PLUS-72-2-US was the optimal device. The micro-inverter MICRO-0.3HV-I-OUTD would not match the selected photovoltaic panel power output (390W) with the micro inverter maximum power input (360W). Both the string inverters SMA Sunny Boy SB 6.0-US and SE11400A-US were not economically ideal within our system due to the micro-inverter being much more affordable and not requiring the power optimizer add on hardware. The MICRO-0.3HV-I-OUTD also included complimentary monitoring software that optimized the maintenance process for the solar power system.

3.3 Charge Controllers

Charge Controllers are an important part to any circuit that uses any form of a power source regardless if it uses PV panel technology, wind energy, or energy from the grid. The charge controller allows the circuit to maintain a safe voltage to keep the circuit stable. This is necessary in a circuit to prevent any sort of overheating or harm that can come from an unstable circuit. The way the charge controller works is that it will block any reverse current in the circuit, prevent overcharge, prevent over discharge, protect from electrical overload, and/or display battery status and the flow of power [15]. Charge controllers are not always needed due to the fact that some panels have a low power output so there is no need to control the voltage and current. The OUC structure needed to have a yearly output of 850 kW so there was a need for a charge controller.

For a large voltage panel with a high power output a standard charge controller can be installed onto the circuit, but this is advised against. In a high-power PV circuit, a standard charge controller will lose from 20% to 60% of what the panel is rated at [11]. This loss in output power is significant and while the standard charge controller can protect the system its harm on the system output is the reason for its exclusion in big power PV circuits. For this, a Pulse Width Modulator (PWM) or a Maximum Power Point Tracker (MPPT) should be used in the circuit. The PWM and the MPPT still protect the system but they also make the output power of the circuit more efficient.

3.3.1 Pulse Width Modulation (PWM)

Pulse width modulators is a very popular technology used in PV panels. The PWM is used alongside circuits that utilize batteries to store the power converted. It allows for a safe and effective way to charge the battery using solar energy. Some of the advantages of the PWM are listed below [22].

- Ability to recover lost battery capacity and desulfate a battery.
- Dramatically increase the charge acceptance of the battery.
- Maintain high average battery capacities (90% to 95%) compared to on-off regulated state-of-charge levels that are typically 55% to 60%
- Equalize drifting battery cells
- Reduce battery heating and gassing
- Automatically adjust for battery aging
- Self-regulate for voltage drops and temperature effects in solar systems

The PWMs ability to recover the battery capacity and ability to detect that the battery is sulfating allows the circuit to have less battery failures. This can prevent a corrosion in the grid as well as the battery plates. The increase in the battery acceptance is necessary because since the battery is always charging and discharging, the efficiency of the battery needs to remain high. The battery acceptance keeps the battery charging efficient and in turn keeps the whole circuit efficient. With this in mind, the "high average battery capacity is important for battery health and for maintaining the reserve storage capacity so critical for solar system reliability. [22]" Equalizing the drifting battery cells is important for maintaining a constant charge resistance throughout the PV cells. This constant charge resistance prevents any uneven charge acceptance which can cause deuteriation in the cells. The PWM also helps the battery charge at a faster rate than normal which decreases the chance of the battery overheating. The adjust of the aging battery life for the longevity of the battery to much be longer. The self- regulated voltage drops in the circuit prevent outside factors from damaging or affecting the effectiveness of the system [22]. The PWM is a necessary addition to high powered PV panels that utilize battery power.

The way the PWM works is that it monitors the amount of voltage going into the battery. It "slowly lower the amount of power applied to the batteries as the batteries get closer and closer to fully charged. This type of controller allows the batteries to be more fully charged with less stress on the battery, extending battery life. It can also keep batteries in a fully charged state (called "float") indefinitely. [23]" The PWM sends various pulses to the battery, reads the charge amount, and decides to give it charge or not. Based on every pulse, the PWM self- adjusts its pulse, changing the length and speed of each pulse, to charge the battery [4].

A disadvantage of the PWM is that it cannot be scaled to different amps and voltages because the controller must match the battery bank. It's a clear what you see is what you get example. This causes a drawback in the amount of amps that the controller can get, usually maxing out at 60 amps [40]. This disadvantage can be noticeable or not depending on the implementation of the system. If the system design is to have no growth and have the same constant values throughout then this disadvantage will not affect the circuit all that much. On the other hand, if the system was designed to grow with time this disadvantage greatly limits any growth of the circuit. The other disadvantage of the PWM is that it can only be implemented with a circuit that uses a battery as it's form of storage. This means that PWMs cannot be used if the circuit is being tied into the grid or if the circuit is using the solar power and putting it right back into whatever the circuit is designed to power.

3.3.2 Maximum Power Point Tracking (MPPT)

The maximum power point tracking is used as a tool to help the solar panels be as efficient as possible. It can be used to convert from DC to DC as well as converting from DC to AC. The DC to AC maximum power point trackers can sometimes be implemented directly into the solar inverter. The way the MPPT works is that it the MPPT forces the solar inverter to work at the voltage calculate to be the most efficient by varying the resistance of the inverter input using power electronics [21]. The higher the resistance, the higher the voltage across the solar panel [21]. The MPPT finds the desired voltage by going along the IV curve specified to each different PV panel and tries to set the resistance to the peak of the IV curve. Due to a constant change in weather and amount of sunlight that affects the PV panels constantly the MPPT is always working along the IV curve.

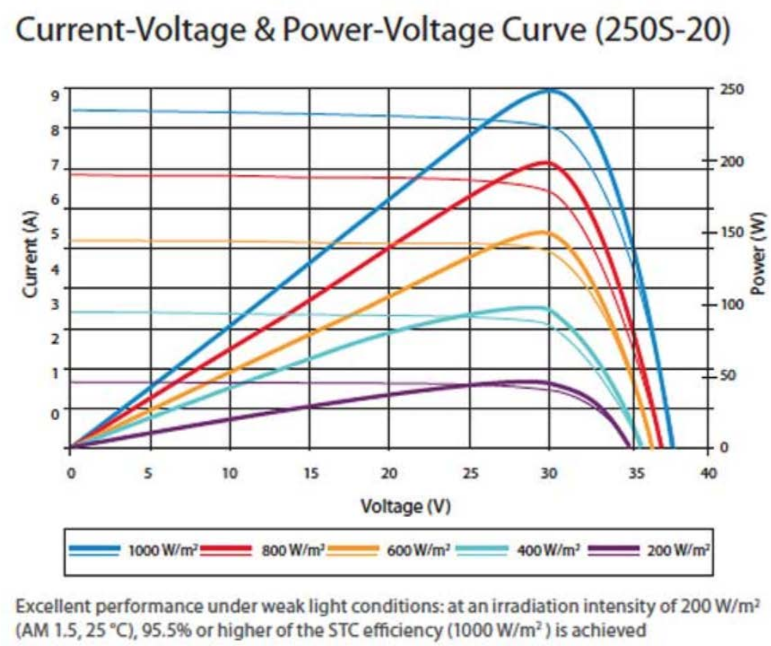


Fig. 16. IV curve. Reprinted with permission from Solar Quotes.

This IV curve shows five different possibilities depending on the temperature and solar light hitting the PV panel. This only five different options that can happen in infinite number of curves that are constantly changing. With the current on the Y axis and the voltage on the X axis, the MPPT uses this to decided what to do to make the panels as efficient as possible. The MPPT is a crucial addition to any circuit that uses solar energy because it will help provide the best possible output available.

Having a good MPPT in a circuit is essential to having an efficient PV panel and energy output. While one MPPT is good, two is even better. The case for two MPPT's in a system is simple, while one can help the overall circuit having a dual-MPPT functionality allows much greater system design flexibility, significant cost savings and higher levels of harvested energy [23]. With this addition to the circuit not only does it help the system have much more functionality, the second MPPT can also act as a backup in case a malfunction in one of the two installed MPPTs. This idea also works if there is a case of one of the PV panels not getting enough sunlight or, in the case of a bad installation, the PV panels is shaded at certain times throughout the day. The second MPPT can act as a single MPPT which can still help the system continue to have an efficient output. This failsafe system is a good implementation for any circuit to have. “Connecting two arrays with different solar azimuths or tilts, different string lengths (Voc) or different PV modules to a single-channel MPPT inverter would result in a highly inefficient system and, in some instances, an unsafe one.” [23]

Table 7 shows how an implemented dual-MPPT system has an effect on a circuit compared to a single MPPT system.

TABLE VII
SINGLE MPPT VS. DUAL MPPT

Single Inverter Attribute	Single MPPT	Dual MPPT
Allow connecting arrays with different solar azimuth angles	No*	Yes
Allow connecting arrays with different solar tilt angles	No*	Yes
Allow connecting arrays with different string lengths	No*	Yes
Allow connecting strings of dissimilar modules	No*	Yes
Allow connection more than two strings without combiner fusing	No**	Yes
Provide better monitoring granularity	No	Yes
* Can be done but results in low harvesting efficiency, lower harvested energy ** Violates NEC requirements. Dual MPPT provides two channels and code allows two strings per input without need for fusing		

The majority of MPPTs are built and designed separately to be used with the batteries that are installed in the PV panels to store the energy converted. For the OUC group, this meant that a lot of the MPPTs found could not be used because they were not designed to go straight into the electric grid. This conversion of DC to AC power did not mean that the circuit would not use MPPTs. Instead what occurs is that for DC to AC power, the MPPT is already installed in the inverters. The inverters are what the circuit uses to convert the power and with the MPPT installed it would still be efficient power.

In the inverters, the MPPT can be used in two different ways. The first implementation of the MPPT in the inverter is converting all the DC power straight into AC in on big step. The second implementation of the MPPT in the inverter is getting the DC power and putting it through the MPPT and then converting that DC output from the MPPT and putting into the DC to AC conversion [35]. In this implementation, the only thing being used in the first step is the MPPT and sometimes a voltage amplification. There is a third way to implement the MPPT into the inverter and it is using a multistring inverter. This multistring inverter uses the same idea of the second implementation where the DC power is put through the MPPT first and then through the DC to AC conversion. This multistring inverter "is beneficial since better control of each PV module/string is achieved. [35]" The following image is a good representation of the MPPT implantation in an inverter.

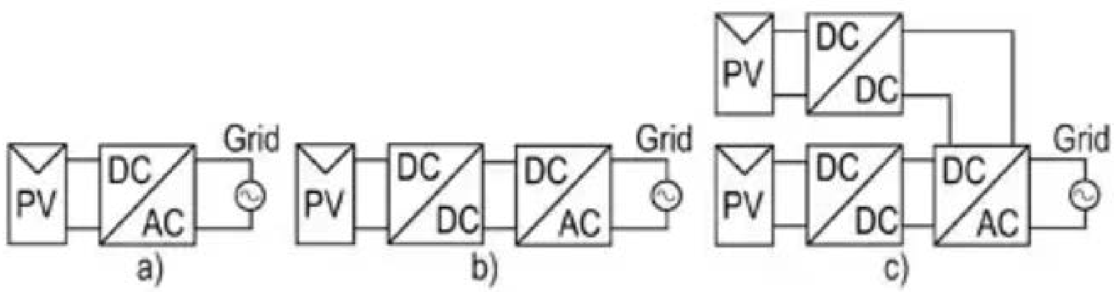


Fig. 17. Connecting PV Panel to Grid Possibilities

3.3.3 PWM vs MPPT

Pulse Width Modulators and Maximum Power Point Trackers both have different pros and cons when implemented in a system. They are both used for different purposes and can be used as standalone charge controllers or can be used together in the same circuit. The biggest advantage that the PWM has is how much it helps to keep the battery life in its prime stage for as long as possible and keeps the battery effective throughout its life cycle. The disadvantage of the PWM is that it cannot be used if a circuit does not have a battery implementation in its design. The advantage that the MPPT has is that it takes the inputted DC voltage and will give the most effective DC output for the design. This helps keep the voltage levels at the most effective points. The disadvantage of the MPPT is that when tied into the grid it cannot be used as a standalone component rather it is used in inverters. This disadvantage makes some of the MPPTs in the market null and void as they cannot be used in a grid integrated circuit.

Table 8 showcases all the pros and cons between the PWM and the MPPT. [23]

TABLE VIII
PWM SOLAR CONTROLLERS VS. MPPT SOLAR CONTROLLERS

PWM Type Solar Controllers	MPPT Solar Controllers
PROS	
- PWM controllers are built on a time-tested technology. They have been used for years in Solar systems, and are well established - These controllers are inexpensive, usually selling for less than $350 - PWM controllers are available in sizes up to 60 Amps - PWM controllers are durable, most with passive heat sink style cooling - These controllers are available in many sizes for a variety of applications	- MPPT controllers offer a potential increase in charging efficiency up to 30% - These controllers also offer the potential ability to have an array with higher input voltage than the battery bank - You can get sizes up to 80 Amps - MPPT controller warranties are typically longer than PWM units - MPPT offer great flexibility for system growth - MPPT is the only way to regulate grid connect modules for battery charging
CONS	
- The Solar input nominal voltage must match the battery bank nominal voltage if you're going to use PWM - There is no single controller sized over 60 amps DC as of yet - Many smaller PWM controller units are not UL listed - Many smaller PWM controller units come without fittings for conduit - PWM controllers have limited capacity for system growth - Can't be used on higher voltage grid connect modules	- MPPT controllers are more expensive, sometimes costing twice as much as a PWM controller - MPPT units are generally larger in physical size - Sizing an appropriate Solar array can be challenging without MPPT controller manufacturer guides - Using an MPPT controller forces the Solar array to be comprised of like photovoltaic modules in like strings

Based on group designs, engineering requirements, and OUC requirements the OUC group implemented an MPPT in the design in the form of an inverter and did not use a PWM. The decision to use an inverter with an MPPT was due to the groups requirements to send energy back into the electric grid. To send the energy into the grid the DC voltage needed to be inverted into AC, hence the inverter. When thinking of designs the OUC group was brainstorming ideas of using a battery along with sending power to the grid, once the OUC group talked to the OUC engineers it was clear that a battery was not going to be used in the design. The reason for this was because the sculpture was going to also take power from the grid, meaning that a battery would be an excess and unnecessary element in the overall design. With no implementation of a battery there was no need for a PWM in the circuit, only an MPPT in the inverter.

3.3.4 MPPT and Inverter Comparisons

As stated before, the majority of MPPTs are built and designed separately to be used with the batteries that are installed in the PV Panels.
This meant that the MPPTs that the OUC group used were already installed in the DC to AC inverters. For this purpose, the following comparisons were used between which inverters had the most efficient MPPTs installed. [36]

TABLE IX
INVERTER PRODUCT COMPARISON

Name	ECO- WORTHY	WVC Waterproof	SUN- 1000G2
MPPT Efficiency	99%	99.5%	99%
Peak Output Power	1000W/900W	1200W	1000W
AC Voltage Range	90V-140V	80V-160V	95V-140V/ 185V-265V
Inverter Efficiency	92%	N/A	>92%
Installation	Grid- Tie	Grid- Tie	Grid- Tie
Size	41*28*15.5cm (16.14″*11″*6.1″)	N/A	N/A
Cost (Shipping Included)	$289.99	$269.99	$455

3.4 Prototype Design

For this project, different design ideas were thought of. Having a solar sculpture outside of the Orlando City soccer stadium that took the place of a generator was one of the purposes for this project, but having it be aesthetically pleasing was also an important part for the OUC group to consider. The OUC group decided to implement different elements to make the solar sculpture more than just a sculpture with PV panels, but also more interactive for the foot traffic. To add elements such as LEDs and sensors, a certain type of MCU was chosen for these functions. The MCU had to work with a Printed Circuit Board (PCB), which was required to be in the design, to get all the functionalities working.

3.5 Microcontrollers (MCU)

The roles of the microcontroller are to control matrices of LEDs or an LCD, measure the incoming voltage and current generated by the PV (photovoltaic) panels and calculating and displaying the efficiency and the amount of energy/money saved, and additionally to possibly handle Infrared sensors. Therefore, depending on the design and desired result the choice of the microcontroller was essential for this type of project and various technical specifications had to be considered.

Power consumption was a huge concern; since the requirements of 850kWh per year exists we had to carefully consider the amount of power required to power the choice of microcontroller (Low cost/Low power vs. High cost/High power) and what exactly we would consider required for the microcontroller to do. However, with regards to power consumption, the design either had to compensate by added additional PV panels or use as low-powered a microcontroller as possible while still fitting our design goals.

Memory was a factor, albeit not too big of an issue where you can't go wrong with too much memory. However, since the project prototype would be a 1/8 scaled model of the actual sculpture we needed to take that into considering for the software being able to drive all of the components (LEDs, displays, sensors) when multiplied by eight times. Therefore, we aimed not only for just enough memory to run the current design, but also to make sure the software could run in the environment of the actual model.

Wi-Fi (Wireless LAN) or Bluetooth was also a consideration in the scenario of programming an accompanying application software for the sculpture. The App would allow control of the sculpture in some form wirelessly for either controlling sensors, LEDs, displays, etc. If we were storing information to a database for example, then a microcontroller with the ability to use Bluetooth or Wi-Fi would become a mandatory requirement.

Temperature max, or how high of a temperature the chip can handle, before overheating, malfunctioning, or even affect the operation life time of the microcontroller may or may not have been an issue. Since the solar sculpture would be outside and in Florida weather we might have needed to consider how hot the chip may get, but the microcontroller would most likely be shielded inside of a box (not exposed to the sun and other environmental effects) and installed inside of the sculpture itself in a locked compartment. Therefore, at most we would only need a chip that can operate under a constant room temperature of 100°-110° F (~40° C) which is not a problem for any microcontroller.

The number of GPIO Pins (General-purpose input/output Pins) was extremely important. Since the solar sculpture's main design point was about aesthetics, it was likely that the sculpture would contain the usage of LEDs or other components for artistic value over technical/functional value. Therefore, it was mandatory that we could estimate the number of I/O ports that would be used to drive the LED matrices or LCD screens and other components required. Additionally, for scaling the number of LED or sensors for the actual sculpture means it was necessary to either recommend a different microcontroller board to switch to or pick a controller that already contained enough pins for the scaled model and the actual model.

There were two methods we could choose to use to drive these LEDs which were Charlieplexing and Multiplexing (row/column display multiplexing). Charlieplexing would allow us to drive up to $n * (n - 1)$ LEDs with 'n' IO pins, but a downside of using Charlieplexing was the maximum number of LEDs that could be lit simultaneously was n-1. Therefore, Charlieplexing could only be considered if we did not need many or all of the LEDs to be lit simultaneously (depending on the application desired) and the current limit of the microcontroller needed be considered since it would impose a brightness limit unless we added external hardware (LED or Tri-State drivers). The other choice was Multiplexing through the rows and columns of a matrix of LEDs; multiplexing would allow for a maximum of $\left(\frac{n}{2}\right)^2$ LEDs with 'n' IO pins to be driven and also allowed access to all of the LEDs simultaneously (through straightforwardly accessing strictly by rows and columns), but the brightness may have suffer due to LEDs being current driven; this meant we could scale the intensity of the light by manipulating the amount of current. However, downsides for this could lead to reduced lifetime of the LEDs themselves which for a long-term product such as a sculpture we prioritized the least amount of maintenance as possible while maintaining a visual brightness from the LEDs. To accomplish this, a solution was to use current limiting (resistor) for the LEDs so we could aim for a desired brightness without burning out the LEDs by aiming for less than the maximum current limit of the LED. Utilizing the LEDs we could create some form of "light show" where the LEDs follow some arbitrary pattern of flashing for aesthetic purposes.

3.5.1 Raspberry Pi 3 Model B (BCM2837)

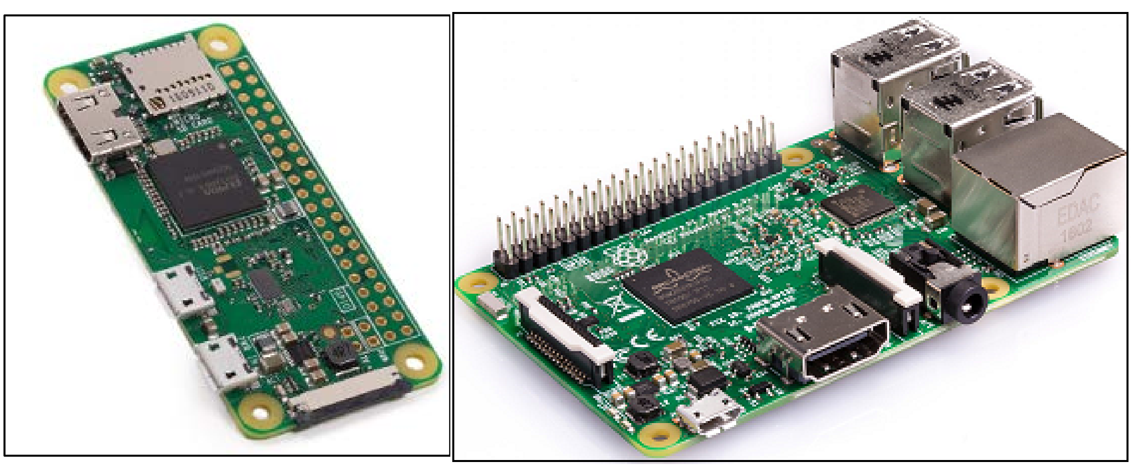


Fig. 18. Raspberry Pi Zero W and Raspberry Pi 3 Model B (respectively)

One of the potential microcontroller chips we considered was the Raspberry Pi 3 Model B which uses a Broadcom chip, BCM2837, which its architecture is identical to the BCM2836 with the only difference that the CPU used is now a Quad Core ARM Cortex-A53. The latest model for the Raspberry Pi series, the Pi3 B, boasts very high specs for a microcontroller such as 1GB of RAM and 64-bit Quad Core 1.2GHz CPU. Also, the Pi3 B comes with 40 General IO pins and the ability to use wireless LAN and Bluetooth.

What was nice about the Raspberry Pi was the cost was actually very cheap for the hardware specifications compared to other microcontrollers and that it supports many different languages such as Python, C/C++, Java, JavaScript, etc. However, in the case of the Solar Sculpture this may not have been ideal because although the Pi3 B boasts very high performance it also consumes a lot more energy compared to a lower cost board; according to the documentation on the official Raspberry Pi website the Pi3 B is powered through a 5V micro USB supply and the current required can vary depending on the components connected to it (power requirements of the Pi will increase when making use of additional various interfaces), but in general the current will range from 700-1000mA (depending on peripherals) and upwards to 2.5A is recommended and the maximum power the Raspberry Pi can use is 1 Amp. If we wanted to extend the power requirements over 1 Amp we would have had to connect the Pi to an externally-powered USB hub; The GPIO pins can draw 50mA safely, distributed across all the pins; an individual GPIO pin can only safely draw 16mA. The HDMI port uses 50mA, the camera module requires 250mA, and keyboards and mice can take as little as 100mA or over 1000mA. Therefore, in consideration we would have only used the Pi3 B if there were fancy things we would like to do; for example: server hosting, running specific applications, delving into audio, anything requiring an OS to run, etc.

The unique or appealing features of Raspberry Pi boards are: it can actually run a full Operating System (or is an OS itself in a sense) such as Linux as an example, price is low, and well documented information available. Obviously, this was one reason for the large power consumption, but it’s also possible to program to a Pi Bare metal somewhat similar to other microcontrollers, but does not contain concise documentation and information which may have been an issue. In general, the Raspberry Pi was a great microcontroller for projects cost-wise and for general use; however, for the design of the Solar Sculpture it might have been overkill or unnecessary and would have drawn more issues with compensating with more PV panels to run the Pi itself.

3.5.2 Raspberry Pi Zero W (BCM2835)

Similar to the Pi3 B, the Raspberry Pi Zero W is a lower-cost and lower-powered version that cuts some of the components to become a more compact microcontroller. Extended from the Pi Zero family the Pi Zero W contains the same hardware specifications, but with the added benefit of an 802.11 b/g/n wireless LAN and Bluetooth; like the Pi Zero its hardware specifications consist of 1GHz single-core CPU, 512MB RAM, HAT-compatible 40-pin header, micro USB powered with mini HDMI/USB. These hardware specifications were more than enough to meet whatever goal we would have wanted. Therefore, what we were really interested in was the power consumption compared to the Pi3 B and other microcontrollers we had researched. Table 10 outlines power requirements of these two Raspberry Pi models. Taken from the official Raspberry Pi FAQ, we can see that the Pi Zero W would most likely have consumed a bit less than half than if we were to have used the Pi3 B.

TABLE X
SIMULATED AVERAGE/MAXIMUM
POWER CONSUMPTION FOR RASPBERRY PI

Simulation/Specification	Pi3 B (amps)	Pi Zero (amps)
Boot	0.75 (Max) 0.35 (Avg)	0.20 (Max) 0.15 (Avg)
Idle	0.30 (Avg)	0.10 (Avg)
Video playback (H.264)	0.55 (Max) 0.33 (Avg)	0.23 (Max) 0.16 (Avg)
Stress	1.34 (Max) 0.85 (Avg)	0.35 (Max) 0.23 (Avg)
Recommended PSU current capacity	2.5A	1.2A
Maximum total USB peripheral current draw	1.2A	Limited by PSU, board, and connector ratings only
Bare-board active current consumption	400mA	150mA

However, this did not tell us the exact amount of power drawn in amps under different situations and only a maximum of what the Pi itself could handle. Luckily, we were provided with a table of each model under various situations that had been tested by the manufacturers.

Therefore, now that we had information when each model of Pi is Booted, Idle, and under Stress we could compare the averages between the Pi3 B and Pi Zero W. We concluded that the Pi Zero W on average would have consumed at most half the amount of power to run. Between those two models, the microcontroller we would have used would be the Raspberry Pi Zero W.

3.5.3 Arduino Mega ADK (ATmega2560)

Another potential microcontroller we had considered using was from Arduino, the Arduino Mega ADK, which had very good documentation and resources available. One of the reasons for considering the Mega was because it was specially designed to work with Android. We had considered designing an App to function alongside the Solar Sculpture and communicate with either Bluetooth or Wireless Lan. Outside of those reasons, the

Mega ADK is a very solid board that is based on the ATmega2560 as its chipset architecture. The Mega ADK contains a numerous 54 Digital I/O Pins (15 of which provide PWM output) and other respectable specifications listed in the table below.

As a comparison between the Raspberry Pi series, the Arduino Mega was a step down in terms of hardware specifications; however, it would also have consumed less power in comparison while still meeting useable standards for our Solar Sculpture. Although, we could've considered using the Arduino Mega 2560 since it's identical to the Mega ADK, it has two key differences. The Mega ADK supports Android which could have been useful or useless, but the real key factor is that the Mega ADK supports DC current per I/O Pins at 40mA compared to the Mega 2560 at 20mA which was significant because we would be driving hundreds of LEDs in a scaled version of the sculpture. Since the location of the Solar Sculpture had been determined to be the Orlando Soccer Stadium the LEDs brightness was definitely a factor where it should shine bright enough to see it across the stadium and far away. Overall, the Mega ADK was a solid choice because it was lower powered compared to a Raspberry Pi although at a higher price point. It also fit our needs and had plenty of documentation and supporting hardware/software components like LEDs, IR sensors, IDE, etc.

3.5.4 Texas Instruments MSP430FRXX FRAM

TI's MSP430 is a well-known and popular microcontroller as a low-cost and ultra-low-powered microcontroller with many variations in the MSP430 family. The MSP430 has standard documentation and some support, but not as in-depth as say Arduino or Raspberry Pi. There are many variations of the MSP430FRXX family with varied specifications ranges (# of I/O pins, RAM, timers, etc.) and one in particular that can work is the MSP430FR5962.

Table 11 contains the MSP430FR5962 hardware specifications which are the lowest compared to the Raspberry Pi and Arduinos before. However, the main attractiveness of the MSP430 was it being ultra-low-powered as well as very cheap to purchase, but one downside for choosing the MSP430 was it did not natively come with any form of Bluetooth or Wireless Lan if we wanted to communicate with the microcontroller through an App. This version of the MSP430FRXX contains 68 general purpose I/O pins which was great for using a lot of LEDs for our Solar Sculpture. However, the MSP430 datasheet does not specify the maximum current a GPIO pin can source/sink which was very important when dealing with LEDs in general. This could be estimated by using two conditions: 1) The MSP430 uses CMOS GPIO, so the high-level output voltage VOH will decrease when a pin sources current and VOL will increase if it sinks current. 2) When sinking large amounts of current, the impact of increased power dissipation is the increase in junction temperature. Which means calculating $Temp\ (junction) = theta\ (j-a) * P + Temp(ambient)$ as long as the temperature is still within the abs. max rating for the device (85C in this case) then it should have no issues. Because this was a very important issue since we were dealing with driving hundreds of LEDs, estimating the maximum current the ports could handle was not very appealing which could have affected the lifetime of the LED or burned them out completely.

3.5.5 Microcontroller Comparison

TABLE XI
MICROCONTROLLER PRODUCT COMPARISON

	Raspberry Pi 3 B	Raspberry Pi Zero W	Arduino Mega ADK	TI MSP430FRXX
Microcontroller	BCM2837	BCM2835	ATmega2560	MSP430
GPIO Pins	40 pin extended	HAT-compatible 40-pin header	54 (of which 15 provide PWM output)	68
RAM	1 GB	512 MB	256 KB of which 8 KB reverse by bootloader	8 KB
Operating Voltage	4.75 – 5.25 V	4.75 - 5.25 V	5 V (3.3V interfacing available)	1.8 – 3.6V
Operating Temperature Range (C)	-40°C to 85°C	-40°C to 85°C	-40°C to 85°C	-40°C to 85°C
Misc.	4 USB 2.0, HDMI port, micro SD card port, Wireless LAN, Bluetooth support	Lower power consumption, smaller board, Wireless LAN, Bluetooth support	Wireless LAN, Bluetooth support, Android compatible	Ultra-low-powered

3.6 Applications

Applications or Apps are usually denoted as a software program that allows a computer or mobile devices like smartphones to perform tasks or provide an interface to a user to do some task. Apps relevant to our Solar Sculpture project were Android Apps. The reason for developing an Android App over an iOS App would be because Android is open-sourced and was easily portable within our means.

The App's way of communicating with the Solar Sculpture would have been through Bluetooth or Wireless Lan. This would have been a fundamental requirement for our microcontroller's choice if we chose to develop an App for the project. However, we had to question the usefulness of an Application software for our product, the Solar Sculpture. The questions we had to ask before designing such an App were: Who is this app for (the users or clients)? What does this app accomplish? Has it been done before (is there a similar existing app)? Is it worth the effort (profitable in time or money)? And is the app feasible to create (in a timely manner)?

