Project FLOW

Fun Low-power Observer-interactive Waterfall

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Sponsored by: OUC

Group 5

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1 Executive Summary

While conducting solar sculpture research online, the team was surprised to find the vast majority of analogous projects consisted of stationary constructs that failed to make actual use of the solar energy being collected. Based on this observation, the team conceived the idea for an interactive kinetic solar sculpture, which will utilize its solar power to entertain observers and demonstrate the practicality of solar energy in real-time.

The solar sculpture will utilize an optical sensor in concert with computer vision software to allow for immediate interaction between the installation and the observers. An array of water solenoids at the top of the sculpture will be triggered on or off based on stimulus from observers in front of the sculpture. These water effects along with decorative LEDs will be create an impressive aesthetic display for passerby. All components will be powered through the use of solar panels, thus demonstrating to observers the capability of solar energy in real-time.

The proposed solar sculpture design will expand upon the idea of a 'waterfall swing', in which the person swinging travels through openings created in a falling water display. Rather than parting a waterfall for passerby though, this installation will have an array of contiguous water solenoids, which toggle on or off as the motion of passerby is observed. A rendition of the proposed design of the installation in *Figure 1a*. To pay homage to the installation's location in a residential area for up and coming health care workers, the sculpture is modeled off a DNA pattern, with the graphical waterfall array and solar panels being held up by unraveling "strands" of the DNA structure. The waterfall effect also ties into the water treatment facility that also happens to be in the immediate vicinity.

At night, the waterfall's solenoids will unleash a continuous stream of water and LEDs located at the top of the sculpture will project colored lights onto the waterfall in response to observer movement in front of the sculpture. Movement will be tracking on a horizontal and vertical axis with horizontal movement toggling the LEDs on and off and vertical movement affecting the intensity or brightness of the LEDs.

The water recirculation system alone will have several aspects to provide a constant source of water to the solenoids at the top of the sculpture. A basin will need to be used at the bottom of the sculpture in order to collect water from the waterfall feature and recirculate it. The water will then pass through a filter in order to remove any contaminates that may clog the system. A 1-hp water pump will then pump the water to a plenum at the top of the sculpture, which provides the water to the solenoid valves that are controlled by the microcontroller. In order to simplify the system, the pump will run at a constant speed. This means the volume and pressure of the water being provided will need to be enough to operate with all solenoid valves open simultaneously. An overflow water return hose at the end of the plenum will need to be used so that the excess water to will return to the basin when the solenoid valves are closed.

The primary goal of this project is to produce a solar sculpture that educates on the practicality of solar power through entertainment. The majority of our sculpture's structure will be a framework, saving cost on building materials for the full-scale realization of the sculpture. Interactivity is stressed in our design, in the hopes of engaging passerby and thus drawing more attention to the installation.

This project is of course being done in concert with a team of mechanical engineers. The mechanical engineering component of our team will focus on building the helical structure, which will support the graphical waterfall display and solar panels.

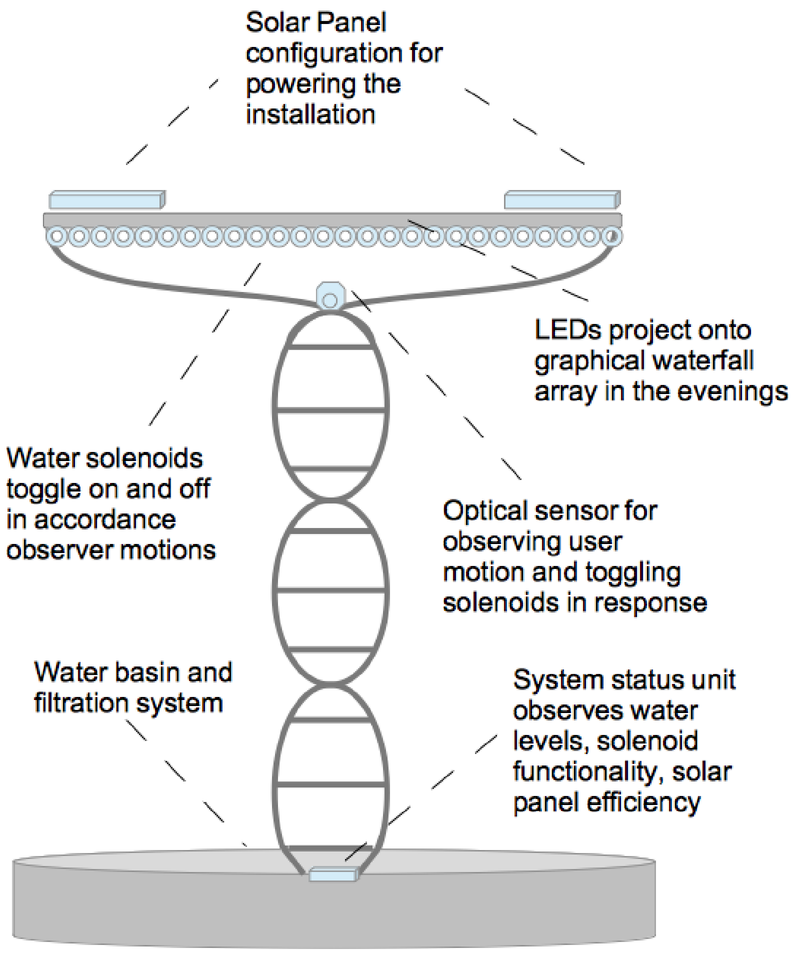

Figure 1a - frontal view of the proposed solar sculpture installation.

The platform upon which the solar panels rest is elevated outwards, so that by virtue of the overhang the graphical waterfall effect results in a 2D wall of water falling in front of the 3D helical structure.

Provided below in *Figure 1b* is the installation structure as rendered by the mechanical engineers on the team. It is important to note that this rendition represents the *structure* of the installation only, electrical hardware components are not featured as they are not considered by the mechanical engineers in the stress testing of the structure as of yet. The mechanical engineering team has put the helical structure through a variety of wind simulation tests.