A few ideas or reasoning's behind developing an App for this project was aimed at multiple goals. These goals included but were not limited to: ease-of-access, maintenance, portability, and control over the microcontroller handling the LEDs, IR-sensors or other external components we planned to use. Therefore, since we were requested as a requirement to calculate the current power/energy saved from this Solar Sculpture and display it, we considered creating an App to store these values as an average in a database and upload these to a server. This application would then have access to query this database of values and if these values ever hit a standard deviation below the requested energy saved (850kWh per year) it would give a warning or an indication for the people managing the sculpture for maintenance to see if there is anything wrong with the PV panels or other issues.

Another idea would be the App being able to communicate via Bluetooth or Wireless Lan to the microcontroller and select patterns for the LEDs to display as different light shows since the sculpture would be present in front of many people in the Orlando Soccer Stadium. This would be controlled by the people managing the stadium while a game was on-going. Alternatively, we could have implement audio control with a speaker using the App and it could broadcast something from the sculpture either as a microphone, sounds, or music, etc.

Software for designing the mobile App would have been developed using Android Studio because it's Android's official IDE and would have been helpful developing an app for the platform. It also supports languages such as Java, C++, and XML; where Java or C++ would have been used to develop the backend and XML for the frontend (UI).

3.7 Wireless

Wireless communication has become a standard for many appliances and applications in the world today. Therefore, we needed to consider when to use wireless communication depending on the task and if it was necessary. Most wireless apps just execute simple tasks utilizing a microcontroller to control something from a distance.

Then we considered replacing external components with wireless versions of themselves. In cases of wiring or length/distance, a wireless component may have been a better design overall. For our project we used hundreds of LEDs for the scaled version; therefore, "communicational wireless LEDs" were just not practical because the design would most likely be communication between a wireless Tx and Rx to communicate with another microcontroller/device controlling a set of LEDs. However, compared to wireless sensors the technology and products already exist. We may have been able to integrate wireless IR sensors or other wireless sensors in the design of the Solar Sculpture. An example application of using a wireless sensor for the design was since we knew where the location of the Solar Sculpture would be built we could have potentially measured the distance of the entrance into the stadium and looked for compatible sensors that met the distances and have the sensors communicate with the microcontroller wirelessly to do something such as change the pattern of the LEDs or display something.

3.8 LCD Displays

A liquid-crystal display or LCD display is a flat-panel type of screen used in a wide variety of applications for displaying content indoors or outdoors. Common examples of what LCD displays are used for are: computer monitors, televisions, smartphones, calculators, digital cameras, etc.

One of the requirements for the Solar Sculpture was to have a visual display of the calculated amount of net gained/saved power from the PV panels and in addition we wanted to display that value converted into a value of currency (USD) to help promote the value of renewable energy resources in a unit people would understand rather than say Kilowatt hour. Therefore, the LCD display was a major component and certain factors needed to be considered upon selecting the correct display. The factors that we considered when selecting a display for the Solar Sculpture were: the size of the display, the cost, the amount of power consumption, readable under outdoors condition, and the compatibility with the microcontroller we were using.

3.8.1 Potential LCD Displays

3.8.1.1 7 inch Display Screen for Raspberry Pi A+/ B+/ Pi 2/ Pi zero/ Pi 3

This LCD screen is fairly large at 7 inches; the screen's resolution comes in at 1024x600 pixels and the dimensions of the screen itself is 186 x 152 x 25 mm. The size is pretty large and should have been a good fit for any sculpture's design unless the design of the sculpture was slim or the diameter was fairly small. This LCD screen is compatible with all the current models of the Raspberry Pi series (more importantly it's compatible with Pi Zero and Pi 3) which is connected via an HDMI cable specifically for the Raspberry Pi and the screen and Pi can be powered with a 5V power supply. Overall, a good screen to use for the size at a price of around $54.

3.8.1.2 3.5'' TFT Display & RTC for Raspberry Pi A+/ B/ B+/ 2/ Zero/ 3 (26 pin)

This 3.5" TFT LCD screen comes with a RTC module (Real Time Clock) and utilizes TFT technology (thin-film transistor) which would improve the quality of the images displayed. However, the cost of the usage of TFT displays is the power usage compared to a regular LCD display. The way a TFT LCD display works is it is a large sheet of transistors which each are controlled independently; this TFT screen is an active-matrix where each pixel is illuminated individually which results in a more fluid, sharper, and brighter display which is done with a quicker refresh rate. The display's specifications are listed in the comparison table, (**Table 12**).

The TFT LCD display's RTC module could have been useful since it can keep track of the date/time and we can possibly use that when controlling to display either seasonal or the time of day (day/night). The size is half the size of the 7 inch screen previously mentioned and the resolution would also suffer due to that at 320x480 pixels, but they should still be respectable unless the statue were relatively large compared to the display. Therefore, as long as the display is visible and not too tiny it should have been sufficient. Another positive difference between the 7" screen and the 3.5" was the power consumption of the 3.5" does not need any additional power supply and the 7 inch requires at least 5 volts to power the Pi itself and the display. Overall, the 3.5" was a more attractive screen compared to the 7 inch due to the cost being roughly half of the 7 inch display (~$25 vs ~$54) and the power consumed would not be an issue as long as we could power the Raspberry Pi itself.

3.8.1.3 I2C 2.42" Compatible SSD1306 128x64 OLED Display Module

This 2.42" OLED display utilizes I2C Protocol (Inter-integrated Circuit Protocol) which is a protocol that allows multiple "slave" circuit chips to communicate with the "master" chips. The advantage of I2C was it only required two signal wires to exchange information between the two devices which meant we would only need to connect two wires between the I2C ports on the Arduino and this LCD screen (SCL and SDA pins on an Arduino). However, a problem with I2C was it technically is a bottleneck depending on the memory and processing power of the microcontroller used and how large of a LCD display it needs to drive; luckily, this was not an issue for the intended use if we did use this OLED display because we would only have displayed characters/text to the screen and not high resolution images. The 2.42" OLED display's hardware specifications are listed in the comparison (**Table 12**).

From Table 12, the specifications of the OLED display is smaller than the previously mentioned displays, but to compensate it has I2C interface for ease of installation and OLED under direct sunlight should be slightly more readable outdoors than a regular LCD screen by overpowering the sunlight with its brightness. However, it was not confirmed that the screen would have had better visibility compared to a more expensive transflective model, but from a price perspective, $19.75 compared to around $135 for a decent sized transflective LCD display is significant. However, we would recommend our sponsor, OUC, utilize a type of transflective LCD display to be suitable under direct sunlight for the full-sized sculpture if they wish to use an LCD display.

3.8.1.4 Crystalfontz 128x64 Parallel Graphic LCD

A 128x64 pixel graphic LCD that has a yellow-green backlight that utilizes "positive mode" which uses the brightness of the sun as more light gives it more visibility. This is due to the display having dark letters on a light background; this display can be installed using 8-bit interface wiring and is compatible with Arduino. The display's hardware specifications that are relevant are listed in the comparison in Table 12.

The hardware specifications that this display has can definitely get the job accomplished. One reason that we stayed away from character LCD displays over graphic LCD displays was because even though most likely we would only be utilizing characters for displaying text we would have no way to scale the text to be visible. Additionally, those character

LCDs are fairly small, but come in at a very affordable price ($10 price range). However, a major issue regarding the screen is the actual size is possibly too small but is the only really affordable for a transflective LCD display at a price of around $20. A similar transflective LCD display, Crystalfontz 320x240 Parallel Graphic LCD, is about double the size with a resolution of 320x240 pixels would cost almost $100 which is five times the price. Overall, this 128x64 graphic LCD display was useable since we could most likely fit all the information we needed to display onto the screen and it comes with the advantage of being readable in the sun, but the size may have been an issue and needed to be reconsidered.

3.8.1.5 20x4 Character LCD Display (yellow/green backlight)

A standard 20x4 character LCD display module with a yellow/green LED backlight has nice contrast and is interfaced either using a parallel bits or over a single-wire serial interface by using a Serial Enabled LCD backpack or similar hardware. There are various 20x4 character displays and compatible with most microcontrollers; in fact, the MSP430 can only really utilize smaller character displays like this which is due to the MSP430's low amount of RAM and flash. This character LCD display's hardware specifications are listed in the display comparison Table 12.

What was nice about this 20x4 Character display was that it's a transflective so it would be readable outdoors under the sunlight. The screen's size left something to be desired, but it would get the job done at the bare minimum assuming there was nothing else that needed to be displayed besides the energy taken in from the PV panels and the conversion of currency saved. Arduino is very easy to program and drive a character display because there are many supporting libraries for LCD screens. If we had gone with an MSP430 variation of microcontroller then this type of display would be the maximum we could run with an ultra-low-powered and memory controller. Overall, transflective LCD display types are the best, but are very expensive compared to regular or reflective models. This particular 20x4 character display costs around $20 which is about double the price of a regular 20x4 character display, but the price would be worth it since readability was a very important factor when using a display outdoors.

3.8.1.6 Adafruit 3.5" TFT 320x480 Touchscreen HXD8357D

The last display we considered utilizing, the HXD8357D, was a touchscreen LCD display that is compatible with an Arduino. This display is a 3.5-inch TFT touchscreen that has a resolution of 320x480 pixels which includes individual RGB pixel control. Additionally, this display has a controller built into it with RAM buffering which means that almost no work would be required from the microcontroller. The hardware specifications are listed in Table 12.

The idea of utilizing a touchscreen over a regular LCD was mainly for additional user interaction or maintenance. It would have consisted of a touchscreen user interface for a user to select what interface they would like to view. One of the functions on the touchscreen would have been an RGB slider to control the currently lit LEDS to the RGB color combination on the screen. Another function could have been a way to switch between LED patterns that are programmed and selectable via touchscreen. Lastly, there would have been the default home screen that would show the current energy saved and how much money the sculpture has saved. Overall, the specs of the 3.5” touchscreen by Adafruit were pretty solid; a concern we had was the readability of the touchscreen outside. However, regardless of that this touchscreen had very good documentation and should have been easy to install with three ways of interfacing (8-bit, SPI, and I2C with additional hardware) and numerous libraries for Arduino that would have enabled a solid and decent looking user interface on the display.

3.8.2 Display Comparison

Table 12 gives a concise overview of the different displays available to use for the sculpture. We paid special attention to things that would have affected how the screen fit into our electrical system as well as how well the screen could perform the function we needed it to. It had to be a screen that could withstand Florida weather and also be able to catch the attention of passersby of the sculpture. To that end, the screens with extra functionality that we were not likely to use had less chance of being picked.

3.9 Monitoring the Power generated from PV Panels

To fulfill the requirement of displaying the net estimated solar energy produced from the PV panels, one way we could calculate the annual solar energy output of our Solar Sculpture was manually using the global formula that can estimate the electricity generated is $E = A * r * H * PR$ where ‘E’ is energy (kWh), ‘A’ is the total solar panel area (m^2), ‘r’ is the solar panel yield or efficiency (%), ‘H’ is the annual average solar radiation on tilted panels, and ‘PR’ is the performance ratio, coefficient for losses (between 0.5 and 0.9 where the default value is 0.75).
However, decided to calculate the annual output by utilizing PVWatts, created by the National Renewable Energy Lab (NREL), a free worldwide calculator that can calculate the energy production and cost savings of PV systems throughout the world.
PVWatts can estimate the monthly and annual irradiation and energy production in kilowatts and energy value by filling in information such as: location, parameters of the system for size, electric cost, array type, tilt angle, and azimuth angle. This tool is immensely useful as it has a loss calculator to also factor into the result as well as advanced parameters to consider such as inverter efficiency and ground coverage ratio. To accomplish this goal, we entered our system’s information into this calculator and simulated the average annual output to make sure it was above 850kWh per year.

However, we also had to factor in other components such as: the microcontroller, LEDs, sensors, etc. These needed to be considered and calculated for their annual consumption as well and subtracted from the total. This value was then coded into the microcontroller to be displayed onto our LCD display screen.

Besides the estimated annual solar energy produced, we thought it may also be nice to develop a way to monitor the current incoming voltage, current, or the watts generated at that particular moment, which would update every so often and be displayed along with the estimated solar energy produced and value of money saved.

TABLE XII
LCD/OLED/TFT DISPLAY COMPARISON

	7" Display for Raspberry Pi	**3.5" TFT Display & RTC for Raspberry Pi**	**I2C 2.42" 128x64 OLED Display**	**Crystalfontz 128x64 Parallel Graphic LCD**	**20x4 Character LCD Display**	**Adafruit 3.5" TFT 320x480 Touchscreen**
Size	7 inches	3.5 inches	2.42 inches	66.52 x 33.24 (mm)	77(W) x 26.5(H) (mm)	3.5 inches
Resolution	1024x600 pixels	320x480 pixels	128x64	128x64 pixels	20x4 Character	320x480 pixels (18-bit color capable)
Interface	HDMI	HDMI	I2C	8-Bit	8-Bit	8-Bit (requires additional 4-5 digital pins for read and write to display (12 pins total)) or SPI (5 pins); plus 4 pins for touch screen control
Dimensions	186 x 152 x 25 mm	83mm x 55mm x 16mm	62 x 40 x 6 mm	95.5x 50.2x 13.6(MAX)	98(W) x 60(H) x14MAX(T) (mm)	56mm x 85mm x 4mm / 2.2" x 3.4" x 0.2"
Backlight	Yes	Yes	N/A	LED Yellow Green	LED/Bottom(Yellow-green)	6 white LED backlight with DC/DC constant-current boost

Voltage	5 V	5 V	5 V	5V (3.3V logic compatible)	5 V	5V compatible (3.3V or 5V logic)
Misc.	N/A	Powered directly from the Raspberry Pi, no additional power required. RTC module	Color Depth: Monochrome (White)	STN, Positive, Transflective, Yellow Green	STN/Y-G/Transflective/Positive	Touchscreen, includes individual RGB pixel control

To accomplish that we would have had to figure out how to monitor the voltage and current from the PV panels and then send that data to our microcontroller display before being able to display the value. To display the value on our LCD display we would then use this data (voltage and current) being monitored to calculate the power and finally send that value to our LCD display. Therefore, we had to decide on a microcontroller to use before continuing with the design process. After much research and discussion, we decided to go with an Arduino-based microcontroller due to its superior documentation, supporting hardware, and libraries.

The Arduino comes with many built-in supporting functions and libraries for its IDE and one of these functions we were particularly interested in was the analogRead() function. This function reads a pin as a parameter and returns an int value (from 0 to 1023) and this int value is determined from the selected pin from the function's parameter. This pin can only be one of the specified analog pins on whichever Arduino board being used which in the case of the controller we picked was the Arduino Mega ADK which has 16 analog pins. These pins on the Arduino board are 10-bit analog to digital converter which means it can map input voltages between 0 and 5 volts which will return a 0 to 1023 integer value. Therefore, it leads to a ratio of 5 volts / 1024 units or .0049 volts per unit (or 4.9 mV per unit). For this method, we then reserved at least two of our analog input pins solely for measuring the output voltage and current.

3.9.1 Monitoring the Voltage

To measure the voltage coming in from the PV panel we could create a voltage divider using a couple of resistors across the power supply output which in this case would be the PV panels. However, since we were using an Arduino, the limitation of the analog pins were it could only take in a maximum of 5 volts before we end up frying the Arduino. To negate that from happening we needed to pick the resistor values correctly to get a Vout ratio below 5 volts, but as close to 5 volts as possible. This would ultimately depend on the specifications of the PV panels that we used in the design, but we could most likely contain a 20-volt input with just a 10k ohm resistor and a 3k ohm resistor. For example:

If we were expecting a 20-maximum volt power source then our voltage divider would consist of R1 = 10k ohms, and R2 = ~3k ohms. With Vin at 20 volts we would get

$$Vout = \frac{Vin*(R2)}{R1+R2} \text{ which would be } Vout = \frac{20*3000}{13000} = \sim 4.61\ volts.$$

This 4.61 volts would be converted into a digital value from 0 to 1023 after entering the Arduino's analog input pin. Then that digital integer value is directly proportional to the maximum power supply output voltage (in this case it would be 20 volts). We would then store this value coming into the microcontroller in a variable or a storage source if we would want to create an average over a certain amount of time. Of course, there would be small errors, so it would just be an estimate and the accuracy could vary depending on the value of the resistors chosen.

3.9.2 Monitoring the Current

For measuring the current coming in there were a couple options available. The method without buying any additional hardware or software to measure the current for us was to insert a very small or basically a "shunt" resistor in series with the output (PV panels in our case) and then measure the voltage drop across this resistor. However, we had to take care in the resistors choice because the amount of power generated over the resistor needed to be a very high-wattage resistor that could handle the load. Then using Ohm's law, we could calculate the current. For example, let's use a resistor of 0.01 ohms and say the amount of current passing through it is 5 Amps.

$$V = A * R = 5\ V * 0.01\ Ohms = 50\ mV;$$

Assuming that 5 Amps is around the maximum current generated from the PV panels in this example it would be a bad or too small of a representation. The reason behind this is because the range on the analog input for the Arduino is 0 to 5 volts; we can see that the voltage drop is too small across this 0.01 ohm resistor to give an accurate proportion after converting the digital value into a voltage and then calculating the current across the resistor within the microcontroller.

There were a few ways to remedy this. One way was to use an amplifier (for this example we could set the gain to 10), but a high gain amplifier is susceptible to noise and may not have been ideal for this purpose. Another way would have been to increase the value of our "shunt" resistor to increase the value of the voltage drop, but this also would have negative effects on the system. If we were to have increased the value of this resistor it would have resulted in power depletion and reduced the maximum output voltage (less energy generated overall). One final way was to use additional hardware; in this case a Hall Effect current sensor would be suitable for the job. Using this Hall Effect device, we could completely replace the small resistor and amplifier with a corresponding current sensor that produced a good ratio of (mV/Amp) output. Utilizing existing hardware, such as the Allegro MicroSystems ACS712, was overall a better solution than reducing the potential of the system by avoiding the use of additional hardware.

3.9.3 Communicating and Displaying Values on an LCD

Once the analog pins on the Arduino receive the voltage values we could call two analog Read(pin), where the 'pin' parameter is the actual pins connecting to the voltage divider Vout and the current sensor's Vout. We could store these values into a variable and then choose to calculate the power which is just the voltage times the current to obtain the wattage. Finally, we could easily utilize the Arduino's libraries for LCD displays; for example, if a variable names such as current and voltage exist and store our values we could easily just program onto the Arduino to do something like lcd.print("Current: "); followed by lcd.print(current) or lcd.print("Volts: "); lcd.print(voltage) or lcd.print(power). These print functions would be contained inside a loop with delays suitable for how often or how many ticks should pass before we want to read and display the updated current voltage or current to the LCD display.

3.10 LEDs

To add some flair to the sculpture, LEDs were used to light it up at night and create eye-catching displays. The art students who worked on this project decided on how best to use the light from the LEDs to beautify the sculpture, and our team programed the MCU with the algorithms to execute their vision. To add LEDs to the sculpture, it was necessary to solder the LEDs onto wires coming from pins on the MCU. To get the most variety possible, the wiring of the LEDs needed to be carefully planned. They needed to be able to extend for relatively long distances as the sculpture may have been up to 15 feet tall and 8 feet in diameter. This meant that transistors may have been used to boost the output signals of the MCU so that they could drive many LEDs that were over 15 feet away from the pin that was driving them.

The LEDs were driven by the microcontroller hidden within the sculpture and were used to create some type of display to passersby. The LED's could display something as simple as alternating light patterns or they could convey information in pictures or writing if the LED's were set up in a matrix. In any case, the LEDs chosen for this project were low power, low heat dissipation, and had a long MTBF so that minimum maintenance is required. The ease of changing one of the LEDs was also a considered factor so that if one fails, replacement will not be an arduous task.

To help decide on the LEDs to use for this project a decision matrix was used to weigh factors such as luminescence, heat dissipation, power requirements, voltage requirements, current requirements, cost, size, lighting properties. For the engineering requirements it was necessary that at least 90 LEDs could be mounted on the sculpture and driven by the MCU used. To give a large amount of flexibility when it came to lighting choices, special multiplexing algorithms would be employed by the MCU to fully utilize its pins. This is covered in further detail in the section on the MCU but to multiplex the LEDs, they must be soldered together such that they share a common cathode/anode at their row, and a common anode/cathode at their column. Whether the anode or cathode is at the row or column does not matter, only that they are opposites and that the LEDs are oriented to work with the placement of the anode (**Fig. 19**) [14]. This method of arranging LEDs allows for individual control of each LED.

3.10.1 LED Limitations

A limitation here was that each column must be driven individually, and each row must be grounded individually, for a common-row cathode arrangement. This was achieved by employing pins on the MCU to attach to each column and using the same pins to control MOSFETS to open channels to the ground at the corresponding column. Another limitation was that if an entire row were to be activated, the voltage supplied by the MCU must be enough to power each LED. This meant that there was a limitation to the number of LEDs in a single row that may be driven. Fortunately, rows of LEDs may be arranged in parallel and share the same node voltage. Again, there was a limitation here; the current supplied must be enough to cover the current requirements of each row, as it will divide as rows are added according to Kirchhoff’s current law.

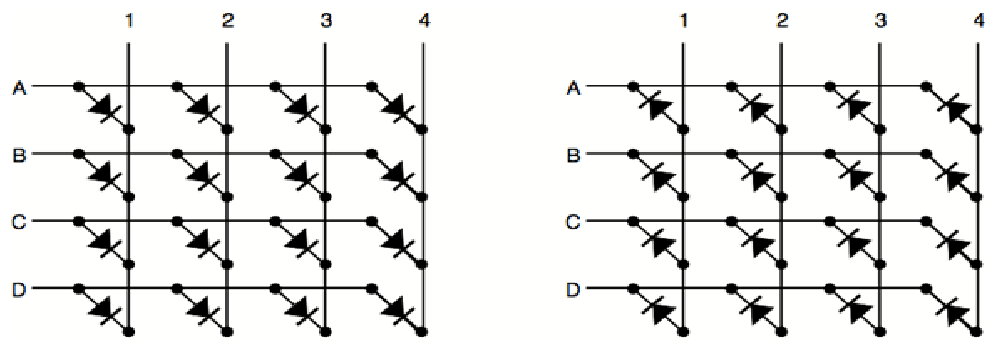


Fig. 19. LEDs arranged with a common-row anode (left) and a common-row cathode (right)

Something else that had to be considered when setting up LED arrays was the use of resistors. Since an LED is a semiconductor, its current increases exponentially as a function of voltage supplied [9]. This means that the current must be limited by some resistive element in the circuit as it’s unrealistic to expect that the output voltage will be constant. In every row of LEDs, it was important to have a resistor to limit the current in the LED, or it would likely be damaged by overcurrent, or worse, the MCU or PCB would be damaged.

To decide what resistor should be used, the type of LED had to be known first as each kind has a different operating voltage. By comparing LEDs in Table 13 the most suitable resistors could be picked out for each by simulation or circuit analysis.

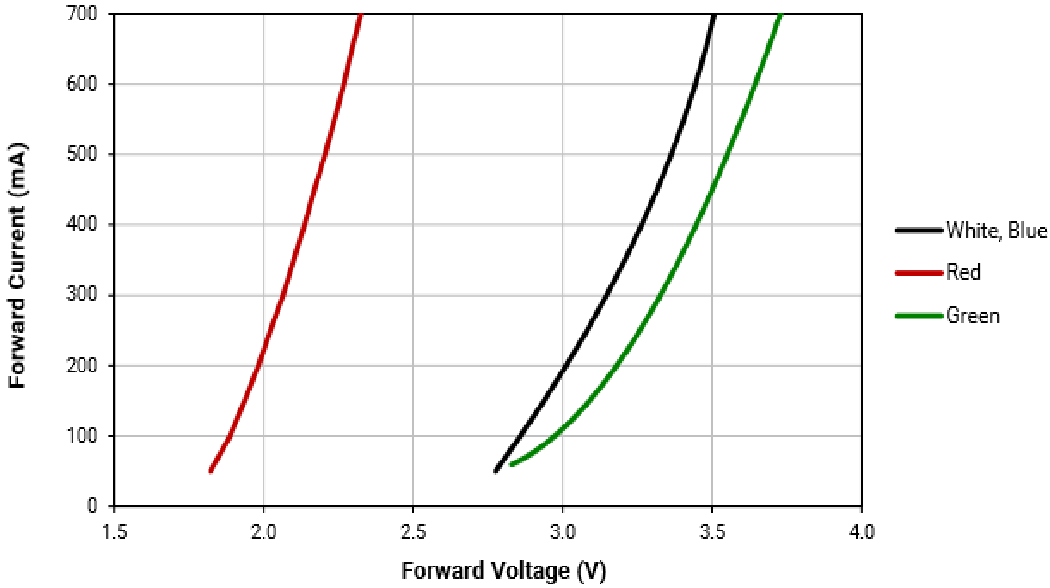


Fig. 20. Red, green, and blue LEDs operating point diagram. Reprinted with permission from Cree.

3.10.2 LED Drivers

These devices have fast responses by sensing current in the circuit and responding appropriately, which helps protect the LEDs as the current they generate will change as the temperature of the junction changes while in use, as will the output luminous flux (**Fig. 34**) [7]. This feature finds use in our project by being able to respond to changes in the output to the LEDs (intensity changes, pulses, etc.). A driver can drive from 4 to 12 LEDs based on input voltage and forward voltage requirements of the LEDs. The drivers did have some limitations and drawbacks though; their output is not constant, it is dependent on input, which was a problem for us because the input we could provide was limited to the output of the MCU, meaning that the potential of the driver was somewhat wasted and the number of LEDs in a row we could drive was also limited.

More robust drivers do exist that can produce higher outputs from a small input and can handle larger arrays of LEDs, but these are significantly more expensive. Despite the extra expense, a more robust driver would have been the way to go for this project. There were likely to be many LEDs on the sculpture and the sculpture may have been up to 15 feet tall, therefore it seemed likely that long runs of LEDs would be necessary. Just one of the more robust drivers can handle over 70 1-Watt LEDs, which would dramatically cut down on the amount of extra wiring and circuitry required for supplying power to the LEDs. The other advantage to this driver was that it could handle LEDs with higher forward current requirements. These types of LEDs are brighter and may have been necessary to make the sculpture stand out as it would already be in a well-lit downtown area, which would be even more lit up on the days when there is an event at the stadium.

3.10.3 LED Quality Considerations

The desired coloring of the sculpture may have been achievable using only monochrome LEDs or a mixture of monochrome and RGB LEDs. Monochrome LEDs produce one color and can have different levels of luminous flux based on the amount of current in them (**Fig. 32**). RGB LEDs have red, green, and blue LEDs in one package, and some have a white LED in the package too. One major advantage to the monochrome LEDs was that the output to them is less complicated than RGB LEDs. Monochrome LEDs required no consideration of different forward voltages or currents (not considering current changes to affect luminous flux), different thermal tolerances, or different efficacies (**Table 13**). There was also the issue of cost; Comparable RGB LEDs are more expensive as they necessitate having three LEDs. The monochrome LEDs also only require one voltage input, even when multiple LEDs are present in a package because they work off the same forward voltage and current. The RGB LEDs require different currents and voltages, so they must be individually fed, meaning an RGB LED needs either 3 or 4 inputs, depending on whether a white LED is also included in the package.

Another consideration was which type of LED to use on the sculpture. The two types that we explored for the sculpture were surface-mount device (SMD) and 5mm LEDs. The 5mm LEDs were attractive because they are small, cheap, and have pins for their anode and cathode which makes it easier to solder them. The downside to these LEDs was that their viewing angle is reduced compared to SMDs, their current and temperature tolerances are lower, and they are not as bright [7]. SMDs could be purchased individually and soldered to a surface of your choice, or they could be purchased already soldered to a surface. The advantage of buying them already mounted on a surface was that manufacturers provide a package that takes thermal issues into consideration and provides convenient points to solder outputs.

There was also the matter of choosing LEDs based on which MCU would be selected. Most MCUs only provide a maximum output of 5 volts, but some of the LEDs under consideration required a lot of voltage to drive them, especially if they were going to be in long arrays, and quite spread out. The LED drivers may have partially mitigated this problem, but even they have lower limits on inputs that 5 V may not cover. It may not have been feasible to run many of the high-power LEDs, particularly the groupings of SMD LEDs. To ensure that the MCU could drive the LEDs, it may have been necessary to make custom arrays of 5 mm LEDs or SMD LEDs.

Alternatively, we used LED strips. In an LED strip, many SMD LEDs are placed on a thin flexible PCB, in various densities per unit distance. These had a few big advantages over the other LEDs considered. First, the strips are composed of sections that may be cut to produce a desired length run of LEDs. Second, each section has its own connections, so they are highly customizable, which was useful as we did not know the exact configuration the LEDs on the sculpture would take when a final design was chosen. Third, the LEDs are already soldered onto wires so all that was required on our end was to solder the exposed connections on the strip to the pins on our PCB to drive as many LEDs as we desired (bound by voltage and current requirements of course) and we only needed to solder six joints (**Fig. 21**). To help us make our final decision, we constructed a table comparing the most pertinent aspects of LEDs for our project (**Table 13**).

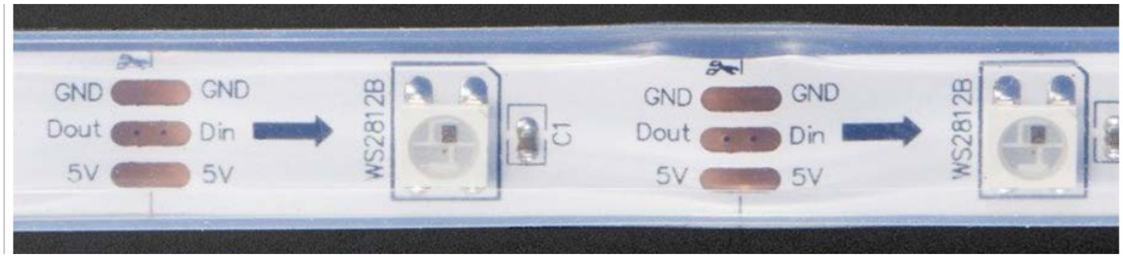


Fig. 21. A section of a strip LED with waterproof coating. The connections may be cut and soldered as needed. Reprinted with permission from Adafruit.

By inspecting five LEDs which are representative of the different types of LEDs available out there we were able to make our final decision on which LEDs to use for the actual sculpture (**Table 13**). Our final decision was mainly influenced by how the LEDs would fit in with the rest of the technology used while still giving the art students sufficient range of color and choice of lighting patterns for beautifying the sculpture. To fit in with the technology we were using, a key issue was being able supply the necessary input voltage to drive the LEDs.

Most of the LEDs required less than 5 volts per unit (a unit being the smallest amount you can purchase; some units were one LED, and some were multiple LEDs on a single package), but one required 12 volts. This would have made driving them more challenging as the output voltage of a pin on the MCU is just 5 volts, thus we needed to create, or purchase, the hardware to supply sufficient voltage to them. Another consideration for us was whether the LEDs were individually addressable. This was not important from an engineering perspective but for the aesthetic properties of the sculpture, we were certain that more range in lighting patterns would be beneficial. One of biggest concerns when choosing LEDs was the cost. The range was large, stretching all the way from 50 cents apiece to over 23 dollars apiece, and reflected some very important differences in the LEDs. Differences such as the amount soldering that would have been required, whether they were already mounted onto something that could be affixed to the sculpture or we were going to have make a mounting mechanism, whether they were already waterproofed or we were going to have to figure out how to waterproof them, their upper temperature threshold, if the package had a white LED or if white would be simulated by combining red, green, and blue at the same time, and to what degree are they were protected from ESD.

To get a better idea of how current and temperature in the LED would affect its output, as well as how the visible angle property of the LED would affect how people see the lights on the sculpture, Figure 34, Figure 35, and Figure 36 are added.

TABLE XIII
A COMPARISON OF LED FEATURES THAT WILL HELP
US MAKE OUR FINAL DECISION (* luminous flux ≈ candela ÷ 4π)

Name	Lumileds Luxeon Rebel – Endor Star RGB High Power LED	Cree Xlamp MC-E – RGBW High Power LED	Shenzen Fedy Technology Co., LTD FD-5WSRGB-A	Standard Density (30 LEDs/m) LED Flex Strips	Adafruit NeoPixel Digital RGBW LED Strip – White 30 LED – WHITE
LED Type	SMD/MCPCB	SMD/ MCPCB	5 mm lamp	SMD (30/m strip)	SMD (30/m strip)
Individually addressable	Yes	Yes	Yes	No	Yes
Cost Each ($)	15.33	23.06	0.50	10.99/meter	16.95/meter
Luminous Flux, Max. (lm)	90 R 161 G 70 B	31 R 67 G 8 B 370 W	(calculated from candela*) 239 R 398 G 72 B	100 R 400 G 100 B	13 R 28 G 13 B 270 W
Color/s	RGB	RGB, White	RGB	RGB	RGB
Viewing Angle (Degrees)	125	115 RGB 110 White	45	125	125
Forward Voltage Rating Typical/Max (V)	2.90/3.51	3.2/3.9	3.0/3.4	12/-	5/6
Reverse Voltage (V)	Not designed for reverse voltage	5	Not stated	Not stated	Not stated
Forward Current Rating Max. (mA)	700	700	100	60/segment	20/segment
Max Junction Temperature (°C)	150	150	80	85	85
ESD Tolerance (V)	8000	8000	800	Not stated	4000
Size (mm^2)(mm^2)	400	400	26.42	1000/segment	425/segment
Waterproof	No	No	No	Yes, IP65	Yes, IP65
Compliance/s	RoHS, REACH	RoHS REACH	RoHS, REACH	RoHS	RoHS
UL Listed	Yes, E352519	Yes, level 1, E349212	Not stated	Not stated	Not stated

On the high end of the spectrum the **Cree Xlamp MC-E RGBW High power LED** was a very attractive choice in most aspects. It has relatively high luminous flux for each color, it has high ESD tolerance, it can handle reverse voltage, it meets all the environmental and safety standards, it has a high junction temperature threshold, and, unlike most, it has a separate white LED in the same package for brighter whites. Two significant downsides to this LED were the lack of waterproofing as standard and heatsink requirement. These LEDs heat up a lot and in Florida's summer heat that could have been an issue. We would have had to resolve these issues if we had chosen these LEDs as they must be able to handle Florida weather, which involves significant rain and sun.

The **Lumileds Luxeon Rebel – Endor Star RGB High Power LED** was quite similar to the offering from Cree, but it was a little less expensive, has no standalone white LED, and is not designed to work in reverse bias. These compromises may have been acceptable depending on the rest of the circuit.

In the middle of the cost spectrum was the strip LEDs, **Standard Density (30 LEDs/m) LED Flex Strips** from LED Supply and **Adafruit NeoPixel Digital RGBW LED Strip** from Adafruit**.** The major advantage here was that they were ready to use. They were already contained in a waterproof packaging and could be mounted directly on the sculpture. They are also made in sections that could be cut to fit whatever size needed. The downside was that UL listed products of this nature are harder to find, and the voltage requirements could differ widely from product to product, and thus, current requirements also.

3.11 Sensors

On this project, sensors would have provided a complementary element to the LEDs on the sculpture to provide the MCU input to change its output to the LEDs. They could have also helped provide input for calculations made about the amount of power the solar panels are producing. There were a few relevant types of sensors that could be placed on the structure to react to different stimuli in the environment of the sculpture; light sensors can detect when people are approaching the sculpture, sound sensors can detect how much noise is present in the environment and alter the LED display accordingly, and an actinometer, which measures solar radiation, can detect when the sun sets and how intense the sun is at any moment [16].

The light sensors would likely have been the most useful for the interactive aspect of the sculpture. The idea was that when people approach the structure, the sensors detect their presence and provide the MCU with input to activate some code that changes the display depending on which light sensors are triggered. The art students would have provided the display pattern to us and we would transform it into code for the MCU to execute based on input from the sensors. The number and type of the sensors would have depended on the available input pins to the MCU, the accuracy of the sensor, the reliability of the sensor, the cost of the sensor, and the electrical needs of the sensor.

A light sensor is activated based on the type and intensity of the light incident upon it. Light sensors may sense infrared light, visible light, or UV light, and these may be broken down into more specific wavelengths but that was unnecessarily specific for this project.

3.11.1 Optical Proximity Sensors

A good choice of proximity sensor for this project was infrared sensors. These can detect heat (thermal infrared sensors) or a specific range of wavelengths (quantum infrared sensors). Those that detect heat are easy to maintain, and require little thermal consideration, but they are slow to respond and are less sensitive. The other type, that detects wavelengths of infrared radiation, has faster response times but has the major drawback of requiring cooling to operate properly [37]. Some Thermal infrared sensors (TIR) can use the I2C interface to communicate with an MCU, others use an analog output. Infrared sensors have variable ranges of detection, have high heat tolerance, and have acceptable accuracy and resolution for our project. These sensors detect both ambient temperature and the temperature of the body they are pointing at [37]. Others eliminate sensing the ambient temperature and only sense the temperature of the body to which they point. The main motivation for using Infrared sensors was that they are relatively inexpensive, accurate, and they have become time tested by many implementations in all sorts of applications that we use every day. A concern that we had, given how hot Orlando can become, is that nearby objects could also trigger these sensors accidently as they heat up on particularly hot days, so the sensors ability to handle such matters needed to be considered. Some commercially available infrared sensors are listed and compared in Table 2 which helped us narrow down our choice/s for which ones were most suitable for the sculpture, and for our prototype.

To make the decision about which optical sensors to use for this project, the most crucial factor was at what distance would the sensor detect movement. We researched several sensors and came up with four that had acceptable ranges of detection. The number of acceptable sensors for the full-scale model was still uncertain as we were unable to find UL listings for the sensors we examined.

We also found it challenging to find sensors that were UL listed. We continued to look at some viable candidates for our model and discussed our reasoning for making our final choice.

We chose two products each from two vendors to compare. From the company Vishay, we chose a sensor that detects from 100 centimeters to 1 meter and another that detects up to 1 meter. Both the Vishay offerings had the significant advantage of being very inexpensive. They also have higher temperature tolerances than the offerings from Sharp, and a very handy control and read interface, the I^2C bus. With the I^2C interface we could have had many sensors hooked up together without having to sacrifice many pins on the MCU as it also has an I^2C output (we could not have used the interface if it did not). This interface requires only two special pins from the MCU and one general purpose IO pin to function.

The two special pins provide a clock output and a data output, while the GPIO pin addresses the sensor so that we could individually address many sensors in parallel. The fact that the I^2C interface is digital meant that coding the MCU for the Vishay sensors would have been easier than coding for an analog output, which is what the Sharp sensors have. The Vishay sensors also had very good documentation to assist us in implementing the sensors in the design, including a suggested circuit, 3D models, and even code examples.
The Sharp products were not without their advantages though. The biggest advantage they had was that they can sense the same or further than the maximum distance of the Vishay sensors (1.5 m).
The **Sharp GP2Y0A710K0F** can sense something moving up to 5.5 meters away. Given that this sculpture may be far away from people, it may have been necessary to have such long-range sensors to trigger the various LED lighting algorithms we would have created.

TABLE XIV
A COMPARISON OF DIFFERENT SENSORS
THAT MAKE DETECTIONS BASED ON ELECTROMAGNETIC RADIATION

Name	**Vishay VCNL 4200**	**Vishay VCNL 4100**	**Sharp GP2Y0A710K0F**	**Sharp GP2Y0A60SZ0F/ GP2Y0A60SZLF**
Sensor Type	PS, ALS	PS, ALS	PSD	PSD
Interface	I^2C, SMBus	I^2C, SMBus	Analog	Analog
Operating temperature Max. (°C)	85	85	65	60
Size (mm)	3 x 8 x 1.8	3 x 8 x 1.8	58 x 17.6 x 22.5	22 x 8 x 7.2
Frequency Max. (kHz)	400	400	-	-
Moisture sensitive	Yes	Yes	Not stated	Yes, Level 1
Operating Voltage (V)	2.5-3.6	2.5-3.6	4.5-5.5	4.5-5.5
Max Supply Voltage (V)	5	3.6	7	5.5
Operating Current (mA)	0.350	0.195	30	33
Supply Current Max. (mA)	800	800	50	50
Sensor Range Max. (m)	1.5	0.1-1	1-5.5	0.1-1.5
Cost ($)	2.95	5.04	19.50	11.95
Compliances	RoHS, REACH	RoHS	RoHS	RoHS
UL listed	Not stated	Not stated	Not stated	Not stated

The Sharp products use an analog output instead of a digital one like the Vishay products. This was not a disadvantage per se as the MCU we were using could handle analog inputs, but the total number of pins available for analog input was limited to 16. Whereas the I^2C port can technically handle 2^7-1 sensors that use that interface. The genuine disadvantages of the Sharp products were their lower thermal thresholds and their higher costs.

3.11.2 Actinometers

An actinometer may have found a lot of utility in this project. They are devices that can measure the intensity of solar radiation [16]. For measuring the output of solar cells, a type of actinometer called a photovoltaic pyranometer is used. It is sometimes called a reference photovoltaic cell because the active part of the device is a photovoltaic cell, just like in the solar panels. Since our project used solar panels, we may have wanted to make measurements of the solar radiation flux density, W/m^2, to use as a way to let us know how much energy we were getting from the solar panels. This information could have been used to display output to the public about how much energy is being put into the grid by the solar panels, how much money is being saved by the sculpture, and how much carbon dioxide output is reduced by using solar energy. These figures would have been significant because the whole purpose of the project was to promote solar energy and show the public that solar energy can be aesthetically pleasing as well as functional.

3.11.3 Sound Sensors

Sound sensors, also known as auditory sensors, are a type of sensor that utilizes the sound waves or air vibration made in the surrounding area of the sensor's location. Louder sounds will produce a larger vibration and higher pitch sounds produce more frequent vibrations. Sound sensors use a diaphragm, a thin piece of material, which vibrates upon meeting a sound wave. The sound sensor will then send a signal to the microcontroller which can be used for useful interactive scenarios through programmable means.

Sound sensors can also record or measure the sound "level" it meets. Sound levels are measured in decibels (dB) which individual sound sensor products can pick up a range of dBs. This sound level is sometimes measured as a percentage (%) and a range of percentage (e.g.: 5-10% vs 20-30%) can represent a state the sound sensor is currently in. Sound sensors for example, tend to be simple microphones or used as microphones to detect sound from the surroundings.

3.11.3.1 Grove Sound Sensor

The Grove sound sensor is a simple microphone module that is easy to use and supports easy integration with grove logic modules or microcontrollers such as Arduino or Raspberry Pi by a cable connecting to the pins on the microcontroller and Grove sound sensor. This sound sensor's hardware specifications are listed in Table 16:

From Table 15, we can see that the **Grove sound sensor** is tiny coming in at only 24 by 22 mm and weighs very little (**Fig. 39**).

TABLE XV
GROVE SOUND SENSOR AND FAIRCHILD SOUND SENSOR COMPARISON

Name	**Grove Sound Sensor**	**Fairchild LMV324**
Size (mm)	24 x 22 x 9.8	44 x 23 x 9
Operating voltage (V)	3.3-5.5	2.7-5.5
Operating current (mA)	4-5	0.1 (per channel)
Operating temperature (°C)	Not stated	125
Gain (dB)	26-46	40
Microphone sensitivity (dB)	48-52	50-75
Microphone frequency (kHz)	16-20	10-100
Cost ($)	4.90	10.95
UL Listing	Not stated	Not stated

What was nice about the small size was we could hide it easier out of sight using something if we were to have implemented multiple of these near the Solar Sculpture. The Grove sound sensor also has high support for Arduino based boards and can be integrated to our microcontroller, the Arduino Mega ADK, by utilizing one of the sixteen existing input analog pins. The way the Grove sound sensor works is to connect to the analog input port on the Arduino is the Arduino can read in the port the sensor is soldered onto via the built in function analogRead(). So when the sound sensor vibrates due to either a loud enough sound or a air vibrations it sends an electrical signal voltage through the wire to the Arduino's input pin; the analogRead() function will then read and convert that voltage into a int value from 0 to 1023 and return it in the code. We could have then utilized this int return value and checked if a variable storing this value hit a certain threshold and did something. For example, we could have changed LED patterns, LED colors, or changed other things currently controlled via the microcontroller. Overall, the Grove sound sensor was a decent product choice due to its price around $5 and ease of implementation with our microcontroller. However, an issue was that just one would be insufficient to pick up quieter or enough sound in multiple areas/directions. In that situation we would have needed to purchase many of them, which we may not have had enough pins to support, or we would have needed to buy additional hardware to support them. It was better to look for a stronger sound sensor instead.

The alternative to the Grove sound sensor that we looked at was the **Fairchild LMV324** from Sparkfun (**Fig. 39**). Its properties are like those of the Grove sound sensor, but it seemed that it may be more sensitive, in that the range of frequencies that it can detect is higher. What we were trying to sense with the sound sensors were the sounds that people would be making while attending events at the stadium, so both these sensors can "hear" somewhere in the human range, 20-20,000 Hz, but the Fairchild sensor can sense more of that range, and far over which was an advantage.

TABLE XVI
GROVE SOUND SENSOR SPECIFICATIONS

Dimensions (mm)	24 x 22 x 9.8
Weight	7g
Operating Voltage Range	3.3 / 5.5V
Operating Current (Vcc = 5V)	4-5mA
Voltage Gain (V= 6V, f = 1kHz)	26dB
Microphone Sensitivity (1kHz)	52-48dB
Microphone Frequency	16-20 kHz

So when the sound sensor vibrates due to either a loud enough sound or air vibrations it sends an electrical signal voltage through the wire to the Arduino’s input pin; the analogRead() function will then read and convert that voltage into a int value from 0 to 1023 and return it in the code. We then utilized this int return value and checked if a variable storing this value hit a certain threshold and did something. For example, we could have changed LED patterns, LED colors, or changed other things currently controlled via the microcontroller. Overall, the Grove sound sensor was a decent product choice due to its price around $5 and ease of implementation with our microcontroller. However, an issue was that just one would have been insufficient to pick up quieter or enough sound in multiple areas/directions. In that situation we would have needed to purchase many of them, which we may not have had enough pins to support, or we would have needed to buy additional hardware to support them. It was better to look for a stronger sound sensor instead.

3.12 Wires

Linking all the components of our project together required a significant amount of wiring. To make the project realizable, we used wires that are UL listed so that our design could be approved for implementation in a public place. Making sure the wires were UL listed was just the tip of the ice-berg though. The wires needed to be of a suitable gauge for what they were being used for. For example, a wire that is suited to taking power from the microinverter would not be suitable for delivering power to the LEDs. The reason being that the conductivity would likely have been much too high and would have delivered far too much current. Therefore, we had to choose wires that were suited to their application, that is, we used wires that had an acceptable voltage drop, thermal resistance, conductivity and insulation over the length we expected them to travel. Fortunately, wires have been standardized and getting the wires you need has been made very simple by some companies who sell wires by providing large tables of standardized American Wire Gauge wires and their characteristics.

For our project we looked at wires designed for high voltage, high current, low voltage, and low current since we would be dealing with electricity coming from solar panels and electricity coming from a sensor. The tables displaying the standard sizes had a wealth of useful information in them for us. Of course we needed to pick suitable wire sizes for the electrical properties, but knowing the temperatures that the wires could withstand was also very useful as we could compare those to expected temperature fluctuation and be confident that the wires we had chosen would not lead to issues at a later date (**Table 17)**. A factor that was given attention, as it was a requirement of this project, was that the full-scale sculpture needed to be very low maintenance.

3.13 Connecting to Grid

Connecting to the grid was one of the most critical parts of this whole project. This connection from the inverter to grid was what helped produce the most power output and the correct connection was the most important part. A good connection was not only important to the power output, but it was also important to the safety aspect of the system. A connection that is not made properly can damage not only the inverter but the whole circuit itself. To achieve a good connection between the inverter and the grid, the circuit must meet the National Electrical Code requirements. “It is good practice to install the inverter near the backfed load center so that the backfed breaker commonly used to interconnect the inverter with the utility can also be used as the AC inverter disconnect required by NEC Section 690.15.

This places the overcurrent device at the utility-supply end of the circuit and groups the AC disconnect for the inverter near the DC disconnect.” [42]

At the beginning of the semester we had implemented it into our design using solar panels with string inverters. The physical location of the inverter itself was to be placed in a component box at the bottom of the sculpture. Both the mechanical and the art students would integrate a component box into each different design to accommodate for the placement of the inverter. This location allowed for easy access to the inverter, the PCB, and any wires running into the circuit.

After doing more research and talking to our advisor on the project we decided to change the connection from a string inverter to a microinverter. The microinverter allows for more efficient output from a system that has different output solar panels. It allows for the solar panels to be different and to not be affected as a unit but be treated independently. Although this did not change the system connection to the grid it did change the wiring. Instead of having a center box where all the wires connect to one inverter, now have individual connections to the grid from each of the different photovoltaic solar panel systems.

3.13.1 Supply Side and Load Side Connection

There are two standard, safe, ways to connect the inverter circuit to the grid. The two ways that are accepted are to connect the supply side to the service disconnect of the building or to connect the load side to the disconnect of the building.

TABLE XVII
COMPARISON OF THE ATTRIBUTES OF SEVERAL UL LISTED WIRES

UL STYLE NUMBER	AWG SIZE RANGE	VOLTAGE RATING	TEMP. RATING	INSULATION	
				THICKNESS	MATERIAL
1227	30 - 20	Not rated	105°C	0.010"	FEP
1293	30 - 20	Not rated	105°C	0.010"	FEP / nylon
1294	26 - 20	Not rated	80°C	0.010"	FEP / nylon
1327	30 - 16	Not rated	105°C	0.010"	Kynar®
1330	28 - 10	600	150°C	0.020"	FEP
1331	28 - 10	600	200°C	0.020"	FEP
1332	28 - 10	300	200°C	0.013"	FEP
1333	28 - 10	300	150°C	0.013"	FEP
1351	30 - 16	Not rated	80°C	0.010"	Kynar®
1354	-	30	60°C	-	-
1355	32 - 20	Not rated	200°C	0.0055"	FEP - polyimide
1371	32 - 6	Not rated	105°C	0.0055 - 0.020"	FEP
				0.006 - 0.020"	PTFE
1394	32 - 20	Not rated	200°C	0.0055"	PTFE - polyimide
1422	32 - 20	Not rated	105°C	0.005"	Kynar®
1423	32- 20	Not rated	105°C	0.004"	Kynar®
1426	32 - 20	Not rated	105°C	0.006"	Kynar®
1429	30 - 16	150	80°C	0.010"	Irradiated PVC
1430	30 - 16	300	105°C	0.015"	Irradiated PVC
1431	30 - 10	600	105°C	0.030"	Irradiated PVC
1431	8	600	105°C	0.045"	Irradiated PVC
1431	6 - 2	600	105°C	0.060"	Irradiated PVC
1431	1 - 1/0	600	105°C	0.078"	Irradiated PVC

The load side is the most commonly used when using small PV panels. [42] This limitation of load sided connections to usually smaller PV panels is causing supply sided connections to increase. In both residential and commercial implementations of PV panels a higher wattage output for the PV panels leads to less energy used which in turn leads to more money saved. [41] This ultimate goal to save money is causing supply sided connections to increase.

The OUC group implemented high rated PV panels to be able to achieve the main power requirement which is 850 kWh yearly, this meant that the solar panels studied can range between 250W to 400W. This range of high power output PV panels will force the connection that group uses to be supply sided connection. Like stated before, the supply side is used when connecting high powered panels which is exactly what the OUC group did. The exact location in which the solar sculpture will be placed is handpicked by OUC engineers. Coming from the OUC engineers means that the solar sculpture will have to be close to the grid to be able to achieve a supply sided connection.

4. Standards and Design Constraints

4.1 Design Constraints

4.1.1 Time Constraints

This project was concluded in the span of two semesters. The first semester, Senior Design I, consisted of identifying what the group wanted to focus on, analyzing all the components that would be included in the project, designing the project itself and testing out the components on a breadboard all by the start of December. The second semester, Senior Design II, consisted of continued testing of components, putting the components into a single part, and having a finished product by the end of May.

The time span in between the two semesters allowed for very little intricate development of the project. There was not enough time to go back and change designs or components chosen. Once the group decided what we were going to do we had to start analyzing, ordering parts and testing as soon as possible. This meant that all the calculations and all the analysis that the group did had to be both precise and accurate to not fall behind.

For the OUC group we had two external time constraints apart from the due date. We had to wait to figure out what mechanical team and arts we would be working with for the following two semesters. This meant that until we met our teams we could not figure out what design we would be working with and what interactive features we could have that were feasible with the chosen design. The second time constraint was caused by Hurricane Irma. This hurricane caused a major delay in the engineering process and delayed the start date by at least a week and a half. This might not seem like much but in a project in which every week is crucial for the development of the project, this was a big time hurdle to overcome and still meet all the necessary deadlines.

4.1.2 Economic Constraints

The senior design project at UCF is not sponsored for all the teams. This is a factor that is taken into consideration when choosing what project any graduating senior will do. The OUC group had interest in working with renewable energy and using solar panels in our design. With us choosing the OUC sponsored project, the economic constraints that we were facing diminished greatly. We were reimbursed for the expenses that we had. We showed the replica for the 1/8 structure and demonstrated the interactivity that we had chosen. This meant that we did not buy any PV panels or microinverters. This helped both our budget and the OUC budget because we did not use money on small yet somewhat expensive PV panels for our demonstration, OUC would only consider buying the PV panels that we chose to go on the real-life model outside of the Orlando City Soccer stadium.

The expenses that the OUC ECE group had were only those that were relevant to the 1/8th design. This meant that the only materials bought were those that were be used in the final demonstration. With OUC sponsoring us we were able to purchase quality products and fully demonstrate what we wanted without having to worry about unreliable purchases and parts.

4.1.3 Environmental Constraints

The ultimately goal for this project was to place a solar sculpture outside of the Orlando City stadium. This meant that when designing the sculpture and all the features it will have, we had to consider the environment in which it would be placed in. One of the environmental constraints we kept in mind was the weather. Each component we place on the sculpture needed to be able to withstand high heat, high humidity, and a decent amount of rain almost all year long as well as being able to withstand hurricane or tropical storm winds. Another environmental constraint that shaped our design was the amount of foot traffic happening around it. With the sculpture being placed in a high use environment we had to keep all designs safe from bystanders. These environmental constraints were things we could not change but had to keep in mind going forward.

4.2 Manufacturability & Sustainability

4.2.1 Manufacturability

Manufacturability is a general practice where the design should be easy to manufacture. To achieve this, we used commercial products that are available online for any consumers. The exception to this was the solar panels due to the large estimated annual power generated requirement where the panels or similar specifications of panels are unobtainable through public purchase and may require negotiating a price with a manufacturer or distributer.

This extended to software and hardware outside of just PV panels. For instance, our microcontroller choice was based on the Arduino Mega 2560 which uses Atmel's ATmega2560 as the core. Both of these provide much documentation and is open-sourced hardware and software respectively. Arduino especially provides good documentation and support and the hardware is easily obtainable and replicable assuming one follows the guidelines and schematics from this document. For software, the design of our PCB could be replicated and the code for controlling things with our microcontroller could be shared and thus the portability exists through Eagle and Arduino IDE and libraries in C/C++ language.

4.2.2 Sustainability

Sustainability or maintainability is generally the lifespan or durability of the product (i.e.: how long before it breaks). With regards to this project, the Solar Sculpture is supposed to be stationed outside of the entrance to the Orlando Soccer Stadium. Therefore, it must survive and work under Central Florida environment from hurricanes to rain and tornados, etc. Ultimately, from the design standpoint the sustainability was mainly handled by the mechanical team of the project. However, the sustainability of the electrical components and PV panels were considered during the design. Most of the electrical components are shielded and protected within an electrical box stored within the sculpture through a compartment; therefore, the issue of maintenance is mainly directed towards the outside components like the micro-inverters and PV panels.

The maintenance will be handled by OUC, but one of the requirements given to us was the aim to make maintenance as easy as possible. This related to the design of the sculpture which was out of our hands; an example would be avoiding a very tall vertical sculpture with panels on top that would make maintenance on the panels harder. Additionally, if malfunctions with electrical components occur, maintenance should be easy to carry out since it should be accessible with our initial design plans and if it were an issue with the code for the microcontroller malfunctioning we supported easy maintenance and being able to modify the code easily with just an USB peripheral to update and flash the program onto the microcontroller.

4.3 Ethical, Health, and Safety Concerns

Our project, if chosen by OUC, would be built in a public area. As such, ethical, health, and safety concerns were paramount to the realizing this project. The fact that this will be a freestanding structure near a public venue that has a capacity of over 25,000 will all but guarantee public interaction with the sculpture. To make the sculpture safe, we needed to closely stick to the National Electric Code. “Adopted in all 50 states, the NEC is the benchmark for safe electrical design, installation, and inspection to protect people and property from electrical hazards,” so this was the standard we kept in mind when questions arose about how to execute any part of the full-scale implementation of our project [41]. This is an expensive standard, so we would have needed to ask for funding for it or have found it through UCF of OUC. The key issues that were likely to face when it came to safety were to do with proper insulation of any of the electrical components and wiring used. Proper mounting of components and wires so that they are safely out of the reach of passersby. Proper grounding of all components to prevent possibly turning the whole sculpture into a massive conductor that could deliver voltage sufficient to injure, if not kill, someone who touches it. It was important for us to keep in mind this sculpture would be a mini powerplant and would certainly generate sufficient voltage to cause harm.

4.3.1 Fire Safety

Fire safety was also a concern with this project. Though we were not dealing directly with components designed to generate heat, the high currents that would be generated by the PV panels had to be safely insulated with appropriate wire sheathing to handle the heat in the wires. This applied to all the components we used as improper sheathing of the wires could have caused them to melt their sheathing and become exposed in the event of a current spike. Some electrical components could also explode under certain conditions, so for safety sake we wanted to carefully consider where these components were placed such that in the event they explode, their extremely hot contents do not come in contact with something that can catch fire. Essentially this meant that the enclosure we chose needed to be highly inflammable. Since this is a very common need, there are many companies out there who make enclosures for exactly what we require, and we found a case that fit our needs very well (**Fig. 22**). These cases not only handle fire hazards by being made from "self-extinguishing" materials, they also provide IP66-11 weatherproofing, are RoHS compliant, UL approved, and are even gasketed to prevent the escape of hazardous materials in the event of an electrical component exploding. An enclosure like this provides great protection to the public, especially since it can also be padlocked.

Another topic we had to consider when it came to fire safety was how to protect our system from over voltage and overcurrent. To protect our system from too much current, we needed to implement safe and reliable ways to direct excess current to ground. The NEC has several ways to protect a system from too much current and has different methods for doing it, depending on the specifics of the system. One way of implementing overcurrent protection is to use fuses. A fuse simply places a "weaker" wire in sequence with the regular wires near the source of the current. Then if a high current is present in the circuit, the weaker wire melts and leaves an open circuit in its place. The downside to using fuses is that they can only protect the system once, and they usually leave the system useless until they are replaced. The NEC advocates the use of fuses in systems where the voltage is relatively low, which should include most parts of our system.

Another method for protecting our system was to install a circuit breaker. Like fuses they would provide protection for our system, but unlike fuses they are not a single shot device. They would leave an open circuit, but there is nothing to replace when you want to turn the system back on, a switch is simply flipped. A circuit breaker was not ideal for the parts of our system that do not use a lot of current, but it was something we kept in mind as we were testing our system.

To protect our system from overvoltage, we could employ capacitors. Though the system would already have its voltage regulated, we could not assume that a voltage spike would never be present in our system. Placing capacitors between the part of the circuit you want to protect and the ground, and then in parallel with vulnerable system components, will cause the capacitors to open up and direct the voltage to the ground when any spikes of voltage higher than desired occur in the system.

4.3.2 Public Interaction

Another safety concern that needed to be addressed during this project was issues related to the LEDs. Since the LEDs are very bright and we planned to use code that would cause them to flash on and off, two concerns that came to mind were:

1. Causing distractions or affecting the vision of someone who can see the LEDs
2. Causing problems for people with disorders triggered by photosensitivity

Those that we expected would be affected by the first point were drivers in nearby traffic. It was conceivable that the bright LEDs shining right into the eyes of drivers could cause road traffic accidents. To prevent this issue, we considered the direction the LEDs face and their brightness. For the second issue, we could likely have alleviated this problem with some research on these disorders. For example, photosensitive epilepsy is a neurological disorder where seizures can be triggered by not just flashing lights, but also certain patterns. Even when the result is not as severe as a seizure, other symptoms such as headaches and nausea can occur for these people. To prevent this issue, we could consult medical personal at UCF’s College of Medicine, and look at information provided by the Epilepsy Foundation on the best way to implement our lighting without impacting those affected by photosensitive disorders. One not so obvious consideration was that the LEDs, even when they seem to be solidly lit, are always flickering at some frequency, so even imperceptible flickering could cause an issue.

Fig. 22. An example of an enclosure we could use to safely store our electrical components, the L-com NB100805

Though we had been told that the level of public interaction with the sculpture should be limited, we still had to prepare for some level of public interaction with the sculpture, especially since we wanted to implement sensors on the sculpture. The sensors on the sculpture would likely provide some pull to passersby when they notice this feature of our system. The problem we faced was how to limit the public’s interaction with the sculpture to a safe degree. Our intention was to use sensors that would be triggered when someone came within 1.5 meters of the sculpture. This may keep most of the public at a safe distance, but it will not keep everyone away. Some people will approach the sculpture. Placing the sensors on the sculpture in such a way that they are not triggered when people come too close would have provided a good disincentive to people, or we could have programmed the LEDs to do less exciting displays when people come too close. Ultimately, we had to make the electrical system in the sculpture secure enough that the public can interact with it up close without our system posing a danger to them.

To that end we needed to be vigilant about choosing wires that would not become a hazard under any foreseeable circumstances, ensuring all the connections we made between components of the system had no chance of breaking or leaking current into the sculpture, and perhaps even devising a method of drawing charge out of the sculpture in the event a wire or component may come in contact with it. We also considered how the wires would be encased to prevent damage to them. The risk to the public from this sculpture would be quite considerable if we did not take care to secure it. The current and voltage that the solar panels will produce would certainly be enough to cause great harm, or death, should it anyone come in direct contact with it.

4.3.3 Ethical Concerns

The topic of ethics in this project has already been partially addressed by our discussion on health and safety, or at least some potential ethical issues were unearthed. As the designers of the electrical portion of this project we had an ethical responsibility to ensure that it will not harm the public safety, health, or welfare, nor negatively impact our sponsors or college, and that our work would not negatively impact other students and professors involved in the project. Our professional society, IEEE, has a code of ethics that we could fall back on in times of doubt, and that each team member was be familiar with so that all our decisions were made with ethics in mind.

Point number 3 of the code seemed particularly pertinent on this project “to be honest and realistic in stating claims or estimates based on available data”. Since we were “under the gun” the first semester with the requirement that we write a large document about our project, the temptation to use sketchy data or data sourced from places that it may not be wise, or at least cautious, to take data from was constantly there because it would have helped get the work finished faster and put us in a better position to pass the senior design 1 class. This is a clear example of an ethical violation. Our priority is usually doing well in our classes, but this class was different, it was a real-world project, with a real-world company looking to us to provide them with a design based on rigorous research. As such we made the design our priority, not the grades we would receive. Point 7 of the IEEE code of ethics, which concerns criticism, corrections, and credit to work done, was also important to keep in mind over the course of this project. As we (the electrical engineering team) spent a lot of time together on this project friendships grew, and it could have become hard to be critical of a friend’s work to their face. Often, we would prefer to not say anything to each other’s faces about problems we believe are present in each other’s work, and harm relationships, but for the sake of the project we knew we must learn to overcome this as leaving things in the project that our engineering knowledge told us were problems would most certainly lead to not just an unsuccessful project, but potentially a dangerous one. If this project went wrong because of anyone of us, it would have followed us all through our professional careers, a point that we were acutely aware of.

Point 10 in the code was something that would not directly affect our system or the sculpture but was important for us to bare in mind. We should be carrying out our tasks with our team mates in mind. We are individual students, and must each do our own work, but it is not enough for us to be satisfied that we have finished our work and just stand by and watch a team mate fail, or let them tarnish their college record, permanently damage their career, and even their life by violating the code of ethics. This applied to the project in much the same manner as point 7 of the code did. If we were not willing to help our fellow team mates, then we were inviting failure into our project, even if technically we had succeeded as individuals.

4.4 Standards

Following the UL (Underwriters Laboratories) standards regarding photovoltaic panels and power systems regulations made the overall structure safer. Designing the structure within the UL standard limitation enabled the project design approval to be finalized faster. UL standard provided specifications for energy provide specifications for energy efficiency as well as environmental safety. After plenty of safety research and scientific experience these standards were developed. UL standards are applied all throughout the United States and Canada.

4.4.1 UL 61215

UL 61215 is an adaptation of IEC 61215 standard. IEC (International Electrotechnical Commission) is an international standards organization that creates and publishes standards for all electrical and electronic technologies. UL adopted IEC standards and modified the standards for a better fit to the United States. UL 61215 is a design qualification and approval for photovoltaic panels to guarantee longevity in outdoor locations. This standard can be applied to both crystalline and thin-film photovoltaic panel technology. UL 61215 does not completely apply to the OUC solar sculpture since there are electronic devices attached to the structure. This standard does not cover solar systems with attached electronics, but this standard could be used as a test for photovoltaic systems. More specifically the UL 61215 can test the capability of a panel to withstand the outdoor climate (temperature, humidity, rain, etc.) for a long period of time, or the lifespan of the solar system in regard to its environment.

The final design for the solar structure was required to meet the UL 61215 standards to be approved. Not only did this standard make the EE and CpE design legitimate so it could be assembled, UL 61215 also extends the lifespan of the solar power system. If the design had not passed the UL61215 standard testing, the design would have been rejected and edits would have needed to be made to reach standard approval.

4.4.2 UL 61646

UL 61646 is very similar to the UL 61215 except covering all the photovoltaic panel materials not listed on UL 61215. The standards still test for photovoltaic panel life span in outdoor conditions except the test does not require completing a plus/minus criterion. Instead the test requires meeting a specific percentage of minimum power output. “This eliminates the technology-specific preconditioning necessary to accurately measure the changes caused by the test.”[5] This standard was not required for the solar sculpture since thin-film panel technology was not considered for final panel selection. That being said, if for an unforeseen situation, thin-film might be considered for final panel selection the UL 61646 standard would be applied.

Although thin-film panel technology was not taken into consideration for final photovoltaic panel selection for the EE and CpE design, UL 61646 standard was to be taken into account. During the time that the final design had not been decided upon by the EE and CE team, thin-film panel technology was under consideration in case a drastic design change was to have come into play. If this were to have been so, the structure design with thin-film technology was to meet the UL 61646 standard.

4.4.3 UL 1741

UL 1741 standard deals directly with inverters, converters, charge controllers and inter grid connection system equipment. Inter grid connection cover both off-grid power systems and grid connected power systems. This product safety standard not only lays out the test requirements for the hardware device functionality but also the manufacturing process for the listed hardware and software along with the hardware. The standard optimizes the capability of grid interactivity and dealing with grid reliability. Tests performed under UL 1741 include:

- Anti-islanding
- Low/High Voltage Ride Through
- Low/High-Frequency Ride Through
- Must Trip Test
- Ramp Rate (Normal & Soft-Start)
- Specified Power Factor
- Volt/Var Mode
- Frequency Watt
- Volt Watt

Some inverter manufacturers that compliance with the UL 1741 standard are:

- ABB
- Enphase
- Fronius
- SMA
- Solaredge
- Solectria

This information was important to take into consideration when selecting an inverter to ensure they met the United states standards. From this list stated above the EE and CpE team went about selecting the appropriate inverter for their solar system with ease. The manufactures listed above were the main companies taken into consideration for final inverter selection.

4.4.4 UL 2703

The UL 2703 standard applied more directly to the mechanical team since this standard deals with rack mounting systems for both ground level and elevated photovoltaic panel systems. Also, the clamping devices for designated photovoltaic panels that meet the UL 61215 and UL 1703. The photovoltaic systems that meet the requirements within UL 2703 cover tack mounting systems and camping devices for a maximum of 1000v system. The final voltage output/generated for the photovoltaic system that will be built for OUC solar sculpture will not exceed the 1000v limit required by UL 2703 so the standard was met with no problems.

Since UL 2703 did not directly apply to the EE and CpE team, it was a standard that could influence the final selection of the photovoltaic panel based on the design. Different designs required different photovoltaic panel rack mounting systems that may or may not have matched with the set rack mounting system for the final selected photovoltaic panel. If the set rack mounting system for the final selected photovoltaic panel could not be implemented to the final design, then UL 2703 standard would have limited the amount of photovoltaic panels that were eligible for the final design.

4.4.5 UL 1703

UL 1703 standard is intended to test the photovoltaic panel in environmental conditions. These tests range from:

- Humidity-freeze sequence
- Temperature cycling
- Water and rain exposure
- Fire testing on photovoltaic panels as shown on Fig. 23.

Fig. 23. UL 1703 solar panel testing

These temperature tests ensure that the photovoltaic panels can operate under normal environmental conditions. Also, the UL 1703 standard tests the photovoltaic panels break

down point and degeneration ratio. This results in a rate for the photovoltaic panels durability as well as the lifespan of such panel. The fire test tends to be the most important a key test for the panel to be certified. These tests are intended for photovoltaic panels used in systems with a maximum system voltage of 1500v or less. UL 1703 in a way ties in with UL 2703 since the racking component is also tested alongside the photovoltaic panel. Difference between the UL 61215 and UL 1703 is while UL 1703 tests the specific panel for outdoor conditions the UL 61215 tests the overall system for efficiency in outdoor conditions. UL 1703 is considered the gold standard for photovoltaic panel safety in the United States. The durability and reliability test results directly affect the price of the photovoltaic panel.
Photovoltaic panels across the globe can meet the IEC standard but not all meet the UL United States standards. If the UL 1703 standard was not met by the final photovoltaic panel selected for the solar structure, then the final design would not be approved. Fortunately, most photovoltaic panels pass the UL 1703 standard testing across the globe. Nonetheless, UL 1703 standard was the most important standard when selecting the final photovoltaic panel for design approval reasons.

4.4.6 UL 4730

UL 4730 standard establishes the necessary information that is to be displayed on the nameplate rating. The information, such as production and measurement tolerances, are related to photovoltaic panels. The UL 4730 standard identifies the five following rating conditions that each photovoltaic panel reports:

- P_{max}
- V_{oc}
- I_{sc}
- V_{max}
- I_{max}

Correct statistical nameplates are a crucial factor to be able to correctly calculate energy yields such as a yearly output wattage hour per year. Before initiating standardize testing the photovoltaic panels must be stabilized for consistent results. Even with finalized photovoltaic panels, lab tested panels will still provide a different power output result when compared to a photovoltaic panels power output in outdoor conditions. Nameplate information is required to list the five conditions listed above but are welcome to list more such as weight, dimensions and efficiency. Thankfully all the photovoltaic panels researched by the EE and CpE team had accurate UL 4730 approved nameplate information listed on the datasheet provided the panels manufacturers.

4.5 The National Electrical Code

As we have discussed in numerous parts of this paper, if this project were to be chosen to be made into a full-scale sculpture, it would be built in a public place, and therefore must follow certain standards. Probably the most significant standard it must follow is the National Electric Code. The national electric code “covers electrical wiring and installations" across the whole United States. This code will determine whether our design meets the electrical safety standards to be transformed into a fully-fledged public structure. The standards and instructions set forth by the code are lengthy, but we will cover some of the standards we were able to find that held significance for our project. A good knowledge of these standards increased the chances that our project would be selected for implementation which would be a great accolade for us.

The NEC code prescribes that when wiring is being decided upon, room should be left for the addition of other wires in the future. The code also says that the wires chosen shall be made of copper or aluminum, and their sizes shall be listed in AWG. Further, the temperature rating of the wires should not exceed the minimum temperature rating of the terminal it is attached to. The code calls for rigorous overcurrent protection. In general, any conductor must be protected from overcurrent. This may be means of fuses or grounding any overcurrent. We may use plug fuses for most of our project as the code states that any "circuits not exceeding 125 volts between conductors" may use plug fuses, and most of our circuits were much lower than 125 volts. Fuse locations must also be documented for use by personal authorized to maintain the system. To "minimize effects from a short circuit or ground fault," the number of circuits contained in a single enclosure must be kept low. Fortunately, our project would very likely only contain two circuits in our enclosure, so meeting this standard was not something we had to worry about.

Another aspect that the NEC covers, that was applicable to our project was how systems that are installed outside are treated. Anything exposed to sunlight must be listed as "sunlight resistant" and any box carrying electrical equipment must be listed as "Raintight", "Rainproof", or "Outdoor type" to be permitted for outdoor use. Heating considerations must be considered also. The sculpture will be exposed to the Florida sunlight, which will impart significant heat to the sculpture. Although the mechanical engineers implemented designs that reduced the heat that builds up in the sculpture, there were still heat considerations for us to take care of. The NEC code calls for considering heating effects in both normal and abnormal situations. So, for normal situations, we implemented some strategies to alleviate problems pertaining to heat build. We chose wires that had sufficiently high thermal thresholds, we chose casings for the wires that can transfer heat away from the wires where the casings are not exposed to sunlight, and chose casings that are resistant to sunlight in areas where the casings are exposed to sunlight. For abnormal situations we considered the situation that the sculpture was covered up but the system was not shut off. In that event there may be a buildup of extra heat and we needed to consider how to much extra heat would build up, and how to protect our system from damage in situations where the temperature around electrical components and wires falls into these higher categories.

The standards are explicit about considering people that may come in contact with your system. All factors that are to do with safeguarding the system must be considered. So, for our project we considered the people that will be visiting the stadium that may approach the sculpture, technicians that may need to perform maintenance work on the system, and the people involved in constructing the system. Though care may be taken when placing the sculpture to place a barrier between it and the public, there is no guarantee that people will not come in contact with it every now and then. As such, all of the electrical components on the sculpture had to be fully insulated and given some sort of protection against tampering. Even for those who know what they're doing, and will access more sensitive areas of the sculpture, it was still prudent of us to put in protections for them too.

The code gives the criteria that an electrical component used must meet to be considered as being up to code. If a part is approved by an electrical laboratory that OSHA considers up to their standards, then that part is considered as meeting the NEC code. Though we usually only consider components that are UL listed for the full-scale sculpture, this knowledge helped determine if a part was acceptable when it was not UL listed but its other standards may be equivalent.

5. **Hardware and Software Design**

5.1 Design Specifications

Being the only EE and CpE team for the OUC solar sculpture, the design had to be modified and adjusted between the three mechanical engineering teams. The mechanical engineering team was to choose an artistic design from the Graphics Art and Design School that the EE and CpE team could then apply the solar energy system to. The EE and CpE team had to have several design options to offer for variety purposes that could be picked for the different artistic designs to be chosen by the mechanical engineering teams. All three parties were to work together to finish the overall project while also accomplishing each teams' specific requirements. This team oversaw the electrical components of the solar sculpture. Since this was the only EE and CpE group to provide different options, in a way this team worked as a consultant group for three mechanical teams. The art designs were modified to mold themselves around the best fitting solar system design.

5.2 Hardware Design

For the implementation and testing of the Solar Sculpture to continue we had to decide on what hardware to purchase and justify that it was a suitable product to use in the design. These major components were crucial to the success and how the project would function. The choice of what kind or specifications of Photovoltaic Panels to power the components and generate the required energy to the grid was the fundamental component. Selection of inverter can affect ease of maintenance, installation, and efficiency depending on the type of panels chosen. The microcontroller which acts as the brains of the sculpture, controls all of the external components which are LEDs, sensors, and LCD screen. While selecting these products we kept in mind compatibility, feasibility (cost/efficiency), and that the requirements given to us from our sponsors were met and these components when combined did not break any standards or regulations. Upon purchasing and receiving the components all needed to be breadboard tested to check functionality and testing.

5.2.1 Photovoltaic Panels

The goal of the solar power system design was to have the system output power meet the minimal requirement by OUC even with the attached electronics. Although the grid will power the structure's attached components, the expectation was to have the panels produce more power than the attached components would be consuming as well as meet the minimal yearly output power. The reason for having the structure's electronics components powered by the grid was so the electronics do not depend on photovoltaic panels to provide power to them at night time, and during cloud shading or rainy days.

When selecting the final panel options to present to the mechanical teams and art teams, several specific traits were taken into consideration. The teams' considerations are listed below:

- Photovoltaic panel type

- Efficiency
- Nameplate power output
- Surface area
- Temperature constraints
- Weight
- Voltage/current panel output

Right from the start, thin-film panel technology was discarded. This was decided not only because we were recommended to do so by OUCs advisors but also because of the disadvantages thin-film panel technology usually brings alongside with them. Thin-film technology for the most part needs double to triple the surface area compared to commercial and residential polycrystalline and monocrystalline photovoltaic panels. Structural space constraints presented by OUC limited the amount of surface area space that the photovoltaic panels could cover. To make the best use of the limited space available and gain the most power per square footage surface coverage, polycrystalline and monocrystalline photovoltaic panels were preferred. While thin-film technology would have performed better than polycrystalline and monocrystalline technology under shading, the location of the structure as well as the height of the panel installation made these advantages irrelevant as there would not be any shading issues.

Between polycrystalline and monocrystalline technology for photovoltaic panels the differences are minimal. Even with both panels having small differences between them, the differences were important to be taken into consideration for artistic and temperature constraints purposes. Monocrystalline panels are black or dark blue while polycrystalline panels tend to be blue with a shattered pattern. This was important for the art team since it gave them a small variety of colors and patterns to play with when designing their structure. While the average efficiency for monocrystalline panels is 18% which is 3% higher than the 15% average efficiency for polycrystalline panels, polycrystalline panels tend to have lower temperature constraints. Monocrystalline panels are darker colors making them more absorbent to light which can result in a better efficiency but also makes monocrystalline panels more receipting to temperature increase in contrast to polycrystalline panels. Monocrystalline panels being more sensitive to heat also can lead to them having higher degeneration rates. Florida weather will be rough on which ever photovoltaic panel is chosen for the solar sculpture with its high temperatures. The following techniques can be applied to reduce the effects of high temperature on photovoltaic panels:

- When installing the photovoltaic panels, leave space for air flow under panel for cool down
- Chose photovoltaic panels with lighter colors for less heat absorption
- Place hardware components attached to the photovoltaic panel in electronic box away from the panel

Surface area for the most part means the more surface area being covered the more power output the photovoltaic panel is producing. While ideally the largest commercial panel would be chosen for the solar sculpture, multiple panel sizing options needed to be provided for a variety of purposes. Both residential and commercial panels were presented to the mechanical and art students so these teams could choose which panel sizing best fits their structure design while also meeting the mechanical requirements. Residential panels average size is 65 inches by 39 inches and average size for commercial panels is 77 inches by 39 inches. Commercial panels would be the ideal selection for the solar sculpture but fitting multiple 6.42 by 3.25 foot panels in a maximum 8-foot diameter limit could be difficult, therefore a 5.14 by 3.25 foot panel option was provided. That way even more panels may be installed in the solar sculpture. Average photovoltaic panel thickness, no matter of the type, tends to be around 1.5 inches.

While photovoltaic panel size variety was helpful for the art teams in regard to more freedom when designing the structure, panel weight was a limitation for the mechanical team. Commercial panels have an average weight closer around to 50 pounds while residential panels have an average lower weight of 40 pounds. A commercial photovoltaic panel was the best option for the EE and CpE team but this decision could have obstructed the design freedom of the art team as well as complicate the mechanical teams structure strength. The design structure from the mechanical team needed to be strong enough to withstand Florida rough weather plus meet safety standards while also holding around 100 pounds in solar system electronics.

Maximum photovoltaic panel voltage and current output rates were important factors to consider when making the final selection. Reason being these maximum ratings displayed in each panel's electrical characteristics led to the final inverter selection. Any components attached to the photovoltaic panels needed to have an operation rate where their voltage and current input matched or were in range of the photovoltaic panel. If the operation ranges did not match, then the attachable hardware would not function. All solar energy system hardware provides electrical characteristic datasheets that made comparing and matching easy.

Every photovoltaic panel has a very important nameplate value. This value is the theoretical power output of any photovoltaic panel which is the most useful when calculating the annual output. Through the PVwatts calculator, the nameplate power value of a specific photovoltaic panel is inputted and the tilt degree, system loss and panel location are taken into account resulting in a very accurate calculation of the annual output. This is how the total number of each specific photovoltaic panel can be calculated when the system is put together with all the attached electrical components. That way panel selection comes with ease.

5.2.1.1 Final PV Selection

Final photovoltaic panel selections were based on what type of panel, the size, nameplate power output and voltage/current panel output. Three different photovoltaic panels selections were offered to the mechanical teams to apply to their selected art designs. All the selected photovoltaic panel options meet the requirements set upon the EE and CpE team. The first monocrystalline photovoltaic panel option was the optimal panel from the perspective of the EE and CpE team. This option was selected upon panel longevity and lowest economic cost for overall solar system. Second monocrystalline photovoltaic panel was a smaller residential panel option. This was due to the art students originally planning their designs with a basic 3x5 foot photovoltaic panel in mind. The mechanical team also benefited from this option since the smaller panel meant less weight which intern would have less of a strain on the solar structure. The second option would have required more electronic hardware to not only be able to meet the minimal annual output required by OUC but also power the solar structure's attached electronic components which would make the overall system more expensive. The last option was a polycrystalline photovoltaic commercial panel for color options. Art students appreciated the different color choice option between a black monocrystalline panel to a glimmering blue polycrystalline panel.

Option 1

The best option from the EE and CpE team perspective was the LG NeON 2 72cell 390W monocrystalline photovoltaic panel as shown in Fig. 24. Two of these selected panels with their own selected microinverters on any solar structure at the optimal angle would be more than enough to power the microinverter and meet the minimum annual output required by OUC, with two panels producing 1,096 kWh/year. This photovoltaic panel has a high efficiency rating of 18.8%. The dimensions for this panels are 79.69 x 40.31 x 1.57 inch which sets it at a bigger than average commercial panel. Both the optimum power voltage, V_{mpp} = 39.8v, and open circuit voltage, V_{oc} = 49.1v were within the operating range of the selected microinverter. The only limitation to this option would have been the weight of 47.84 pounds, which could have caused a lot of strain on the solar structure from the mechanical engineering team.

Fig. 24. LG 72 Monocrystalline Panel

Option 2

This second option was provided for ease of use for both the mechanical team and the art design team. The photovoltaic panel for the second option was the LG NeON R Module as shown on Fig. 25. This photovoltaic panel just like the panel from option 1 is made of monocrystalline technology with nameplate power output of 350W. In contrast to option 1, three of option 2 panels at optimal tilt angle would have been needed to be able to meet the minimum annual power output required by OUC. Also counter the power consumed by the attached electronics like microinverter, LED, etc. The three panels will produce a 1,476 kWh/year. This photovoltaic panel has an even higher efficiency rating than the option 1 panel at 20.3%. The advantage for the mechanical

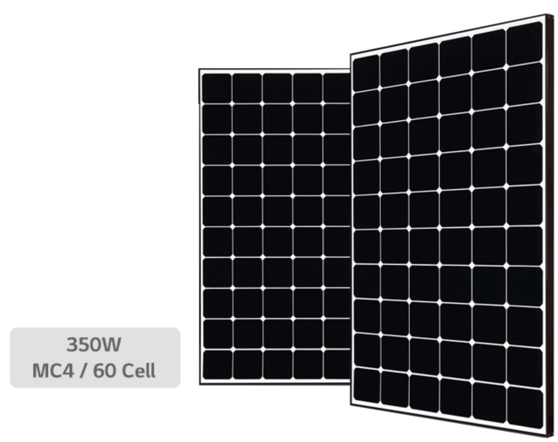


Fig. 25. LG 60 cell Monocrystalline Panel

and art team comes into play with the panel size and weight with the photovoltaic panels dimension measuring at 66.93 x 40.0 x 1.57 inch, equivalent to 5.58 x 3.33 feet. The weight of the panel reduces to 40.78 pounds compared to the panel in option 1. Art students were already designing their structure with 3x5 foot panels in mind and the lighter panel would cause less stress on the overall structure favoring the mechanical team. Both the optimum power voltage, V_{mpp} = 36.4v, and open circuit voltage, V_{oc} = 43.5v were within the operating range of the selected microinverter.

Option 3
For the third option a polycrystalline photovoltaic panel was provided so the art design teams had a variety of panel color options. The photovoltaic panel chosen for the third option was the Amerisolar AS-6P 340W as shown on Fig. 26. This photovoltaic panel just like the panel from option 1 has commercial size dimensions. It is similar to the panel from option 2 with a nameplate power output of 340W. Since the nameplate power output is similar to option 2, three of option 3 panels at optimal tilt angle would have been needed to be able to meet the minimum annual power output required by OUC. Also counter the power consumed by the attached electronics like microinverter, LED, etc. The three panels will produce a 1,434 kWh/year. This photovoltaic panel has the lowest efficiency rating of the three options at 17.52%. The photovoltaic panels dimensions measure at 77.01x39.06x1.97inches, equivalent to 6.42 x 3.25 feet. The weight of the panel was the highest compared the other options at 50.7 pounds. Art students could have had their structure design revolve around a blue colored photovoltaic panel for a more colorful display but the mechanical teams may have suffered since this panel was the heaviest. Both the optimum power voltage, V_{mpp} = 37.5v, and open circuit voltage, V_{oc} = 46.1v were within the operating range of the selected microinverter.

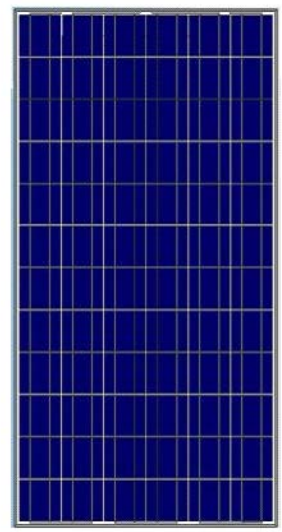


Fig. 26. Amerisolar polycrystalline panel

5.2.2 Inverter

The qualifications the EE and CpE team were looking for to apply to the inverter selection were very simple. Once the optimal solar panel was selected, selecting an inverter was just a matter of matching the photovoltaic panels outputs to the inverters input. Another qualification for final inverter selection was the cost efficiency since the most economical system was desired. The last qualification that was considered was that the inverter be UL listed. A list of manufacturers that are UL listed has been mentioned under the standards section.

Comparing string-inverters and microinverters for the solar sculpture structure had been easy. The maximum number of solar panels that were going to be selected to be implemented in the solar sculpture would range between 2 to 3. String-inverters are used to their maximum optimal functionality when a lot of panels are connected together. With only 2 to 3 panels being implemented in the solar sculpture design a string-inverter would not be used to its maximum capacity. Also, a con for string inverters was that they have shading issues. To combat shading the shading issues, string-inverters use an additional piece of hardware called the power optimizer to each panel. Purchasing power optimizers would have added an additional cost to the total project budget. Since a string-inverter would not have been used to its full capacity and would have had the highest project budget cost, the string-inverter option was discarded. The EE and CpE team selected the necessary amount of microinverters to be implemented into the solar structure.

5.2.2.1 Final Inverter Selection

Fig. 27. ABB Microinverter

For the final inverter selection, the EE and CpE team researched microinverters from manufacturers that are UL listed. In conclusion the ABB MICRO-0.3HV-I-OUTD was selected to be connected to the photovoltaic panels as shown in Fig. 27. The maximum power output from the selected microinverter is 310W while the input power intake is 360W. This input capacity is in range for the selected photovoltaic panels options nameplate output power. Also, the absolute maximum input voltage is 79v which also fits the range for the selected photovoltaic panels output voltage. A neat feature that comes along with the ABB microinverter is the communication radio communicator ABB CDD. The free photovoltaic panel monitoring application allows for easy data monitoring of each individual panel. Monitoring the data can be done via web or mobile device wirelessly. The radio communicator can analytically monitor up to 30 different microinverters so monitoring 2 to 3 microinverters was not an issue. 2 to 3 of the microinverters and the radio communicator combined added up to 8.23 – 11.73 pounds that was considered.

5.2.3 Microcontroller Selection

For the Solar Sculpture, the microcontroller was the controller for the LEDs, Sensors, and Display. When comparing multiple different microcontrollers, we always kept in mind the minimum requirements for the microcontroller needed to control everything and if we could scale that at most eight times. This was due to the prototype we would design being a 1/8 scaled model of the actual design of the sculpture, and in addition since the purpose of the sculpture was to promote renewable resources while being aesthetically pleasing to look at we aimed for minimal power consumption while also leaving leeway for scalability in the design. Therefore, after extensive research and discussion we decided to go with an Atmel AVR family microcontroller, the ATmega2560.

Fig. 28. ATmega2560 microcontroller

The ATmega2560 is a RISC architecture, low-powered CMOS 8-bit controller which can achieve an output of about 1 MIPS per MHz which can allow the customizable design around optimizing power consumption vs processing speed. The ATmega2560 is used in the Arduino Mega 2560 and its variant for android compatibility, the Arduino Mega ADK. The choice behind going with an Arduino based microcontroller for our design was due to documentation (open source hardware/software) for resources and available libraries in particular for controlling LEDs, LCD displays, and sensors. In addition, Arduino microcontrollers were within mid-range specifications between power efficiency of an ultra-low-powered MCU such as TI's MSP430 and the high end specifications of available RAM or utility that a Raspberry Pi could bring for the design.

A great thing for the design of our PCB in utilizing the ATmega2560 is it is a 100 pin microcontroller and, assuming we reserved 30 of the pins for required connections such as power supply, a 16MHz crystal oscillator, RX/TX, GND, etc., then we could potentially be able to use upward to 70 pins for general I/O purposes if we wished to drive for example, 70 LEDs or a mix of components like driving a combination of things such as LEDs, LCD display, sensors, and more. Although that sounds great in theory, we still had to take into consideration the limitations of the ATmega2560 or any microcontroller in general when driving multiple external components.

A limitation we had to consider was the maximum amount of voltage or current our modified version of an Arduino Mega 2560 could draw through any of its pins. The ATmega2560 maximum current output rating before a pin will potentially take damage is 40mA DC current per I/O pin. Although, even if the maximum is 40mA we should keep a rule of thumb to aim for approximately half of that value, ~20mA, for longevity of the microcontroller in mind. Additionally, each VCC and GND pin can take a sum of 200mA and there are four VCC and GND which meant we could utilize up to 800mA total assuming we were operating under a test condition of 20mA at VCC = 5v or 10mA at VCC = 3v for 5v operation and 3.3v operation respectively. Given this information from Atmel we could safely protect ourselves from damaging the device if we did not source or sink over the current limitations documented.

Due to this current limitation, we had a couple of options in regard to components such as LEDs, displays, sensors, etc. However, this mainly applied to LEDs choice since there is a huge range of LED types and specifications (forward voltage and maximum current per LED). Assuming we bought high powered LEDs we most likely could not use more than a handful of them without damaging or frying the Arduino through the ports unless we limited the current below the limit. However, this could result in the LEDs brightness not being satisfactory or the number of LEDs being insufficient to cover the Solar Sculpture because of the 200mA current limit for a range of ports we would have only been able to drive a small number for each 200mA section. To remedy this issue, we would suggest using multiple ATmega2560's to control separate sections of LEDs when scaling up the amount of LEDs becomes necessary. For this project however, the scaled model of the Solar Sculpture did not utilize too many LEDs and we had sufficient pins available to drive everything.

5.2.4 Display Selection

Fulfilling the requirements of a display shows people the appeal of what this Solar Sculpture does, which is to be an artistic and aesthetic sculpture for the public to view while also functioning as a way to generate renewable resources using Photovoltaics technology. So we needed a way to display the annual estimated amount of power generated and additionally, we include a conversion of that amount from kilowatt-hours into monetary value (USD) for the general public to understand in a unit that would make more of an impact to them. After comparing many displays from OLED displays, capacitive touchscreens, and various LCD displays we opted to keep it simple and go with a standard 40x4 Parallel Character LCD display from Crystalfontz.

Fig. 29. Crystalfontz 40x4 Character LCD display (CFAH4004A-TFH-JT)

The reasoning for the choice of going for a character LCD display over a graphic LCD display was there was no real intention of displaying anything else except text displaying the estimated value of energy gained. Similar to the 20x4 character LCD display compared before by the same manufacturer, Crystalfontz, the 40x4 has the exact same specifications as the 20x4 display previously mentioned with the exception of size and this model uses a white backlight color (utilized mainly when it's dim or dark outside). This means, we deliberately chose a display that was transflective to allow it to be readable in the sunlight since this will always be outdoors. Additionally, we were worried about the size not being adequate, but we compromised and went with a lower-cost option of displaying the bare minimum to also keep power consumption in mind to lower the net loss of power due to electrical components.

Even this small display was okay on the scaled model assuming the people are allowed to be within viewing distance. For our prototype of a 1/8 scaled model, this screen was perfect because at maximum the largest diameter of the sculpture should be around 2 feet. We wanted the screen to be viewable as you approach to read or admire the sculpture and we planned to add interactivity with that if allowed. The most we could do within our requirements was with sensors which would have been programmed and controlled by the microcontroller to activate a light show or flash the LEDs when someone approaches to read the screen. One idea we had was that we wanted to utilize a touchscreen and make an application for the user to do something, but due to limitations of safety and maintenance we dropped the idea because if we used a touchscreen it would mean people are allow to be close enough to touch the display as well as the sculpture which is something we cannot compromise due to requirements that the sculpture should not be climbable, people can't get hurt, the sculpture can't be damaged, etc.

Regarding the sizing issue, for our modeled prototype of the Solar Sculpture, this small 40x4 character LCD screen worked just fine, but concerning the actual model if desired we recommend using larger LCD screens which are a lot more expensive (due to these not being available through retail, but through a display company for order) and require more power which may be undesired. Additionally, if we were to have gone for a larger display like a monitor, then our Arduino-based ATmega2560 PCB would not have been able to handle drawing to such a large and high-resolution screen. In this situation we recommend using a more advanced board such as variants of the Raspberry Pi, Beaglebone Black, or a high-powered board that can use HDMI, etc. Again, we do not recommend going with a high-resolution or large screen unless it is mandatory because the amount of power required would be wasted since we are trying to gain a net gain of 850kWh annually and this would only be detrimental and may only slightly improve aesthetic appeal.

To utilize this display, we easily installed/connected the display to our microcontroller via 4-bit or 8-bit parallel interfacing which Arduino supports. Parallel interfacing utilizes multiple pins to control the display at the cost of requiring more pins. Compared to an SPI interface, which is serial peripheral interfacing, or serial interfacing would take up less pins, but at the cost of display quality/refresh rate and not being able to read from the display in serial mode. The 40x4 display uses the industry-standard HD44780 compatible controller which meant we could use the LiquidCrystal library from Arduino that could help simplify and easily control the LCD display.

5.2.5 Power Supply

In Senior Design 2 we had to choose a new power supply. The 5 V, 2 A power supply could not meet the current demands of our system. To give the LEDs enough current, we upgraded to a 5 V, 10 A switching power supply from Adafruit, seen in Fig. 30. This power supply used to DC jack input on the PCB. The previous power supply's 2 A limit meant that the LEDs would not light up properly. The new power supply solved that issue for our system, and the systems we supplied to the three other teams on this project.

Fig. 30. Adafruit 5 V, 10 A switching power supply. We had to upgrade to this power supply to meet the power demands of the Adafruit Neopixel LEDs. Reprinted with permission from Adafruit.

For the whole circuit to work we had to give the PCB a power supply in which all the components could take the needed voltage and be able to work. All the components must be powered throughout the day and into the night. Even though it is a solar sculpture that will work during the day, the need for the components to be on during the night is because a lot of the MLS games are played at night time.

One possibility that the team discussed was taking the voltage that we were sending to grid and seeing if it was possible to use a small amount of that voltage that was being produced. Without any research, this seemed like a good idea if we were able to set up a circuit to control the voltage going into the PCB. After thinking it through we realized that this would have been extremely difficult to implement. For starters, to control the high voltage coming in we would have needed to place a very intricate circuit with expensive parts to make sure not a lot of energy was dissipated. Another fault in our idea was that during nighttime to be able to power our components we would have needed to have either a battery bank in our circuit or taken energy from the inverter that is taking energy from the grid. The OUC engineers expressed their desire to stay away from a battery and our idea to take from the inverter would have needed a lot of timers and switches to take from both sources at the correct times throughout the day. All these challenges and hurdles to power the PCB led to this idea being scrapped and forced us to look at alternative sources.

The next best options that we came up with was to power the PCB from a nearby outlet. This decision was made because the voltage coming from the power outlets is standard throughout the United States and is not too high of a voltage to not be able to manipulate to make smaller. The input voltage also maintains a constant voltage value throughout the day. Even though the input voltage is now significantly smaller, we still had to figure out how to drop down the voltage from 120 V to 5 V without dissipating any power.

We had two options on how to drop the voltage to 5 V. The first option was placing a component on the PCB such as a transformer or a rectifier circuit and have the 120 V go straight into that. Although this option works and would have lowered the voltage to the desired output it would have used a high amount of space on the PCB and would only be used for the functionality of decreasing the voltage. This decrease in available surface area was not the most ideal for our design because the space that the transformer or rectifier would have taken was space that other components needed. The second option was buying a power adapter that connects directly into the wall and would give us an output of 5 V. This power adapter is more commonly known as the small cubes that we plug into the wall that charge our phones.

These power adapters were perfect for our design and contained the following advantages:

1. They already had all the needed components in them
2. They lowered the voltage to a constant 5 V
3. They are reliable
4. They are easily replaceable
5. They would not use large amounts of space on the PCB.

Having all the components already in the power adapter and having them already set up and connected meant that we didn't have to do design for this circuit. This was a great advantage because, the power being the main source of what drives the circuit, we did not have to worry about whether we built it right or not and had more time to focus on the PCB itself.

Fig. 31. Inside of Power Adapter

The power adapter having a constant 5 V output at any time throughout eliminated some of the concerns we were having when talking about the solar panels and night time. This constant 5 V would not fry the circuit or any components in the circuit and would give enough power for all the components to use. Having a reliable source of power was also very important. It meant that we didn't have to worry about the circuit power going out after only a short amount of usage. With the power adapter giving the power into the circuit board at any time that the adapter fails or just comes to the end of its life cycle, the only thing needed is just to replace the cube and the circuit can be back up and running in minimal time. The other important advantage that the power adapter had was that because it is external to the actual circuit board it would not take up any space on the board itself, instead the only thing we needed to do was solder a USB type outlet onto the board and that would be the power source for the whole circuit.

To get the correct power adapter there were not a lot of guidelines that we needed to follow. The biggest factor in choosing the correct and proper was that it needs to be UL listed. A second factor was that it needs to output a 5V voltage and be USB connected. The adapter

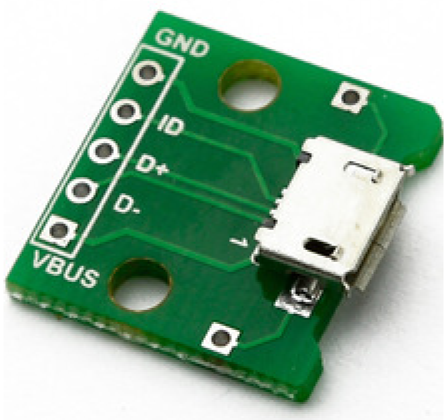


Fig. 32. Power Adaptor to PCB

that we chose was a wall phone charger that has an output of 5V and a current of 2 Amps. The phone charger is called USB Type C AC Charger Power Supply Adapter and can be found on Amazon.

5.2.6 Regulators

Not all components on the circuit board use the same amount of input voltage to power themselves and work. Two components that are on the same breadboard but use different voltages cannot be connected to a constant power source. For this purpose, regulators are introduced into the circuit to be able to power all the components on the board without any problems. The regulator produces either a higher or lower amount of voltage depending on the regulator used. The step up regulator had very bad efficiency and for our project we needed voltages as precise as we could get to not fry the circuits, for this reason we did not want to use step up regulators.

We decided to use some type of step down regulator to insert into our circuit board. The step down regulator is much more efficient compared to the step up and gives a more constant voltage. With us choosing to use a step down regulator instead of a step up regulator we could not have any component that uses a higher voltage than that of the input voltage but we could use components that have lower voltages. For this specific reason, all of our components chosen and used for the circuit board use either a 5 V input requirement or a 3 V input requirement. The components that use the 3 V were connected to the output of a 3 V regulator and are able to function properly.

5.2.6.1 Linear vs Switching Regulator

There were two types of regulators that we could use for the step down 3 V. We could use either a liner step down regulator or a switching step down regulator. Both types of regulators had certain advantages and disadvantages that applied to our project.

Table 18 and Table 19 show the different advantages and disadvantages when the two regulators are compared to each other as well as show their importance level relative to our project and our implementation of our components.

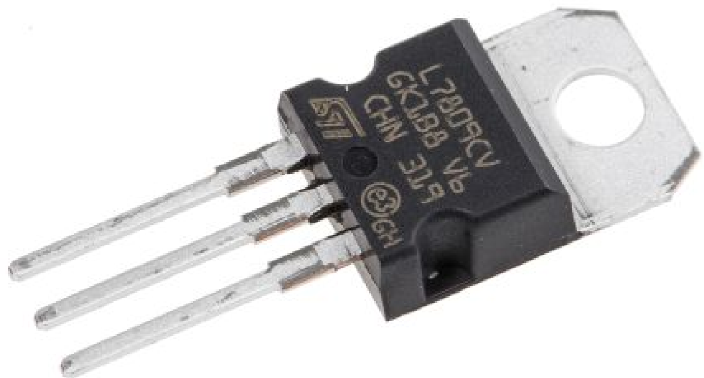


Fig. 33. Standard 3-Pin Regulator

TABLE XVIII
COMPARISON OF PROPERTIES OF
LINEAR REGULATORS AND SWITCHING REGULATORS

	Linear Regulator	Switching Regulator
Design Flexibility	Buck	Buck, Boost, Buck-Boost
Efficiency	Normally low to medium-high for low difference between V_{IN}-V_{OUT}	High
Complexity	Low	Medium to high
Size	Small to medium, larger at high power	Smaller at similar higher power (depending on the switching frequency)
Total Cost	Low	Medium to high – external components
Ripple/Noise/EMI	Low	Medium to high
V_{IN} Range	Narrow (depending on power dissipation)	Wide

Table 19 illustrates the importance of these categories relative to our project and design. Looking at the table the difference between the two types of regulators is apparent. The linear regulator has a very limited design flexibility compared to the switching regulator. The difference in design flexibility was not that high of importance for us since we only needed a step down regulator and did not need a boost or a buck boost inverter.

The efficiency was somewhat of an important factor in our project and the switching regulator was the clear winner. It is more efficient than the linear regulator and gives a better output voltage, normally this would be ideal but because we were only using a small voltage that is within the range of what the components need we could have a little disparity in output and it would not have affected that certain circuit in noticeable way.

TABLE XIX
LINEAR VS. SWITCHING REGULATOR

	Linear Regulator	**Switching Regulator**	
Design Flexibility	2	1	1- Most Design Flexible
Efficiency	2	1	1- Most Efficient
Complexity	1	2	1- Least Complex
Size	2	1	1- Smallest size
Total Cost	1	2	1- Least Expensive
Ripple/ Noise/ EMI	1	2	1- Least prone to Ripple/ Noise/ EMI
Vin Range	2	1	1- Best Range for input

The complexity of the regulator was not that important to our project because our design only needed the regulator to be able to handle a simple system for one component. The size was also very important because this component was being placed onto the circuit board. This meant that the smaller the component, the more space we would have for our design which is always a good thing. The cost of the regulator was higher for the switching regulator because it requires the purchase of components like capacitors to help protect it, although independently this might have caused a problem, the regulator is part of a larger design that will already have the need to buy the extra components (a typical linear regulator still uses capacitors in the circuit for protection). The ripple, noise, and EMI was not something that would greatly affect our circuit board but it was important to have the least amount of ripple, noise, and EVM as possible. The range was also not of high importance for us seeing that we were only using a constant voltage of 5 V throughout the system and using the regulator to step down the voltage to 3 V for a component. The team decided that the benefits of using a linear step down regulator were far greater than that of the switching regulator so we decided to use this component for the circuit board.

The regulator that we chose was the MCP 1703. This regulator is a LOD Regulator that acts a step down regulator with the ability to drop it down to 3 V with a good current for the component as well.

Table 20 illustrates the ideal operating voltage and current that components on the printed circuit board will be under for our designs.

TABLE XX
COMPONENTS OPERATING VOLTAGES & CURRENTS

Component:	Voltage:	Current:
MCU(Arduino ATmega2560 16AU R3)	5 V	20/50 mA
SparkFun Sound Detector Sensor	5 V	34 mA
Vishay Infared Sensor	3 V	350 µA
Adafruit LED Strips RGBW	5 V	49 mA
Crystalfontz 40 x 4 Parallel Character LCD	5 V	1.2 mA
3V Microchip Regulator	5 V	250 mA

5.2.7 LED Selection

In Senior Design 2, we changed our mind about which LEDs we recommended for the full-scale sculpture. We changed our recommendation to the Ribbon Star 50/50, Waterproof LED RGB + WW lights. The reason for this change was that they are much more convenient than our previous choice, which would require mounting and weatherproofing each light. The Ribbon Star LEDs are UL listed, IP68 rated, and UV proof so they are an excellent choice for the sculpture [48]. The specifications of these LEDs can be seen in Table XXI. These LEDs can be controlled by a suitable DMX512 controller, which makes changing patterns a very straight forward task. DMX512 is a standard for lighting controls [47]. The Ribbon Star strips provide three RGB LEDs and three warm white LEDs per 4 in.

TABLE XXI
RIBBON STAR 50/50 RGB + WW LED STRIPS

Property	**Value**
Input Voltage	12 V
Power Consumption	4.4 W/ft
Maximum Serial Connection	20 ft
Lumens	305 lm/ft
Bean Angle	120°
IP Rating	IP 68
Colors	RGB + Warm White
Operating Temperatures	-49 °F to ~149 °F
Certifications	RoHS, CE, UL Listed

After comparing the different LEDs, the choice we made for our prototype was the NeoPixel Digital RGBW strip LEDs from Adafruit. These fit our prototype needs well because they kept costs down, they were individually addressable, they could be driven by 5 volts, they are waterproof, and there are libraries already programmed with functions for the Arduino ATmega2560 MCU that work with these LEDs. For the full-scale structure, the Adafruit strip LEDs was not used as we could not confirm UL listing. An appropriate choice for the full-scale structure would be the offerings from Cree and Lumileds since these are confirmed UL listed parts and have the properties to fulfill the aesthetic requirements.

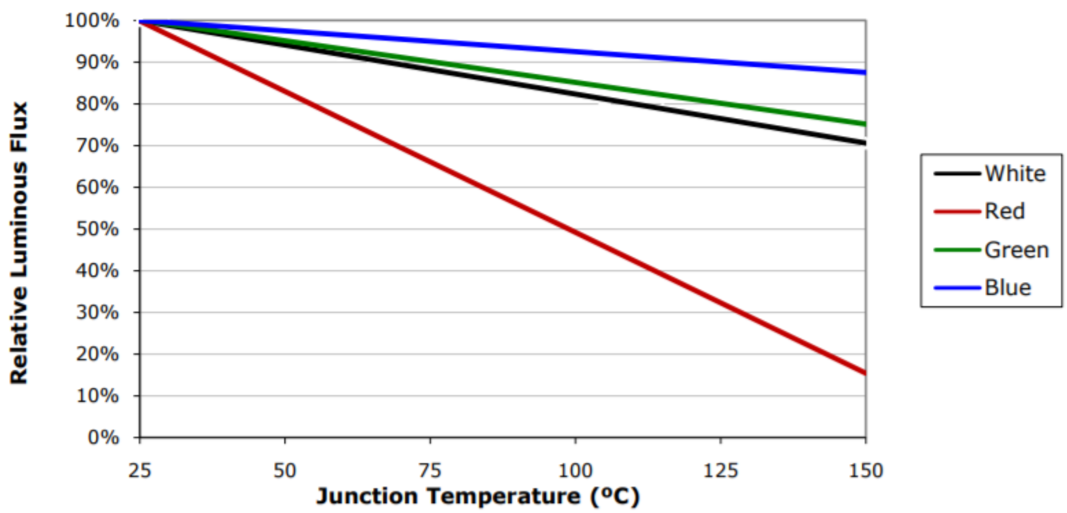


Fig. 34. Relative luminous flux as a function of junction temperature. The higher the temperature goes, the more the luminous flux falls. Reprinted with permission from Cree.

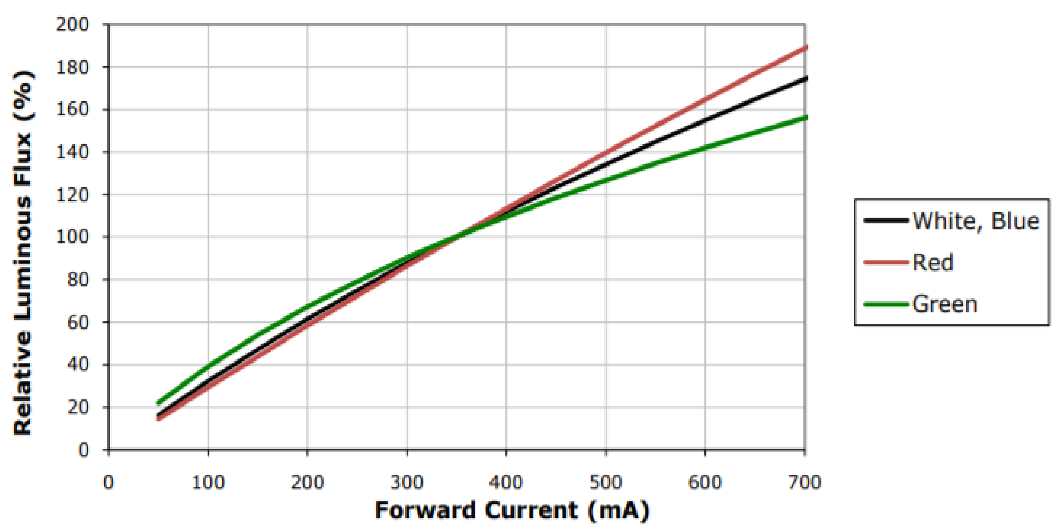


Fig. 35. Relative luminous flux as a function of current. The higher the current goes, the more the luminous flux rises. Reprinted with permission from Cree.

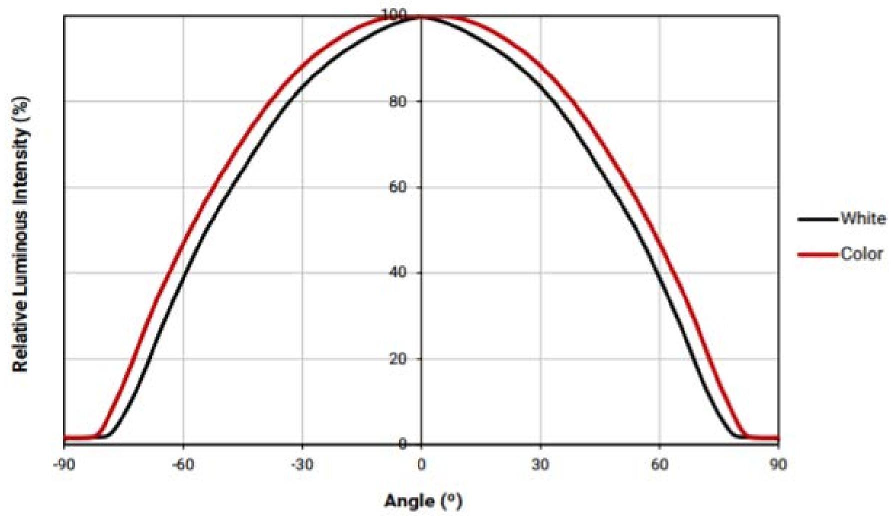


Fig. 36. A graph to represent how the luminous flux, or visible brightness, will fall as the viewer moves out of the direct line of the LED. Reprinted with permission from Cree.

5.2.8 Proximity Sensor Selection

In Senior Design 2 we made a change to the proximity sensor used. The original choice, the Vishay VCNL 4200, had many attractive qualities including good range, low cost, low power, and an ambient light sensor. However, since this sensor must be mounted on its own PCB to be used, we ran into problems making a PCB for it, and getting it to work even when we had it mounted on a test PCB. We decided to switch to the **Sharp GP2Y0A41SK0F** infrared proximity sensor, which can be seen in Fig. 37. At only 30 cm, this sensor has a much shorter range than the VCNL4200 but it was still suitable for our prototype. The Sharp sensor also comes in an integrated package with mounting holes which made it much easier to place on our prototype. Additional details about this sensor can be seen in [49].

Additionally, we made our recommendation of which kind of sensor should be used on the full-scale sculpture. We had trouble finding a UL listed infrared sensor that didn't require reflectors and had a good range. For this reason, we decided to change to an ultrasonic sensor, the **Rockwell 873P-D30AVP2-3500-D5**. This sensor can accurately detect things that are between 0.25 m and 3.5 m away. It is also UL listed and IP 67 rated making it a great choice for our sculpture. The sensor can be seen in Fig. 38 and additional details about it can be found in [50].

For our final decision on proximity sensors we went with the **Vishay VCNL4200** for our prototype. This sensor is economical, has good thermal resistance, and has an interface that allows the use of many of these all controlled by one MCU. Whether this sensor is acceptable for the full-scale sculpture is uncertain. For one, they can sense up 1.5 meters away, which may be close enough, too close, or not close enough for what OUC ultimately wants, as they may not want passersby coming too close to the sculpture. In addition, it is our understanding that all components must be UL listed to be considered for use on the sculpture and these sensors are not, however for a proof of concept model (our prototype), these sensors at least showed that the idea is sound, and a UL listed sensor with similar inputs and outputs could replace them.

Fig. 37. The Sharp GP2Y0A41SK0F infrared proximity sensor. We changed to this sensor due the difficulty in getting the Vishay VCNL4200 to work.

Fig. 38. The Rockwell 873P ultrasonic sensor. It was chosen because of its UL listing, IP 67 rating, and good range for the full-scale sculpture.

5.2.9 Sound Sensor Selection

In Senior Design 2 we were able to decide on which microphone would be suitable for the sculpture. Like everything else for the sculpture, it had to be UL listed and be able to withstand the elements. Finding a UL listed microphone was proving to be very challenging then we came across an article on the audio electronics manufacturer Shure's website that stated 'As a wired microphone does not create a hazardous voltage and does not require a hazardous voltage to operate, a UL listing or other similar safety rating is not required' [51]. After making this discovery, we were able to select a microphone that met the other needs of the electronics used on the sculpture. The microphone we chose was the **GRAS 146AE 1/2'' CCP Free-field Rugged Microphone**. The GRAS microphone is IP 67 rated and designed for use in free-field environments, meaning spaces without much sound reflection. Given that the sculpture will be outside and far from walls, we believed that a free-field microphone would be a suitable choice. This microphone also has an extremely high operating temperature, ~257 °F. For further details on this microphone see [52].

For our choice of sound sensor, we decided to go with the **Fairchild LMV324**. Its extra cost was undesirable but not prohibitive. Again, this was a choice for our prototype as a UL listing for either sensor could not be found, though choosing this sound sensor for now allowed us to examine if the concept of having a sound sensor as part of the final sculpture was realizable. There is the concern that the random environmental noise will just be too hard to filter to make use of sound sensors, but it is our belief that they could add a unique and captivating element to the sculpture.

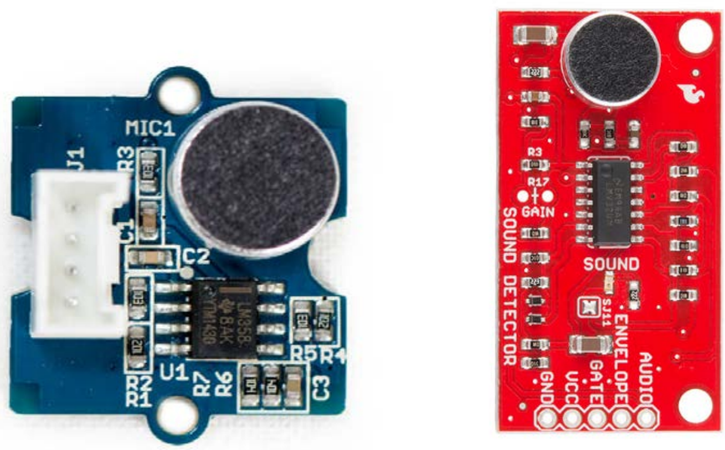


Fig. 39. Grove Sound Sensor and Fairchild LMV324

5.2.10 Current Sensor Selection

In Senior Design 2, on the advice of our advisor Dr. Richie, we decided to add a current sensor to our system to help determine the power output of our solar panel, so that we could better inform the public about the power generated by the sculpture. The sensor we picked to achieve this was the **Allegro's ±15.5 A ACS711** Hall effect-based linear current sensor mounted on the **Pololu ACS711EX** board, seen in Fig. 40. We chose this current sensor for its range, ±15 A, and the fact that it is a Hall effect-based current sensor which detects currents by the magnetic field created as the current passes through a coil surrounding it. In other words, the sensor is never actually in contact with the current. Hall effect-based sensors also have the advantage of being able to accurately detect static magnetic fields, making them well suited to a DC current. More information this current sensor can be found in [53].

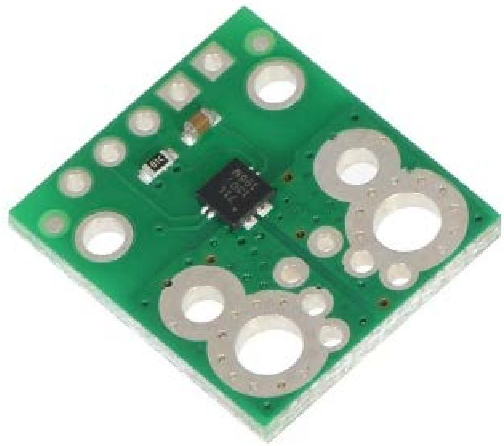


Fig. 40. Pololu ACS711EX board with the Allegro ACS711 IC current sensor. This board was used in conjunction with the voltage divider on our PCB to calculate the power output from our solar panel.

5.3 Breadboard Testing

The testing section is to demonstrate that the hardware and software components ordered by the electrical and computer engineering team are functional. Both breadboard testing and individual component testing was done by the team to layout the groundwork for Senior Design 2. For proof of the testing done, pictures of the breadboard and component testing were taken alongside a brief description and whether the test was successful or not. The breadboard and component testing finalized our last hardware and software selection to be able to complete our project.

5.3.1 LCD Display Testing

The character LCD screen was tested on the breadboard by connecting a +5V DC power source in series with a 10k ohm resistor to Vdd to power the LCD screen. We also connected the power source in series with a 20 ohm resistor to pin LED+ and pin LED- to ground. The connection from LED + and LED – give power to the LED backlight and this is useful for product testing to check if product is functional since the LED displays turned on. A visual representation of the systems set up can be seen in Fig. 41. For a more detailed testing procedure follow the schematic in the datasheet.

Following the schematic and instructions given in the data sheet to connect the LCD display, we concluded the LCD screen was functional. We ran a software test for the program code when the microcontroller arrived. The microcontroller tested if the program code had any bugs or exceptions. If the program code was correct then the LCD screen would display the annual kWh/year being generated by the solar sculpture.

5.3.2 LED Strip Testing

The LED strip was tested on the breadboard by connecting a +5V DC power source in parallel with a 1000µ F capacitor to ground. We also connected LED ground to the power supply ground. So, to test the LEDs we assumed if we applied the correct amount of forward voltage and current the LEDs would turn on at their default stage.

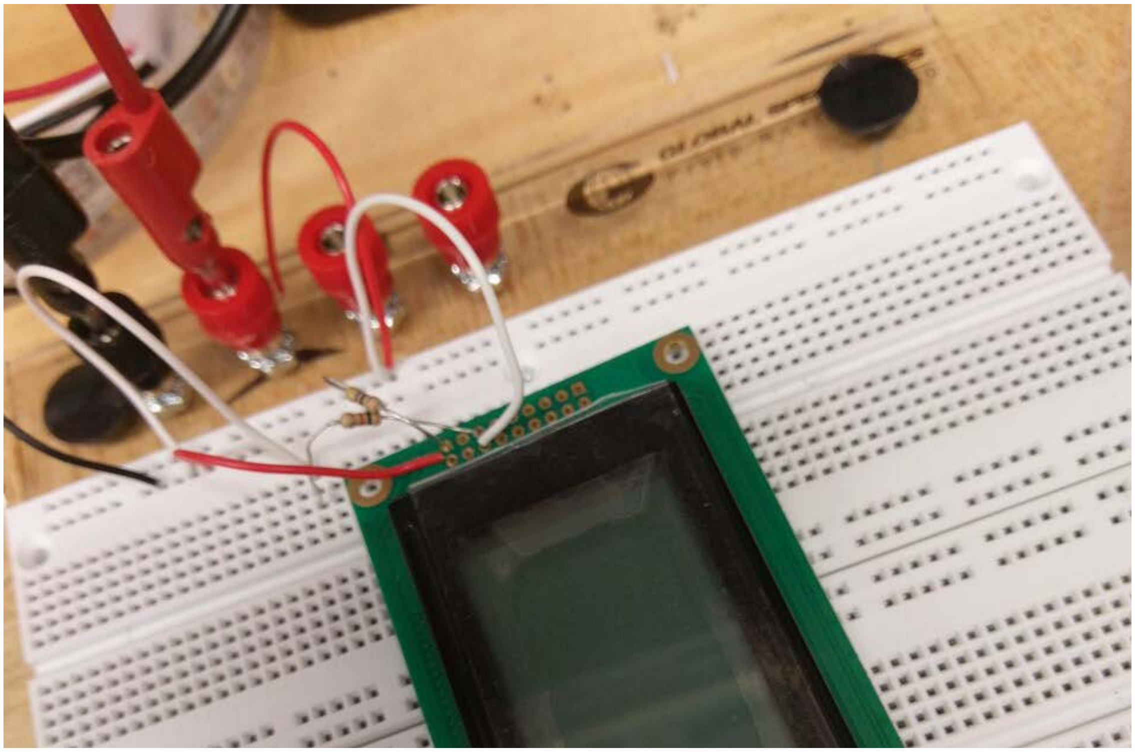


Fig. 41. LCD testing

However, the LEDs did not function as expected so we concluded that we need to complete the circuit by connecting the Din pin on the LEDs to any digital I/O pin in series with a 300 to 500 ohm resistor in order for the LED strip to function. Therefore we concluded we could not properly test the LED strip until we received the Arduino Mega 2560 microcontroller. When we received the microcontroller, we tested the LED strip by setting a specific light up pattern. We also tested to adjust the brightness intensity and to make sure the basic RGBW colors could be displayed. A visual representation of the systems set up can be seen in Fig. 42. For a more detailed testing procedure follow the schematic in the datasheet.

5.3.3 Infrared Sensor Testing

When we received the Arduino Mega 2560 microcontroller we fully tested the infrared proximity sensors. We tested this component by soldering wires to the sensors ports. Port 1 of the sensor was connected in parallel with a 2.7 ohm resistor in LED- port 5.

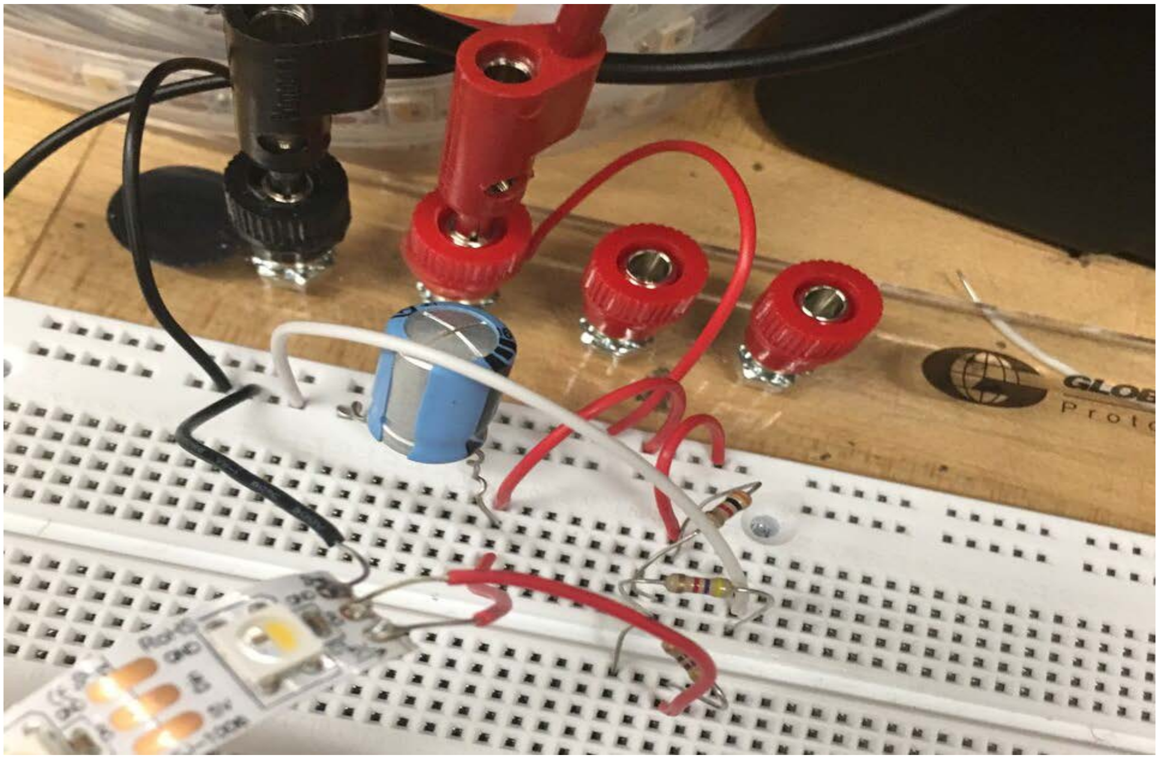


Fig. 42. LED testing

LED cathode port 2 was connected to the gate of a PMOS and the drain of the PMOS was connected to LED+ port 6 while connecting a 5k ohm resistor between the gate and source in parallel to a 2.2μF capacitor that was connected to ground. Port 3 was connected to Vdd in parallel to a 0.1μF capacitor connected to ground. Port 8, 9 and 10 were dedicated connections to the microcontroller. For a more detailed testing procedure follow the schematic in the datasheet.

Upon receiving the microcontroller, we fully tested the functionality of the proximity sensor. We connected the interrupt pin in port 8 to any digital interrupt pin on the microcontroller so when the sensor was triggered it would then send a signal to the microcontroller to activate a section of the software code. The SDA pin on the microcontroller was connected to the SDAT port 9 on the sensor. The SCK pin on the microcontroller was connected to the SCLK port 10 on the sensor. These two pins represented the I2C pin on the microcontroller which was used to communicate between the master and slave devices. In this case the proximity sensor was the slave device and the microcontroller was the master device. All the microcontroller ports were connected in parallel with a resistor.

When the infrared proximity sensor was fully connected to the microcontroller, the result was that a signal was generated that was registered by the microcontroller. This signal was generated when the infrared beam was broken up in distances up to 1.5 meters.

5.3.4 Sound Sensor Testing

The sound sensor component was tested by soldering 5 pins to the header section of the sound detector. Then, connections were made with wires between the sound sensor and the Arduino Mega 2560. The ground port was wired to the Arduinos ground. The Vcc port was wired to the power supply with an input voltage raging between 3.5 and 5.5 volts. The gate port of the sound detector was connected to pin 2 of the Arduino while the envelope port to the A0 port of the Arduino. For a more detailed testing procedure follow the schematic in the datasheet.

Our results for testing the sound sensor were that the sound sensor detected any sound as well as the amplitude/volumes of the sound. The software code took the output from the sound sensor and generated a message to the screen, displaying both when any sound was made, and the different amplitudes captured.

5.3.5 Project Operation

This project was to have three different functioning components in regards to the solar sculpture. These included the LED lighting component, sound detecting component and the motion detecting component.

The LEDs were to interact with both the sound detector and the motion detector. As the public passed by the solar sculpture the LEDs would be triggered to light up in a specified pattern. Same applied to the sound detector, depending on the sound amplitude the LEDs would be triggered to light up in a specific pattern. When both sensors were activated the same functionality would happen as mentioned before. These components would add a level of interactivity to the solar sculpture making the sculpture more attractive giving promotion to renewable solar power.

5.4 Software Design

To implement hardware components for the Solar Sculpture there is software that exists to utilize that hardware. The software used for the project was chosen for multiple reasons such as ease of access, documentation, and being fairly popularly used results in being more portable. Software used for the project consisted of CAD programs like Eagle, and various software and programming languages supporting the microcontroller.

5.4.1 Programming Languages

The programming languages we used for this project was C/C++. The choice for using this language was that the Arduino IDE is a variant of C/C++ and its code can compile as C/C++. The CPEs from the team both had a solid understanding and experience of using C/C++ and could confidently program the microcontroller and components to work as desired.

5.4.2 Arduino IDE and Libraries

What's great about using an Arduino based design for our microcontroller is the open sourced software supporting libraries for their IDE which is available on Windows, Mac OS X, and Linux. The Arduino integrated development environment is written in Java, but uses its own variant of C/C++ as its primary language. These libraries are immensely useful as it provides a way to avoid coding in assembly and using instruction sets directly and instead use a higher level language for readability and portability. Useful relevant libraries for the project are 'LiquidCrystal' for programming the LCD display, 'SPI' for master/slave serial interfacing, 'Wire' for TWI/I2C interfacing for communicating with sensors and other devices, and 'LedControl' to control array or matrices of LEDs.

5.4.3 Bootloader

The bootloader in its simplest form is basically a .hex file that runs like a BIOS for an operating system. What the bootloader was used for was to allow for us to easily communicate with the microcontroller board for us to program over a serial port such as a USB port. Under normal circumstances the bootloader is already burned into the microcontroller, but this is assuming if we were using an Arduino on a development board bought straight from the distributers, then we would not have any issues and could start programming to it using the Arduino IDE. However, that was not the case since we were working with and designing our own version of the Arduino Mega 2560 using a blank Atmel AVR family chipset, ATmega2560, into our own PCB. Then we would have had issues trying to program it directly without relying on additional software or hardware. Luckily, there were a couple of ways to accomplish burning in the bootloader. One way was to buy additional hardware to allow programming our Arduino-based board. Another way would have been to use an additional existing Arduino and have it emulate an AVR programmer to program our ATmega2560.

5.4.4 In-Circuit Serial Programming (ICSP)

In-Circuit Serial Programming or ICSP is a method of using an in-system programming (ISP) header to program the IC (integrated circuit), and in our case the ATmega2560 microcontroller chipset. For an Arduino it would usually have a 2x3 pin ICSP header we could use or more depending on the number of microcontrollers that exist on the PCB. Of these six pins of the ICSP header are MISO, MOSI, SCK, power, GND, and reset and to utilize ICSP we would have connected our programming Arduino to the Arduino to be programmed between both ICSP pins. So, if we wanted to burn the bootloader onto our fresh and brand new ATmega2560, how would we have done that? Luckily, Nick Gammon has a well detailed guide and has written multiple bootloader sketches that are open-sourced for multiple ATmega variants which includes the ATmega2560 that we could use. The first step was to download the bootloader sketch from Nick Gammon's repository and place it in our Arduino IDE's sketch folder, "sketchbook". Then we loaded this sketch in the IDE and uploaded the code into our programming Arduino that was connected to the computer. Then we connected our blank ATmega2560 together with the programming Arduino that had the sketch via ICSP headers.

Fig. 43. ICSP Header and relevant pins

To connect the ICSP pins between the ATmega2560, the correct connections between both microcontroller boards are shown in Table 22.

TABLE XXII
ATMEGA2560 ICSP WIRING REFERENCE

ICSP Pin	ICSP Pin #	ATmega2560 Pin #
MISO	1	22
Vcc	2	10, 31, 61, 80 (any)
SCK	3	20
MOSI	4	21
Reset	5 (Do not connect this!)	30
GND	6	11, 32, 62, 81 (any)

The next step was to connect the Reset pin of our ATmega2560 to the D10 pin of the programming Arduino which provided required reset pulses. Then we could connect our Arduino via USB port and initiate the Serial Monitor program by Nick Gammon. We pressed ‘G’ to start programming our chip with the bootloader and it output that it was erasing the chip and writing bootloader. It displayed done upon finishing. This was how we programed our microcontroller for the Solar Sculpture, and once we had burned the bootloader we finally uploaded our code normally to our microcontroller.

5.4.5 Pseudocode

The Solar Sculpture prototype utilized an Arduino-based microcontroller to function as the brains of the project and control most of the hardware such as LED, Displays, Sensors, etc. By using an Arduino-based microcontroller we had to use the Arduino IDE which allowed us to take advantage of the open-sourced libraries and existing code bases to use for ourselves. Additionally, because the Arduino IDE is a C/C++ variant language we created pseudocode utilizing C/C++ syntax to allow for easier conversion into actual functioning code. Knowing this, we were able to create pseudocode for our microcontroller to use as a guideline for functionality when coding the microcontroller later in Senior Design 2.

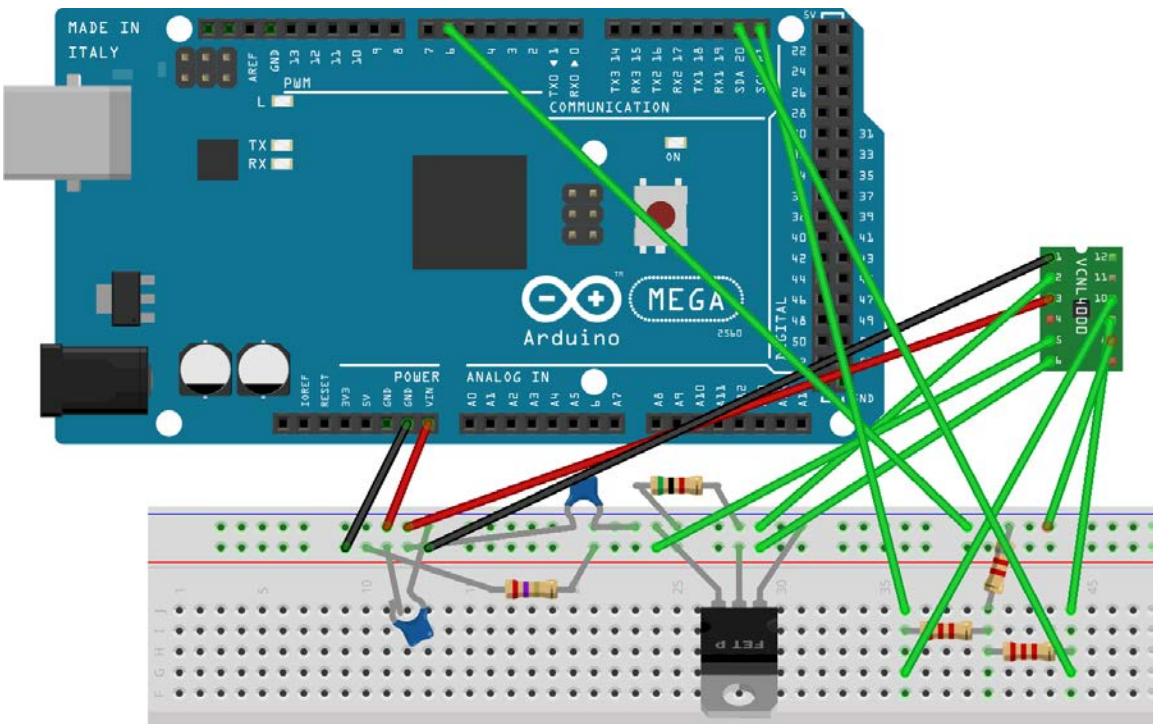


Fig. 44. Arduino Mega 2560 connection to VCNL4200 IR sensor

The pseudocode allowed for an easy to read and understandable explanation of what the code does, which was written in very high-level C/C++ style language, and could be utilized between to stay on the same path during code design and layout of the code.

5.4.5.1 LCD Display Control

```
#include "LiquidCrystal.h"

// initialize lcd library
LiquidCrystal lcd(pin #'s on the MCU that are connected to the display);

void setup()
```

```
{
        // state what size of use the lcd has access to e.g.: 40x4 character lcd display
        lcd.begin(40, 4);
        // (0,0) is the start of the first line of the display
        lcd.setCursor(starting position to begin printing to);
        lcd.print("Print some text to the screen at the cursor position");
        lcd.setCursor(0,1); // go to the next line
        lcd.print("more stuff printed on second line");
}

void loop(){}
```

5.4.5.2 LED Control

For LEDs we purchased Adafruit NeoPixel Digital RGBW LED Strips; therefore, we were able to utilize the manufacturer's library: the Adafruit_NeoPixel library for Arduino. The following pseudocode is very general and the function names and variables are subject to change, but the overall syntax should fit the form of the code.

```
#include <Adafruit_NeoPixel.h>

#define PIN # and other global variables (hardware connections)

// create/declare LED object calling Adafruit_NeoPixel constructor
// can have multiple strip objects connected to different pins
Adafruit_NeoPixel strip = Adafruit_NeoPixel(# of LEDs, Pin #, NEO_RGBW);
Adafruit_NeoPixel strip2 = Adafruit_NeoPixel(# of LEDs, diff Pin #, NEO_RGBW);

// initialize LEDs
void setup()
{
        strip.begin();
        strip.show();

        // set brightness (0 (off) to 255 (max))
        strip.setBrightness(54);

}

// creating a pattern of colors to certain LEDs stored in a function
void setPattern(Adafruit_NeoPixel strip)
{
        for(number of LEDs we want to change to this color)
        {
                strip.setPixelColor(number of LEDs to iterate through, color);
        }
```

```
	for(number of LEDs we want to change to a different color)
	{
		strip.setPixelColor(number of LEDs to iterate through, color);
	}
	…
}

// change a pattern (used with some conditional trigger)
void changePattern(Adafruit_NeoPixel strip)
{
	for(the strip.numPixels() on the LED passed in)
	{
		// do stuff
		strip.setPixelColor(# of LED to iterate, color);
	}
}

void loop()
{
	// set pixel color on LED, where n is the pixel # (0-60), rgb color code
	strip.setPixelColor(n, red, green, blue, white);

	// store rgb color code in a variable
	uint32_t magenta = strip.color(255, 0, 255);
	uint32_t color = strip.color(50, 0, 50);

	// set pixel color using a stored color variable (magenta)
	strip.setPixelColor(n, magenta);

	// update the LED object, will start to change colors after
	strip.show();
	strip2.show();

	// some conditional to change colors once on a certain color
	if(color == strip.getPixelColor(pixel number))
	{
		changePattern(strip); // do stuff
	}

	setPattern(strip2);
	…
}
```

5.4.5.3 Sensor Control

For sensors we bought two variants, a sound sensor (Sparkfun Sound Detector) and an infrared sensor (VCNL4200), so the pseudocode was marked between the two since we may or may not have used one or the other.

// **Sound Sensor**

```
#define pin input (gate connection)
#define analog pin input (envelope connection)
#define interrupt request pin (IRQ pin)
#define pin for LEDs

// interrupt service routine function for pin change interrupt
void soundISR()
{
	int pin_value;
	// query state of the pin and activate connected LEDs according to that state
	pin_value = digitalRead(pin input);
	digitalWrite(pin for LEDs, pin_value);
}
// initialize pin connection to the interrupt service routine
void setup()
{
	pinMode(pin for LEDs, OUTPUT);
	pinMode(pin input, INPUT);
	attachInterrupt(IRQ pin, soundISR, CHANGE);
}
void loop()
{
	int sensor_value;

	// read the value from the analog pin converting an input voltage from 0 to 5V
	// into an integer value between 0 and 1023
	sensor_value = analogRead(analog pin input);

	// conditional sound value (or range) to trigger different things
	if(sensor_value > 10) && (sensor_value <= 50)
	{
		// do stuff
	}
	else if(sensor_value > 50)
	{
		// do stuff
	}
```

```
        // pause for a certain amount of time 1000ms = 1 second
        delay(how long to wait);
}
```

// **IR Sensor**; I2C/TWI Pins for ATmega2560 is pin 20 (SDA), 21 (SCL)

```
#include <Wire.h>

// Device address for the IR sensor from datasheet
int VCNLAddress = 0x51
int value_in;

// initialize wire library
void setup()
{
        Wire.begin();
}
void loop()
{
        // begin transmission to IR sensor to receive data from sensor
        Wire.beginTransmission(VCNLAddress);
        Wire.write(get data from a certain register);
        Wire.endTransmission();

        // request the transmitted byte(s) and read the data from the register
        Wire.requestFrom(VCNLAddress, number of bytes requested);
        value_in = Wire.read();

        if(value_in is some condition met)
        {
                // do stuff
        }
}
```

6. PCB Design, Integration, and System Testing

6.1 Materials

All the equipment we received for our project is shown Fig. 45. We have received our infrared sensors, our LEDs, LCD screens, 3-volt regulators, MOSFETs, USB charger, and ATMEGA 2560 microcontroller chips. We are still missing our development board, sound sensors, and oscillator crystal. Given the nature of our project, i.e. it is large, multidisciplinary, and involves a lot of time to decide on aspects of the project and communicate those decisions, we did not order our parts as soon as we would have liked. This is the explanation for why some pieces are missing.

TABLE XXIII
AN OVERVIEW OF THE MATERIALS FOR THE PROJECT

Part	**BOM part number**	**Status**	**Tested**	**Fig. 45. labels**
LED lights	01	Received	Incomplete	e
Infrared sensors	02	Received	Incomplete	d
Microcontroller development board	03	Not received	Not tested	N/A
Crystal oscillators	04	Not received	Not tested	N/A
Sound detector	05	Not received	Not tested	N/A
Voltage regulators	06	Received	Not tested	c
LCD screen	07	Received	Incomplete	a
USB charger and cable	08	Received	Tested	f
MOSFETS	10	Received	Not tested	b
Microcontroller chips	11	Received	Not tested	g

6.2 System Testing

Due to pieces being missing for our project at the time of writing, we were unable to perform a full system test. In this section we discuss some of the steps we would have taken to test the functionality of the system.

6.2.1 Arduino Mega 2560 (Dev Board) & Software Testing

The Arduino Mega 2560 development board is substantial for the project and is required for many components to test. It is used to test the software code before rolling it out onto the finalized PCB and will be used to burn the bootloader on our ATmega2560 chipset to allow it to be programmed and upload code from the Arduino Integrated Development Environment (IDE). Unfortunately, the Arduino Mega 2560 has not arrived yet and we are unable to breadboard test some components such as LEDs and sensors. However, we will explain how we plan to test and use the Arduino Mega 2560 to test multiple components on the breadboard.

Fig. 45. The parts we ordered to build the prototype for our project, (a) the LCD screens, (b) the MOSFETS, (c) the voltage regulators, (d) the infrared sensors, (e) the LEDs, (f) the USB charger, and (g) the microcontroller processor chips.

Normally, we can test components such as LEDs by supplying the required forward voltage and adjust the current to affect the brightness since LEDs are current-driven devices. However, our LED strips we've chosen are the Adafruit NeoPixel RGBW LED strips; the reason behind this is because the controller chip is inside the LED which means that the chip only uses a single pin for input and a single pin for output. The protocol used is very timing-specific and can only be controlled by microcontrollers with highly repeatable 100nS timing precision. To control these LEDs the Arduino Mega is satisfactory to test if our LEDs are functioning and to test our LED control code.

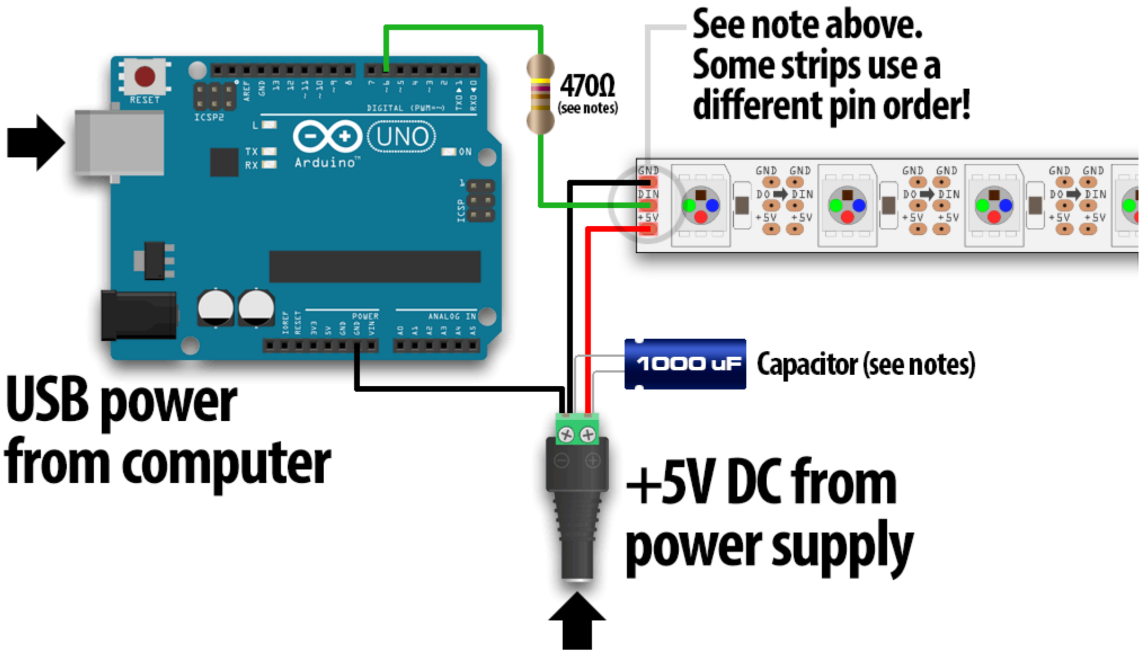


Fig. 46. Arduino connection with Adafruit NeoPixel RGBW LED strips

License/copyright: Phillip Burgess [45]

The Adafruit NeoPixel LED strips will only function when connected to a microcontroller from its DIN (data input) pin to any of the digital I/O pins on the Arduino Mega 2560. Therefore, the LED strips will not function without a data input from a microcontroller. Between the Arduino Mega 2560 and the sensor we connect GND to GND and DIN to any digital I/O pin (in this scenario we connected to pin 6) in series with a 470 ohm resistor (connected on the LED connection side) to protect the first LEDs pixel from damage and power supply (5v) to Vcc in parallel with a 1000µF capacitor to buffer sudden changes in voltage when dealing with a large power supply to protect from damaging the LEDs. After the connections are made we can test sketches uploaded to the Arduino Mega and test if our code works. The software test will test if the LEDs will turn on in certain patterns and colors and see if it can loop a pattern utilizing delays. Experience from the software testing will help shape the code by modifying colors, patterns, and brightness levels in the program.

For sensors we purchased such as the IR sensor, VCNL4200, and our sound sensor, Sparkfun Sound Detector also can be tested for functionality and used to test software code that utilize sensors. Both sensors functionality will be tested using the development board in tangent with the software code tests. The reason behind this is to actually visually tell if the sensors are working properly is if we can actually get a reading off the proximity sensor proccing or the sound sensor's analog output is truly registered and communicated to the microcontroller with a value that can be compared for conditional functions.

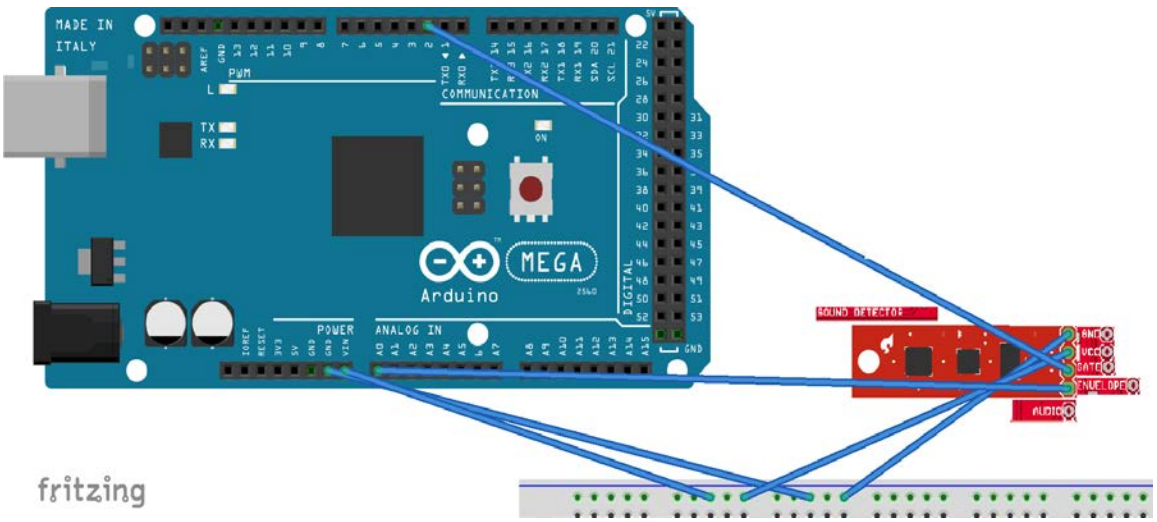


Fig. 47. Arduino Mega 2560 test connection with Sparkfun Sound Detector

To connect the sound sensor to the Arduino Mega we connect the sensor's pins GND to GND (power supply), VCC to VCC (Power supply b/w 3.3v to 5.5v), GATE to any digital I/O pin (in this scenario we used pin 2), and ENVELOPE to any PMW analog pin on the Arduino (in this scenario we used pin A0). After connecting the sensor to the Arduino we can then test software code that utilizes the sound sensor. When the sound sensor will hear a noise at a certain pitch/frequency it will output a voltage to the analog pin on the Arduino which will in turn read the signal and convert it to a readable form of an integer between values of 0 to 1023 which represents a ratio of voltage that we can calculate from. By testing we can figure out what sensitivity the sensor is approximately and the rough value output from various noise levels (low to high noise) and change the condition values for the sensor to proc scenarios we planned out.

To software test the IR sensor requires a connection utilizing the I2C ports on the Arduino Mega 2560 which are ports SDA and SCL to the proximity sensor. In general, to test if the software works is when the infrared beam is broken the interrupt pin should be signaled from the sensor to the Arduino which can then be defined in the program and used as a conditional trigger for other code such as changing LED colors or patterns.

6.3 Printed Circuit Board (PCB)

6.3.1 What is a PCB

A Printed Circuit Board is a thin sheet of metal that, as the name entails, can be printed to meet the needs of a certain circuit. A schematic is first made from a software program that is used to wire a design of a PCB. Different design ideas will use different wiring with overall different elements. Once the PCB design is done and all the wiring is set the PCB is then printed so that the electric components of the circuit can be soldered onto the board. In the present day, almost anything that has some form of electricity or electronic component will have a printed circuit board in place. The PCB will control the design and interconnect all the electronic components.
The schematic software that the OUC group used to design and wire the PCBs was Autodesk Eagle.

6.3.2 Types of Printed Circuit Boards

There are various types of PCBs on the market to use depending on the need of the consumer. The following is a list of the most commonly used PCBs. [8]

- Single Sided PCBs – Single Sided PCBs include just one layer of the base material. They are used on simple electronic devices that do not have too much complexity in the circuit. This type of PCB is the cheapest PCB in the market but it is also one of the least used types of PCBs due to their design limitations.

- Double Sided PCBs – Double Sided PCBs are more widely used than the Single Sided PCBs. With holes in the PCB, they allow the ability to connect one PCB to the other side of another PCB. There are two methods to mounting the PCBs onto each other:
    - Through-hole technology
    - Surface mount technology

- Multilayer PCBs – Multilayer PCBs give extra layers to the designer to make the circuit more complex. “With the accessibility of over many layers in multilayer printed circuit board configurations, multilayer PCBs let designers to make very thick and highly compound designs. [8]” Multilayer PCBs are mainly used for Aerospace needs.

- Rigid PCBs – Rigid PCBs are designed to not allow any movement in the PCB itself. They are made from rigid materials like fiberglass to restrict movement. They are mainly used in large sized equipment that have no need for movement in the system.

- Flex PCBs – Flex PCBs are made to fit into spaces where a normal PCB cannot. They are made from flexible materials and for this reason are generally more expensive than regular PCBs. The advantage of allowing them to be placed in tight spots makes them ideal for space restricted situations such as satellite instillations. They also have three forms:

- Single Sided
- Double Sided
- Multilayer

- Rigid- Flex PCBs – Rigid- Flex PCBs, like the name says, combine the technologies of the Rigid and the Flex PCBs. "The two-in-one circuit is interconnected through plated thru holes. Rigid flex circuits provide higher component density and better quality control. Designs are rigid where extra support is needed and flexible around corners and areas requiring extra space. [26]" These PCBs are the most expensive of the six types.

For the OUC project, single sided and double-sided PCBs were looked at and compared.

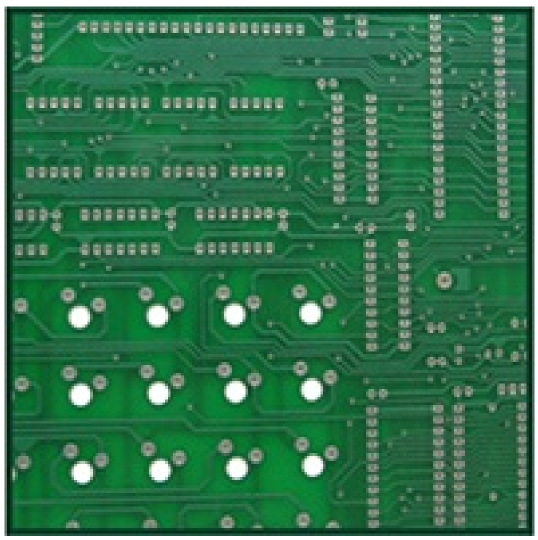


Fig. 48. Printed Circuit Board

3.6.2.1 PCB Dimensions for Single and Double Sided

The PCB was to be placed inside an electrical box that would be accessible at the base of the structure. For our design we could have implemented either a single sided or double sided circuit board. The dimensions for both of them are the essentially the same the only difference is that a double sided PCB is one single sided PCB on top of another. The dimensions for a standard PCB are the following:

- Length(mm): 51-508
- Width(mm): 51-457
- Thickness(mm): 1-4.5
- Assembled Weight(kg): ≤ 2.72
- Bevel(mm): ≥ 3d (120 mil)

- Assembled Weight: ≤ 5 kg
- Primary Side Components/ Solder Joint Clearance Area (mm): 5

3.6.2.2 Single Sided PCB Advantages and Implementation

As mentioned before, a single sided PCB is the lowest cost and most basic type of PCB. Due to their design restrictions, they are rarely used compared to the double-sided PCBs. Even though they have restrictions they have some benefits compared to the double-sided PCB. Some benefits include: [29]

- Ideal for simple low-density designs
- Lower cost, especially for high volume orders
- Lower probability of manufacturing issues
- Popular, common, and easily understood by most PCB manufacturers

Some devices that single sided PCBs are implemented in are: [29]

- Power Supplies
- Relays (automotive and industrial)
- Timing circuits
- Sensor products
- LED lighting
- Radio and Stereo equipment
- Packaging equipment
- Surveillance
- Calculators
- Printers
- Coffee makers
- Vending machines
- Solid state drives
- Camera systems

3.6.2.3 Double Sided PCB Advantages and Implementation

Double sided PCBs are used in systems with more complexity and advanced electric components than those of the single sided PCBs. They allow more intricate designs to be realized. The following are some of the advantages of using a double-sided PCB: [10]

- More flexibility for designers
- Increased circuit density
- Relatively lower costs
- Intermediate level of circuit complexity
- Reduced board size

Some devices that double- sided PCBs are implemented in are: [10]

- Industrial Controls
- Power Supplies

- Converters
- Control relays
- UPS systems
- Power conversion
- HVAC
- LED lighting
- Hard drives
- Power monitoring
- Automotive dashboards
- Line reactors
- Test equipment
- Traffic systems
- Vending machines

Once all the elements and design constraints were known, the OUC group decided on which type of PCB the schematic would be made.

6.3.3 PCB Implementation in Circuit

The OUC group worked with different mechanical and art students to get the best designs with the best electronic implementations based on how interactive the solar structure was. The design idea that was implemented across most of the art and mechanical teams was the use of sensors and LED lighting. This circuit design made the PCB consider the power distribution to these elements along with the power distribution to the MCU.

6.3.4 PCB Design

Once all the elements and design constraints were known, the OUC group began creating the design for the PCB schematic.

6.4 PCB Layout and Design

6.4.1 Overall Circuit

In Senior Design 2 we finalized our PCB board design, which can be seen in Fig. 49. Fig. 50 also shows the final schematic design. We used an external current sensor PCB, sound detector PCB, and inverter for the solar panel. Everything else was incorporated on the main PCB.

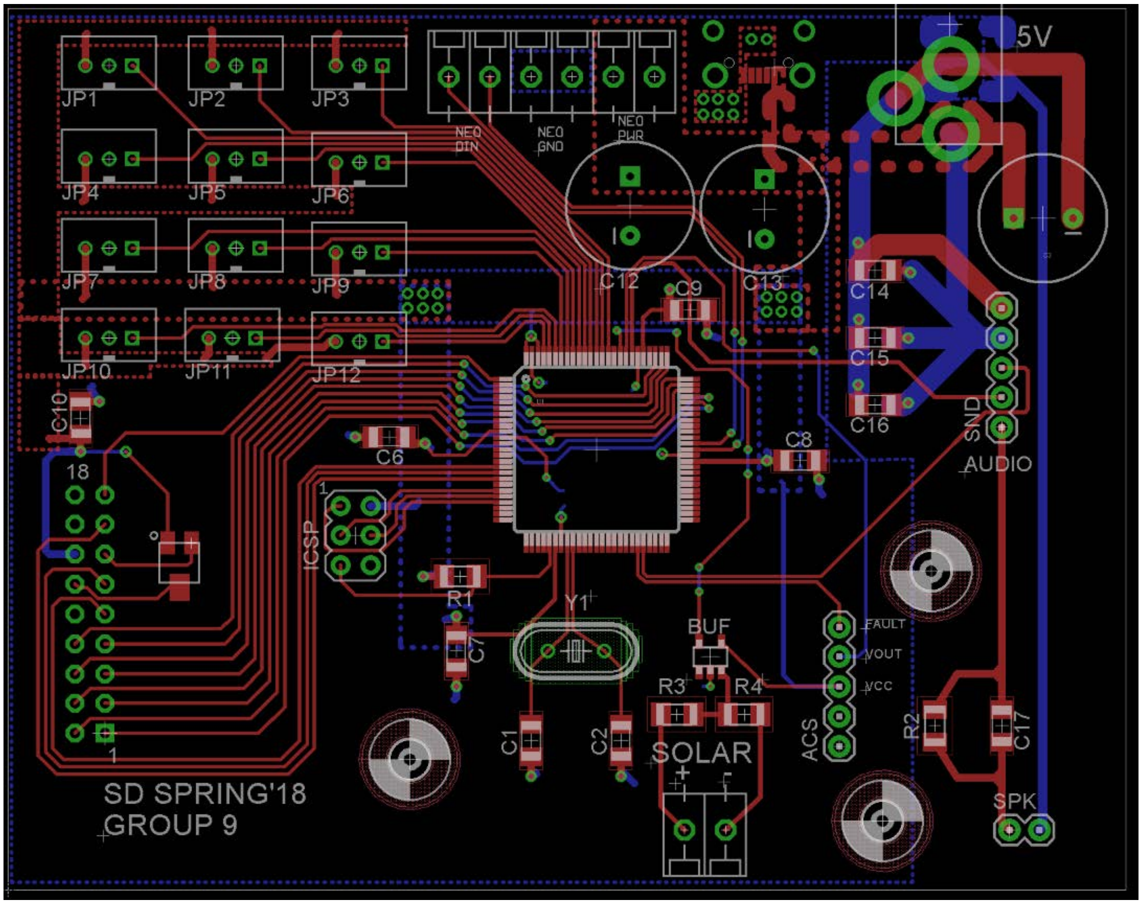


Fig. 49. The final PCB board design. It is a two-layer board that handles all the communications of our system components.

For this design, we used various components to be able to achieve everything we needed. All these components were either place on and soldered to the printed circuit board or were connected to the pins on the board or the pins on the ATmega to work. These connections were made via wiring. To get the correct printed board to send to the manufacturer we had to make a software-based circuit board, make all the connections, and have a circuit board on the software. As stated before in this document the software used was the EAGLECAD software for designing circuit boards.

The concept of designing and sending out a freshly made circuit board to test with all the components was something brand new for the OUC group. The first part of the design was trying to get the correct library for the parts and being able to download and design on the software. For some of the components, the libraries could not be found online so we had to create our own symbols and place the parts precisely with the exact dimensions. These dimensions are usually specified somewhere on that components data sheets and it was up to us to correctly transfer these dimensions and convert them into the component. If were not able to get the correct dimensions on the software we would not have been able to test the components on the board because they would not have fit. For that reason, this step was crucial to having a good printed circuit board.

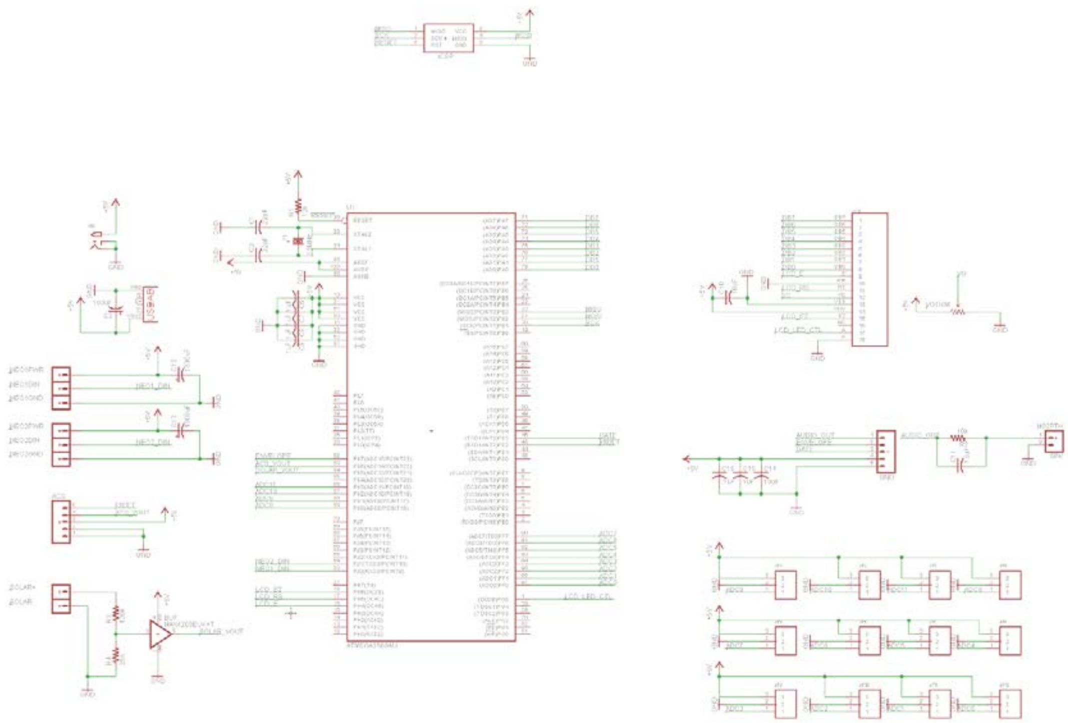


Fig. 50. The final schematic of our system. All the individual connections can be seen and which MCU pin they connect to.

The OUC group first started the design of our circuit and all its components designing them one by one. We would be able to individually design everything without having too much cluster on one design sheet. This was a promising idea but because we are all novice circuit board designers we decided that even though it would be cleaner to have them all done separately, for the sake of time and having all the correct connections we decided to build the circuit board circuit on one project sheet in EAGLE. There were some components that already had the schematic and circuit board provided for us. These components were not added to the Senior Design 1 schematic but were added to the Senior Design 2 schematic. Each was a simple connection that was connected to either the power supply going on the circuit board or to the ATmega microcontroller that we had mounted on the board, or they could have been connected to both.
The following sections show the schematic and circuit boards for the components that we used in our circuit.

6.4.2 LEDs

The PCB design in Fig. 51 shows the connections that were placed with the Arduino ATmega for the OUC projects. This design was more than likely to change as we began Senior Design 2 and as we got a better understating of how the connections in EAGLECAD worked. All the components would be powered individually so none of them would need to be dependent on the Arduino supply voltage. The infrared sensor and the LCD symbols had to be made manually due to the component not having any libraries from the manufacturing company or other library websites.

Provided by Adafruit, Fig. 52 is the schematic design of the LEDs and how they are powered and would be placed on the circuit board. We had not done the schematic because we needed to do more testing to see what the best setup was to have all the lights light up without having any dim ones at the middle or at the end of the LED strip. This testing would have taken place in Senior Design 2.

6.4.3 LMV 324 Sound Sensor

The 324 Sound Sensor is the sound sensor that we would be using for our project. The sound sensor was connected to the 5V rail provided on the original circuit board and was connected to the I/O pins on the ATmega.

The schematic was reviewed throughout the second semester of the senior design project and was updated accordingly. The circuit board was printed and tested to make sure all the needed components had the correct connections and were able to work.

6.4.4 Regulator Design

The PCB design for the regulator is shown in Fig. 54. It uses 0.1uF capacitors on both sides of the input and output pins.

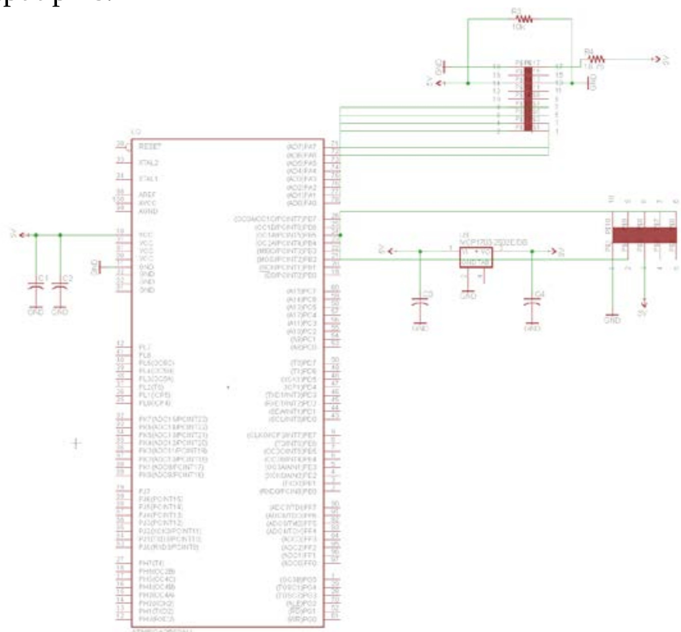


Fig. 51. Overall Circuit

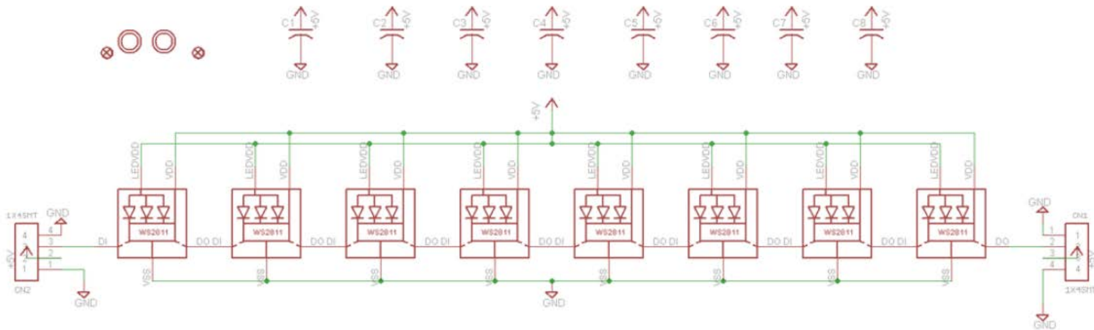


Fig. 52. LED Configuration

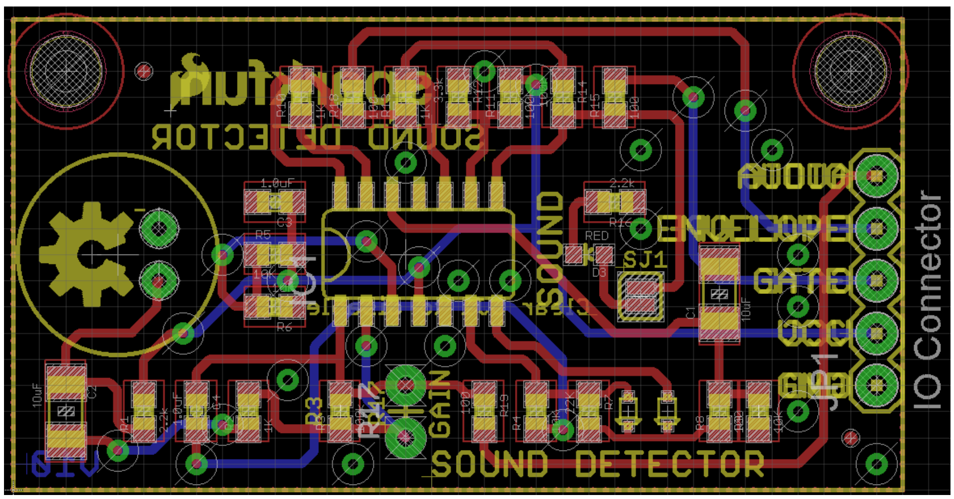


Fig. 53. LMV324 Sound Sensor Board

These bypass capacitors will protect the regulator and stabilize it and get rid of the noise of the voltage going out. The output voltage is now regulated to 3V for the sensor component. The component can be found in the MCP1703 library.

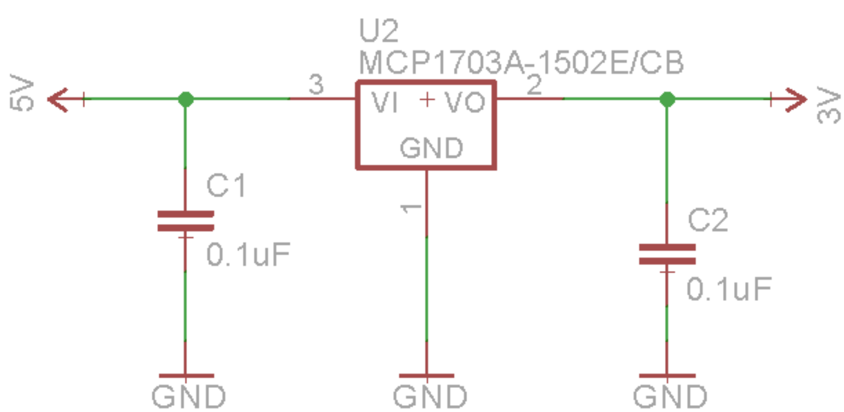
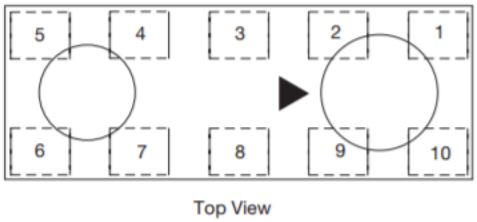


Fig. 54. Regulator Circuit for PCB

6.4.5 Infrared Sensor Design

The pinout in Fig. 55 shows the pinout of the VCNL sensor. The VDD would be powered by the 3V output from the voltage regulator. The sensor pin INT, the sensor pin SDAT and the sensor pin SCLK would be connected to the ITC port to send the relay that it's been triggered.



1	GND	6	LED+
2	LED_CATHODE	7	NC
3	V_{DD}	8	INT
4	NC	9	SDAT
5	LED-	10	SCLK

Fig. 55. Infrared Sensor pin for PCB

7. Administration

7.1 Schedule

To keep us from missing deadlines and to make sure we completed all the tasks we wished to accomplish this semester, we created a Gannt chart. The Gannt chart in Fig. 56 helped us stay informed of where we were in our project, and whether we were keeping on top of things or starting to fall behind and needing to redouble our efforts to get back on schedule. The Gannt chart listed the major pieces of the project and ordered them such that the tasks that needed to be done to complete another task were given a higher priority. The Gannt chart started a little after the beginning of the semester because there was a period where our group was not yet formed and thus we were not working together until the first week listed in the chart. Fig. 57 is our Gannt chart for Senior Design 2.

The Gannt chart was also a useful tool to convey a large amount of information about the project in a compact form. By looking at an updated Gannt chart, one could see how much of the project was finished, when things were projected to be done, what things would be done, if there had been any slippage, or if there would be any slippage. This tool was not only useful for the team to keep up to date on where the project stood, but also for the project sponsor to see if things were on schedule or if some sort of intervention may have been required to restore the project to an acceptable schedule.

7.2 Bill of Materials/Budget

Table 24 is the updated bill of materials.

For replication purposes, the materials we used in this project were well documented. To that end, we have created a bill of materials. This bill of materials (BOM) can be seen in Table 25. The BOM attempted to give some structure to keeping track of all the pieces we used to build our system. The BOM contains enough information on all the materials we used in our system to replicate it. It also gives information on what part of the system each piece of equipment was used in. This system is defined by us using Arena Solution as a guide [46], and the explanation of each non-obvious field follows this paragraph.

BOM level is designed to create a relationship between parts. Those that are part of a related portion of the system have the same BOM number. Part number is a unique number we assign to each part. We are using a non-intelligent, simple sequential numbering system as we did not have enough parts to justify an intelligent numbering system. The phase column tells whether the part is a part that is already in production or if it is a pre-production part. All our parts are in production parts as (1) we required parts with known reliability for our system and (2) we did not require any highly specialized parts. Procurement type conveys whether the unit is an off-the-shelf product, or it was made specially for us. All our parts are off the shelf for the same reasons that all our parts are in production.

TABLE XXIV
UPDATED BILL OF MATERIALS FOR FINAL PROTOTYPE

BOM level	Part number	Part name	Phase	Description	Amount	Cost (total)	Units	Procurement type
1	01	Adafuit neopixel digital RGBW LED strip	In production	The strip of LED lights used on the prototype	2	$53.90	Meters	Off-the-shelf
2	02	Sharp GP2Y0A41 SK0F	In production	Optical Proximity sensor	7	$97.65	Each	Off-the-shelf
3	03	Arduino Mega 2560 R3	In production	The MCU board for program	1	$45.95	Each	Off-the-shelf
3	04	Crystal 16Mhz	In production	The crystal to provide the clock input to the MCU	1	$0.95	Each	Off-the-shelf
2	05	Sparkfun sound detector	In production	The sensor used to detect ambient sound levels	1	$10.95	Each	Off-the-shelf
2	06	MCP1703T -1502E/DB	In production	Voltage regulator to step 5V down to 3V	1	$1.62	Each	Off-the-shelf
1	07	40x4 Parallel Character LCD	In production	A 40-character 4-line screen to output messages	1	$11.52	Each	Off-the-shelf
3	08	Adafruit Switching Power Supply 5 V, 10 A	In production	A charger with a DC output to supply 5 V, 10 A	1	$25.00	Each	Off-the-shelf
3	09	Pololu ACS711EX Current Sensor	In production	A current sensor with a range of -15.5 to +15.5 A	1	$3.95	Each	Off-the-shelf
2	10	Vishay SI2301BD S-T1-GE3	In production	An N-channel MOSFET to control current flow	1	$0.54	Each	Off-the-shelf
3	11	556-ATMEGA2 560-16AU	In production	The MCU used to transcribe data from sensors to LEDs	1	$12.20	Each	Off-the-shelf

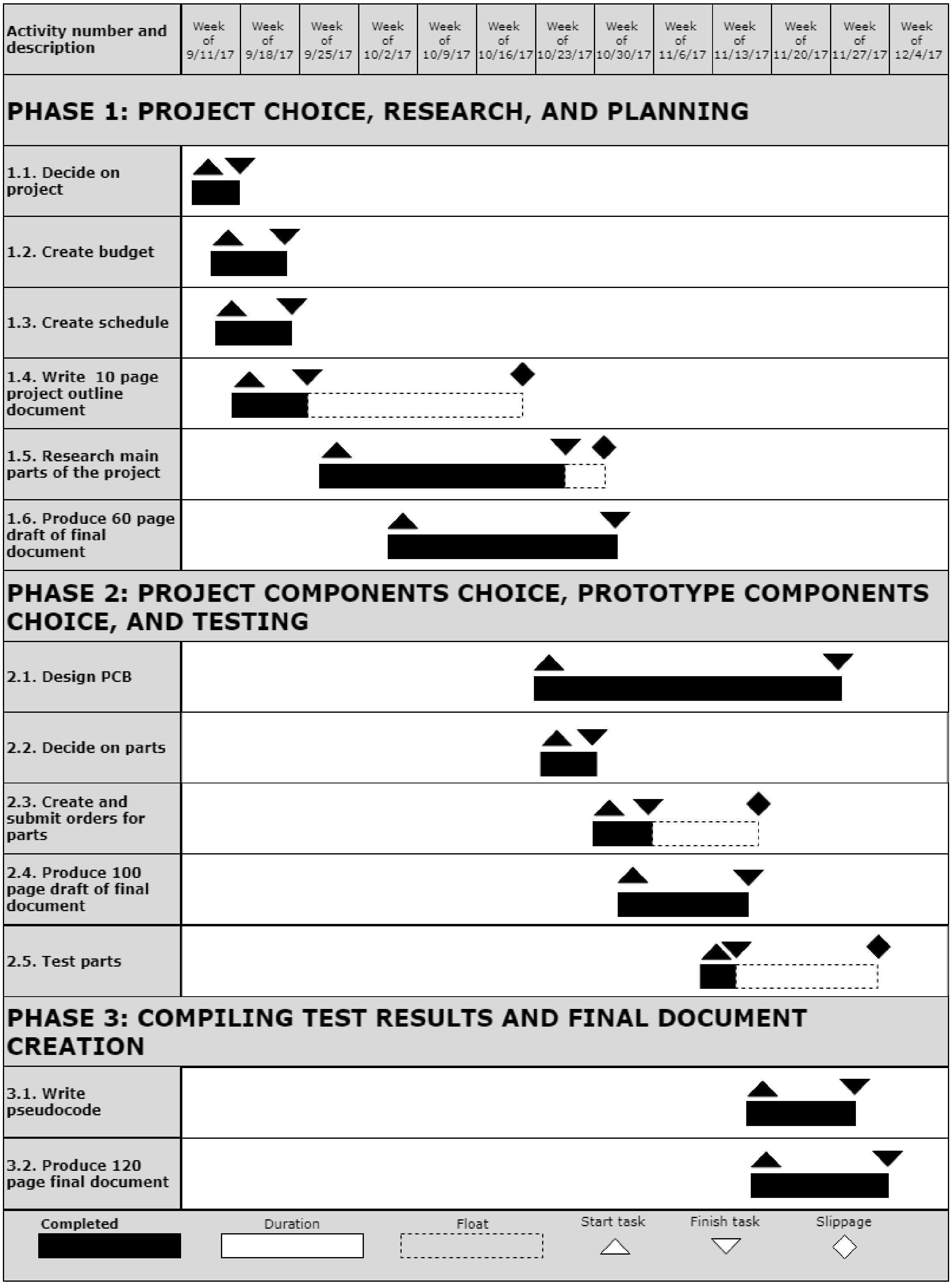


Fig. 56. A Gannt chart detailing our schedule for each piece of the Senior Design 1 portion of the project. Actual and estimated times are shown.

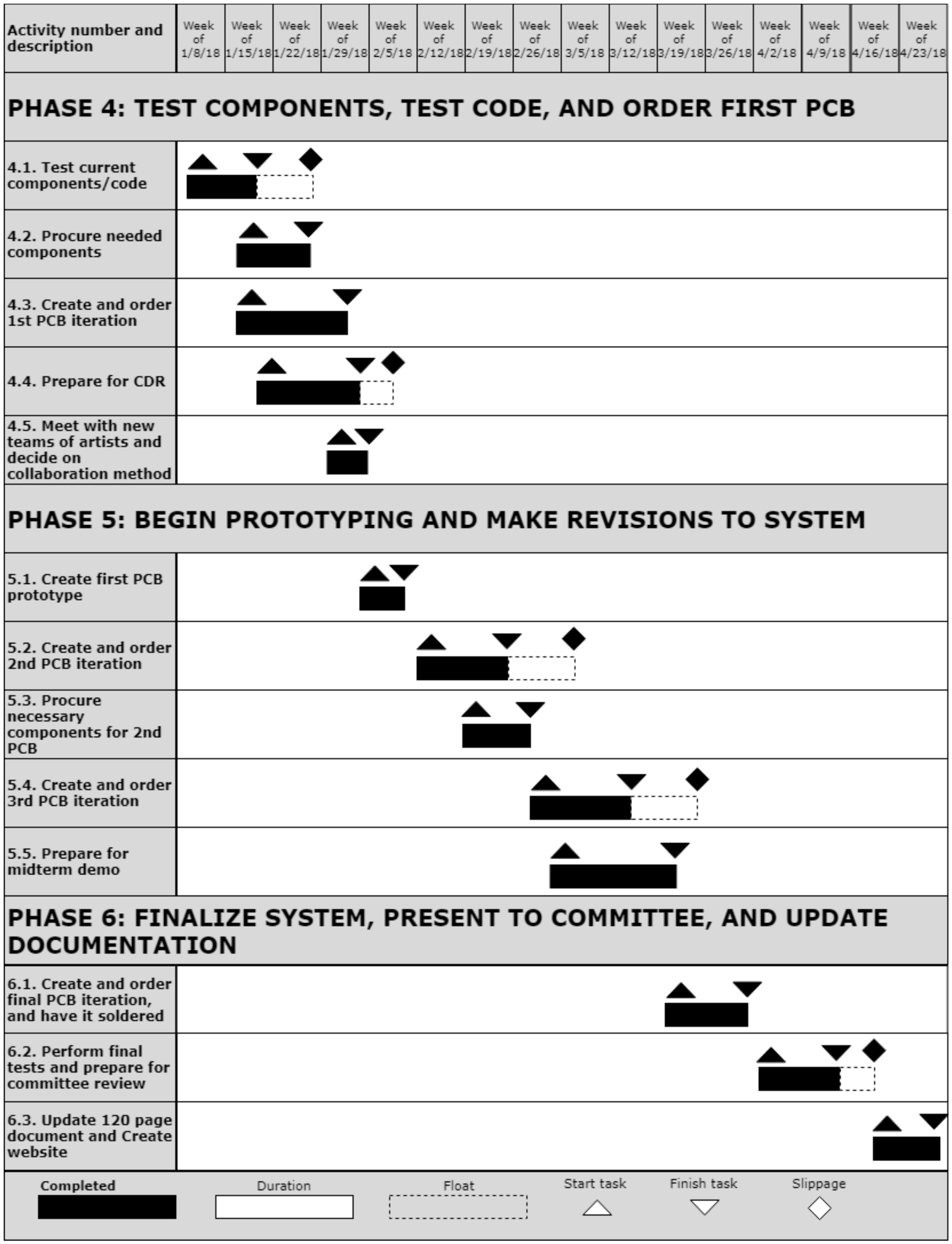


Fig. 57. Senior Design 2 Gannt chart. This chart details our schedule to realize our final prototype and meet Senior Design 2

TABLE XXIV
BILL OF MATERIALS FOR PROJECT PROTOTYPE W/ COSTS

BOM level	**Part number**	**Part name**	**Phase**	**Description**	**Amount**	**Cost (total)**	**Units**	**Procurement type**
1	01	Adafuit neopixel digital RGBW LED strip	In production	The strip of LED lights used on the prototype	2	$53.90	Meters	Off-the-shelf
2	02	Vishay VCNL4200	In production	Optical Proximity sensor	12	$35.40	Each	Off-the-shelf
3	03	Arduino Mega 2560 R3	In production	The MCU board for program	1	$45.95	Each	Off-the-shelf
3	04	Crystal 16Mhz	In production	The crystal to provide the clock input to the MCU	3	$2.85	Each	Off-the-shelf
2	05	Sparkfun sound detector	In production	The sensor used to detect ambient sound levels	1	$10.95	Each	Off-the-shelf
2	06	MCP1703T-1502E/DB	In production	Voltage regulator to step 5V down to 3V	1	$1.62	Each	Off-the-shelf
1	07	40x4 Parallel Character LCD	In production	A 40-character 4-line screen to output messages	2	$23.04	Each	Off-the-shelf
3	08	Quick charge 3.0 18W USB wall charger	In production	A charger with a USB output to supply 5 V, 2 A	1	$7.99	Each	Off-the-shelf
3	09	5-foot USB C cable	In production	A USB A to USB C cable to connect the wall charger to the MCU	1	Free with piece 08	Each	Off-the-shelf
2	10	Vishay SI2301BDS-T1-GE3	In production	An N-channel MOSFET to control current flow	5	$2.70	Each	Off-the-shelf
3	11	556-ATMEGA2560-16AU	In production	The MCU used to transcribe data from sensors to LEDs	3	$36.60	Each	Off-the-shelf

8. Conclusion

Whether at private residences or in public, most people only see solar panels as an ill-fitting addition to the structures they're placed on or public spaces they're placed in. The purpose of this project was to show people that this combination need not be an ugly amalgam, but rather a beautiful solution. For our part in this project, we conceived of a system that provided the art students means to transform the sculpture through lighting and interactivity with the public, as well as produce green energy.

Through our research and testing, we confirmed that we could deliver a system that can sense when there are people within 1.5 meters or the sculpture and can detect a wide range of sound levels. These inputs, coupled with the microcontroller, our code, and the individually addressable RGBW LEDs, can be used to create almost any lighting pattern imaginable. This gave the art students maximum range when creating their concepts. Due to the sensors, the sculpture would also be able to respond to its environment, which gave the artists an opportunity to make their art dynamic.

Our system was able to give the artists tools to make the sculpture as aesthetically pleasing as possible, but our system had to produce the prescribed amount of energy (850 kW/year) too. Our research led us to conclude that two very large commercial monocrystalline panels would produce the necessary energy, or three standard commercial size panels could also be used. The final panel selection was dependent upon the final sculpture design. We concluded though, that microinverters were the best choice for our system. The electricity coming from the microinverters will be conditioned to match the electricity in the grid and will be fed into the grid by OUC.

Related to the power system is our public information system. To enhance public understanding of the value of these solar sculptures, we decided that an LCD screen that is readable even in strong sunlight was an appropriate choice. The LCD screen would allow us to output any message to the public such as beneficial facts about solar power, how much energy the sculpture is providing at that moment, how much money that energy production translates to, etc.

At the heart of our system is the PCB that we made a preliminary design of. This provided the necessary routing for all our components to communicate with each other and, going off anecdotes from other students, would likely require extensive simulation and testing before the final design was reached.

Looking ahead to Senior Design 2, we had to make up for ground that was lost in the first semester due to some confusion over the project requirements that led to a delay in ordering parts, and thus testing. To alleviate this, we worked between semesters to catch up. We learned a great deal the first semester about the volume of work necessary to design an electronic/electrical system, and we were driven by that knowledge in the next semester. We hoped to apply our collective knowledge to this project going forward, work hard as a team, produce a system we could be proud of, and help OUC achieve their goal, to "make Orlando sustainably beautiful."

In Senior Design 2 we made a total of four PCB iterations, changed IR sensor, created a PCB for our sound detector based on the Sparkfun open hardware design, added a current sensor, added a voltage divider circuit on our PCB, and discovered that the just-in-case, higher current power input on our PCB was necessary. Much of Senior Design 2 was spent adapting, improvising, and overcoming the slew of issues we faced getting our system to work as intended. We also tackled the challenge of providing three different art and mechanical engineering teams, with three different designs, systems that could execute their vision for the OUC Solar sculpture. All this combined with the relatively last minute change in the customer's vision for the sculpture.

We learned a lot on this project. The experience gained from working not only with different types of engineers, but people outside of the STEM field altogether, was invaluable. Learning to communicate efficiently and understand what is important to the artists took a little time but once we understood each other, we produced spectacular results. When our system was added to their sculptures, it brought them to life, as can be seen in Fig. 58. The result was enough to convince us that these types of collaborations are a very worthwhile endeavor. I think the attitude and skepticism that the engineers felt going into this project, and even early in the semester, was quashed by seeing where we ended up.

Fig. 58. Two of the $1/8^{th}$ scale models produced by the artists and mechanical engineers. Our system provides the lighting which gave the artists the ability to make them look spectacular.

The knowledge we gained from the process of designing a system, working with people outside our major, handling clients requests, addressing issues of real world implementation, understanding the NEC and UL listing, and pulling together as a team to complete a project has made us much better engineers than we were at the beginning of Senior Design 1. On top of that, we get to see a project we worked on actually be created and placed in public, for all to see. Few other Senior Design teams get to walk out of UCF and be able to say to employers that they worked on a real engineering project that is so well known. For that, we are glad we participated in the OUC Solar Sculpture project.

9. Operators Manual

As an addition to our document, we have added a manual to inform readers how to use the system we developed. The first step to using our system is to power it on. Simply plug in the 5 V, 10 A switching power supply from Adafruit and the system will begin running the code that is programmed into the ATMega 2560 on our PCB. The code for our system can be found in the GitHub repository in [54]. To upload the code to our system, the ICSP pins must be connected to an Arduino Mega 2560 as depicted in Fig. 59.

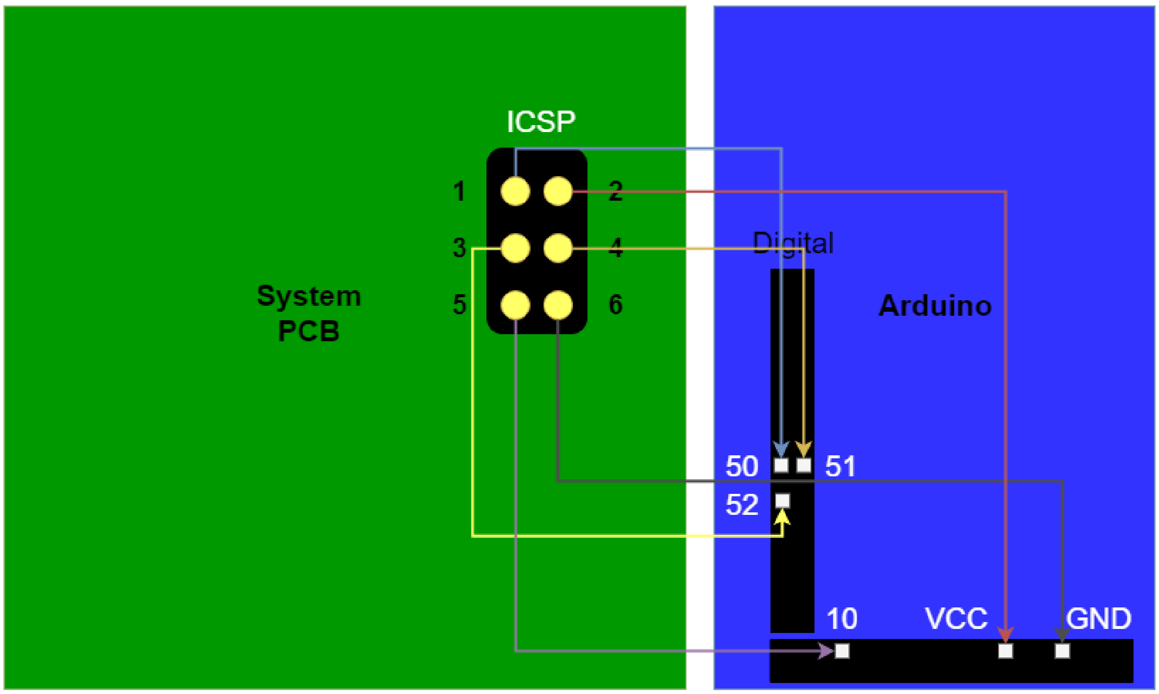


Fig. 59. Hookup guide for programming our system via the ICSP using an Arduino Mega 2560.

Once the ICSP is connected to the Arduino, make sure that the power is disconnected from the system, and that the power wires to the LEDs are also disconnected. Use the Arduino IDE to upload the "Solar_Sculpture_System.ino" file as ICSP. To upload as ICSP, just hold shift and click upload. When the IDE finishes uploading to the system, the ICSP can be disconnected from the Arduino.

All the peripherals may now be connected. The IR sensors are connected to the JST ports. The sound sensor is connected by wires from its male header pins to the female headers on the PCB, marked by the word "AUDIO". The names of the pins on the sound sensor are also written on the PCB for connection guidance. You may note a "SPEAKER" connection on the PCB and the sound detector, the sound detector can pass the sound from the microphone out to a speaker, however this function was not in our design, and so we don't connect it. The LCD is connected by pins according to the pinout guide in Fig. 60. The pins with the same number should be wired to each other. When the LCD is powered on, it may be necessary to adjust the potentiometer with a Philips head screwdriver to set the screen's contrast properly (see Fig. 60 for location).

Two 1-meter strips of LEDs may be connected to the board. The power, ground, and data terminals are marked on the PCB by the words "NEOPWR", "NEOGND", and "NEODIN". Strip one corresponds to ports 2, 4, and 6 for its power, ground and data, respectively. Strip two corresponds to ports 1, 3, and 5 for its power, ground, and data, respectively. This is important for reprogramming the LEDs as it is important to known which strip you are addressing when you program it. The current sensor needs to be hooked up to the solar panel and the PCB.

To connect the current sensor to the solar panel, a wire coming from the positive terminal of the solar panel needs to be crimped to a 0.24 in. ring terminal, then screwed onto the IP+ port. An additional wire needs to be crimped to a 0.24 in. ring terminal and screwed onto the IP- port of the sensor. It should then be connected to the positive terminal of the voltage divider. The male header pins on the current sensor need to be connected to the female headers on the PCB that are marked with the letters "ACS" and with the same names as the male header pins of the current sensor. The two ports with no names are the grounds. The voltage divider on the PCB simply requires that you place a wire coming from the IP- port of the current sensor to the screw terminal marked with a plus sign (+) underneath the word "SOLAR", and a wire from the negative terminal of the solar panel to the screw terminal marked with a negative sign (-), also underneath the word "SOLAR".

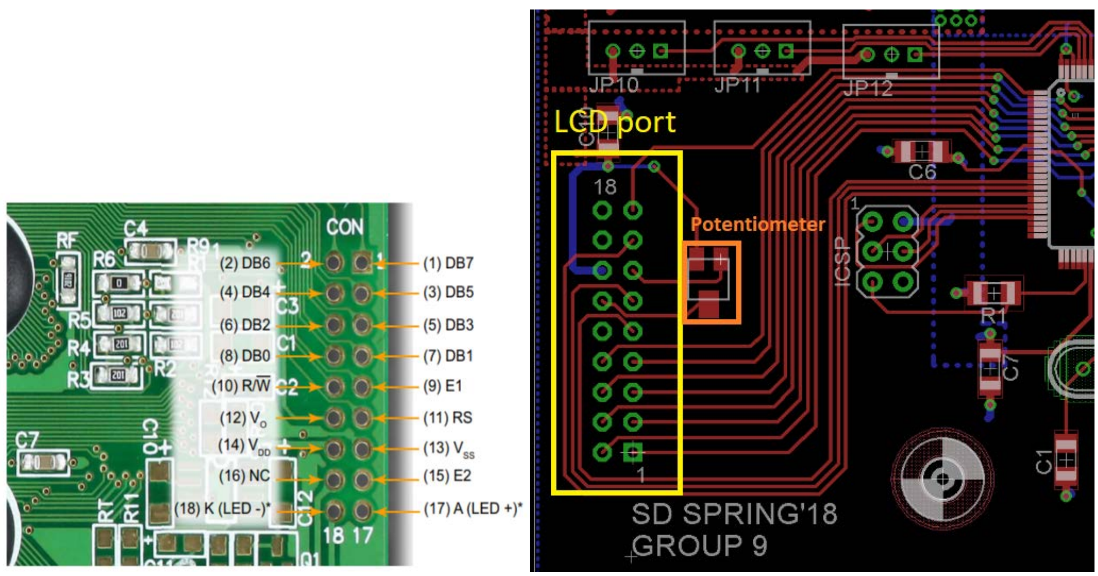


Fig. 60. The numbering of the LCD ports on the LCD (left) and the PCB (right). Pins are numbered 1-18 and right to left, top to bottom on the LCD, and right to left, bottom to top on the PCB.

Following the above guide, the system should be fully connected now. Simply plug the power into the DC jack port. The system is now ready to use. The seven IR sensors are linked to different LED patterns in memory. To trigger an IR sensor, simply come within 30 cm of it. If two or more sensors are triggered at once, the first one triggered takes priority, and the LED algorithms always complete before another begins. Additionally, the IR sensors only show their pattern on LED strip 1. The screen will also turn on for the length of the LED display when the IR sensors are triggered.

To trigger the sound sensor, make a loud noise. This will set off an LED pattern on strip 2 but it will not turn on the screen. As with triggering more than one IR sensor at a time, if the sound sensor is triggered before an IR sensor, the IR sensor will be blocked until the LED pattern on strip 2 finishes.

The current sensor and voltage divider are always reading the output of the solar panel. The code takes care of using the output of the voltage divider and current sensor to calculate the current watts being produced by the solar panel. This figure is displayed on the screen when the IR sensors are triggered along with the amount of money that the power produced so far would cost if taken from the grid.

If one wishes to change how the system functions, the Solar_Sculpture_System.ino file can be altered using the Arduino IDE. The code for the system has been well commented to guide a new user on where to make changes to alter things like LED patterns, colors, screen text, sound detector sensitivity, and IR sensor triggering range. The code for the system is written in C. When changes are made to the code, the system must be hooked up, via the ICSP port, to an Arduino Mega 2560 and reprogrammed as instructed above.

Some issues we have noted with our system are

- The JST ports that connect the IR sensors seem to be a little loose and cause the IR sensor to stop functioning.
- The LEDs we choose do not work well with interrupts.
- High current draw at the end of an LED pattern can trigger the sound sensor, so having the LEDs fade or turn off at the end of a pattern is recommended.

Appendix

A. References

[1] Panjwani, Manoj, and Ghous Narejo. “Effect of Humidity on the Efficiency of Solar Cell (Photovoltaic).” Pakistan, Pakistan, 2014.

[2] “4.5. Types of PV technology and recent innovations.” 4.5. Types of PV technology and recent innovations | EME 812: Utility Solar Power and Concentration, www.e-education.psu.edu/eme812/node/608.

[3] “Aladdin Solar, LLC.” *How Do Solar Panels Generate DC Electricity from Sunlight*, 2008, www.aladdinsolar.com/pvhowitworks.html.

[4] “Article Cat.” *Pulse Width Modulation Charge Controllers Explained*, 9 Aug. 2011, e-bluelight.com/article-345-Pulse Width Modulation Charge Controllers Explained.html.

[5] Chilcoat, Colin. “How much does the US spend on energy research? Not a lot.” *The Christian Science Monitor*, The Christian Science Monitor, 5 Mar. 2015, www.csmonitor.com/Environment/Energy-Voices/2015/0305/How-much-does-the-US-spend-on-energy-research-Not-a-lot.

[6] Chilton, Alexander. “The Working Principle and Key Applications of Infrared Sensors.” *AZoSensors.com*, 27 July 2017, www.azosensors.com/article.aspx?ArticleID=339.

[7] “Cree XLamp XHP35 LEDs.” 4600 Silicon Drive, Dulham, NC, 2015.

[8] Tarun Agarwal. “Different Types of Printed Circuit Boards.” *ElProCus - Electronic Projects for Engineering Students*, 19 Sept. 2016, www.elprocus.com/different-types-printed-circuit-boards/.

[9] “Does LED brightness change with voltage?” *Electrical Engineering Stack Exchange*, electronics.stackexchange.com/questions/256336/does-led-brightness-change-with-voltage.

[10] “Double Sided PCB.” *Amitron | U.S. PCB Manufacturer*, 16 Aug. 2016, www.amitroncorp.com/printed-circuit-boards/double-sided.html.

[11] “Everything you Need to Know About the Basics of Solar Charge Controllers.” *Northern Arizona Wind & Sun*, www.solar-electric.com/learning-center/batteries-and-charging/solar-charge-controller-basics.html.

[12] Fan, Zhiyong, and Qingfeng Lin. “Nanotechnology.” *Reducing reflection losses in solar cells | SPIE Homepage: SPIE*, SPIE., 14 Feb. 2014, spie.org/newsroom/5343-reducing-reflection-losses-in-solar-cells?SSO=1.

[13] Honsberg, Christina , and Stuart Bowden. “Reflectance.” *Reflectance | PVEducation*, PV Education, www.pveducation.org/pvcdrom/characterisation/reflectance.

[14] “How Does Led Matrix Work?” *How Does Led Matrix Work?*, 4 Nov. 2011, appelsiini.net/2011/how-does-led-matrix-work/.

[15] “Introduction to Charge Controllers.” *Wholesale Solar Banner*, www.wholesalesolar.com/solar-information/charge-controller-article.

[16] Kaur, Kalwinder. “What is an Actinometer?” *AZoSensors.com*, 8 Aug. 2013, www.azosensors.com/article.aspx?ArticleID=247.

[17] Landau, Charles. “Optimum Tilt of Solar Panels.” *Optimum Tilt of Solar Panels*, 11 Nov. 2015, www.solarpaneltilt.com/.

[18] “Language Reference.” *Arduino - Reference*, www.arduino.cc/en/Reference/HomePage.

[19] Lenardic, Denis. “PV and Art.” *Photovoltaic and Art*, 23 Dec. 2015, www.pvresources.com/en/pvart/pvart.php.

[20] “Lockheed Martin Parking Catches Sun Power.” *Lockheed Martin* , 20 Oct. 2015, www.lockheedmartin.com/us/news/press-releases/2015/october/151020-mst-lockheed-martin-parking-catches-sun-power.html.

[21] “Maximum Power Point Tracking.” *Maximum Power Point Tracking - Solar Power Information | Solar Quotes*, www.solarquotes.com.au/inverters/mppt/.

[22] “Morningstar Corporation.” 1098 Washington Crossing Road, Pennsylvania.

[23] “MPPT vs PWM Solar Controllers.” *Enerdrive Pty Ltd*, 4 Oct. 2017, www.enerdrive.com.au/mppt-vs-pwm-solar-controllers/.

[24] Liyan Gong. “PCB Dimensions Specification – PCB DFM Part 10.” *Seeed Studio Blog*, 12 July 2017, www.seeedstudio.com/blog/2017/07/14/pcb-dimensions/.

[25] “Printed Circuit Board.” *How Products Are Made*, www.madehow.com/Volume-2/Printed-Circuit-Board.html.

[26] “Rigid Flex Circuits, Rigid Flex Circuit Boards | Flexible Circuit.” *Flexible Circuits*, www.flexiblecircuit.com/product-category/rigid-flex/.

[27] Sendy, Andrew. “Solar-Estimate.” *Solar Reviews*, 23 Aug. 2017, www.pviews.com/solar-panels/.

[28] Senior, Kathryn. *Solar Powered Road Signs*, Energy Saving Secrets, 28 Dec. 2012, www.energysavingsecrets.co.uk/solar-powered-road-signs.html.

[29] “Single Sided PCB.” *Amitron | U.S. PCB Manufacturer*, 24 May 2016, www.amitroncorp.com/printed-circuit-boards/single-sided.html.

[30] “Solar Panel Direction: what direction should solar panels face?” *Sinovoltaics - Your Solar Supply Network*, 22 July 2015, sinovoltaics.com/learning-center/system-design/solar-panel-direction-what-direction-should-solar-panels-face/.

[31] “Solar Panel Tilt Calculator.” *Solar Panel Tilt Calculator - DIY Solar Kits*, www.gogreensolar.com/pages/solar-panel-tilt-calculator.

[32] “Solar Power Trees | Spotlight Solar Products.” *Solar Trees | Spotlight Solar*, spotlightsolar.com/products/.

[33] “Solar-Estimate.” *Solar Reviews*, 23 Aug. 2017, www.solarreviews.com/solar-energy/pros-and-cons-of-monocrystalline-vs-polycrystalline-solar-panels/.

[34] “Stop Signs.” *Solar Traffic Systems, Inc*, ustrafficsystems.com/stop-signs/.

[35] Taranovich, Steve. “An Engineer's Guide to Power Inverters for Solar Energy Harvesting.” *An Engineers Guide to Power Inverters | DigiKey*, 4 Apr. 2012, www.digikey.com/en/articles/techzone/2012/apr/an-engineers-guide-to-power-inverters-for-solar-energy-harvesting.

[36] “The 10 Best Solar Grid Tie Inverters For Solar Panel Systems -.” *Survival Renewable Energy*, 27 Oct. 2017, www.survivalrenewableenergy.com/10-best-solar-grid-tie-inverters/.

[37] “Thermal Infrared (TIR).” *Dexter Industries*, www.dexterindustries.com/manual/thermal-infrared-sensor/.

[38] Thomason, Mark. The Solar Powered, Electric Vehicle Charging Station at the University of Central Florida. pp. 2–9, The Solar Powered, Electric Vehicle Charging Station at the University of Central Florida.

[39] “U.S. Solar Market Insight.” *SEIA*, 11 Sept. 2017, www.seia.org/us-solar-market-insight.

[40] Admin. “What is the difference between a PWM and MPPT charge controller? Shop Solar.” *Silicon Solar Store*, 13 Nov. 2013, www.siliconsolar.com/what-is-the-difference-between-a-pwm-and-mppt-charge-controller/.

[41] Wiles, John. “John Wiles.” *IAEI Magazine*, 10 July 2014, iaeimagazine.org/magazine/2013/11/16/supply-side-pv-connections-a-closer-look/.

[42] Wiles, John. “Connecting Inverters to the Grid.” 2009.

[43] Zipp, Kathie. “Dual MPPT Defined, Understanding Solar MPPT.” *Solar Power World*, 18 Feb. 2014, www.solarpowerworldonline.com/2014/02/dual-mppt-defined-understanding-mppt/.

[44] Zipp, Kathie, et al. “What are the different types of solar inverters?” *Solar Power World*, 25 Aug. 2017, www.solarpowerworldonline.com/2016/05/different-types-solar-inverters/.

[45] Creative Commons [Online]. Available: https://creativecommons.org/licenses/by-sa/3.0/

[46] Arena Solutions [Online]. Available: https://www.arenasolutions.com/resources/articles/creating-bill-of-materials/

[47] Wikipedia [Online]. Available: https://en.wikipedia.org/wiki/DMX512

[48] Ecolocityled [Online]. Available: http://www.ecolocityled.com/product/rgbww-waterproof-strip-light/rgbw-led-strip-lights

[49] Sharp [Online]. Available: http://www.sharp-world.com/products/device/lineup/data/pdf/datasheet/gp2y0a41sk_e.pdf

[50] Rockwell Automation [Online]. Available: http://literature.rockwellautomation.com/idc/groups/literature/documents/br/sensor-

br001_-en-p.pdf?eventcategory=Brochure&event-action=Download&eventlabel=SENSOR_FamilyBrochure_EN

[51] Shure [Online]. Available: http://www.shure.com/americas/support/find-an-answer/ullisting-for-wired-microphones

[52] GRAS sound and vibration [Online]. Available: http://www.gras.dk/products/measurement-microphonesets/constant-current-power-ccp/product/771-146ae

[53] Pololu [Online]. Available: https://www.pololu.com/file/0J497/ACS711.pdf

[54] GitHub [Online]. Available: https://github.com/sonicaeon/OUC-Solar-Sculpture

B. Copyright Permissions

Permission request to Lockheed Martin – 4/26/18

Dear Sir/Madam,

I am contacting you to request permission to use an image of your parking lot with a solar panel covering. I am a student at UCF doing a senior design project that involves solar technology in public spaces and the image is useful to me in demonstrating a point.

Sincerely,
Simon McGlynn

Permission request to Hornen Traffic Electronic Factory – 4/26/18

Dear Sir,

I am a student at The University of Central Florida in the United States of America. I am requesting permission to use one of your images that displays a stop sign with a solar panel in an engineering paper I am writing for one of my classes. I have attached the image I am requesting permission to use.

Sincerely,
Simon McGlynn

Permission request to Palmer Electric – 4/26/18

Dear Sir/Madam,

I am a student at The University of Central Florida. I am requesting permission to use one of your images, that displays an electronic vehicle charging station with solar panels at UCF, for an engineering paper I am writing for one of my classes. I have attached the image I am requesting permission to use.

Sincerely,
Simon McGlynn

Permission request to Energy Matters – 4/26/18

Dear Sir/Madam,

I am a student at The University of Central Florida. I am requesting permission to use one of your images for an engineering design paper I am writing for one of my classes. I have attached the image I am requesting permission to use. Thank you for your consideration.

Sincerely,
Simon McGlynn

Permission request to Solar Quotes – 4/26/18

Dear Sir/Madam,

I am a student at The University of Central Florida. I am requesting permission to use one of your images for an engineering design paper I am writing for one of my classes. I have attached the image I am requesting permission to use. Thank you for your consideration.

Sincerely,
Simon McGlynn

Permission request to Adafruit – 4/26/18

Dear Sir/Madam,

I am a student at The University of Central Florida. I am requesting permission to use one of your images for an engineering design paper I am writing for one of my classes. I have attached the image I am requesting permission to use. Thank you for your consideration.

Sincerely,
Simon McGlynn

Permission request to L-com – 4/26/18

Dear Sir/Madam,

I am a student at The University of Central Florida. I am requesting permission to use one of your images for an engineering design paper I am writing for one of my classes. I have attached the image I am requesting permission to use. Thank you for your consideration.

Sincerely,
Simon McGlynn

Permission request to LG – 4/26/18

Dear Sir/Madam,

I am a student at The University of Central Florida. I am requesting permission to use one of your images of solar panels for an engineering design paper I am writing for one of my classes. Thank you for your consideration.

Sincerely,
Simon McGlynn

Permission request to Orlando Utilities Commission – 4/26/18

Dear Sir/Madam,

I am a student at The University of Central Florida. I am requesting permission to use your logo for an engineering design paper I am writing for one of my classes, as our project sponsored by OUC. Thank you for your consideration.

Sincerely,
Simon McGlynn

Permission request to Orlando City Soccer Club – 4/26/18

Dear Sir/Madam,

I am a student at The University of Central Florida. I am requesting permission to use your logos for an engineering design paper I am writing for one of my classes, as the project is sponsored by OUC in partnership with Orlando City Soccer Club. Thank you for your consideration.

Sincerely,
Simon McGlynn

Permission request to Sharp – 4/26/18

Dear Sir/Madam,

I am a student at The University of Central Florida. I am requesting permission to use one of your images of a Sharp GP2Y0A41SK0F infrared proximity sensor for an engineering design paper I am writing for one of my classes. Thank you for your consideration.

Sincerely,
Simon McGlynn

Permission request to Rockwell Automation – 4/26/18

Dear Sir/Madam,

I am a student at The University of Central Florida. I am requesting permission to use one of your images of a Rockwell 873P ultrasonic sensor for an engineering design paper I am writing for one of my classes. Thank you for your consideration.

Sincerely,
Simon McGlynn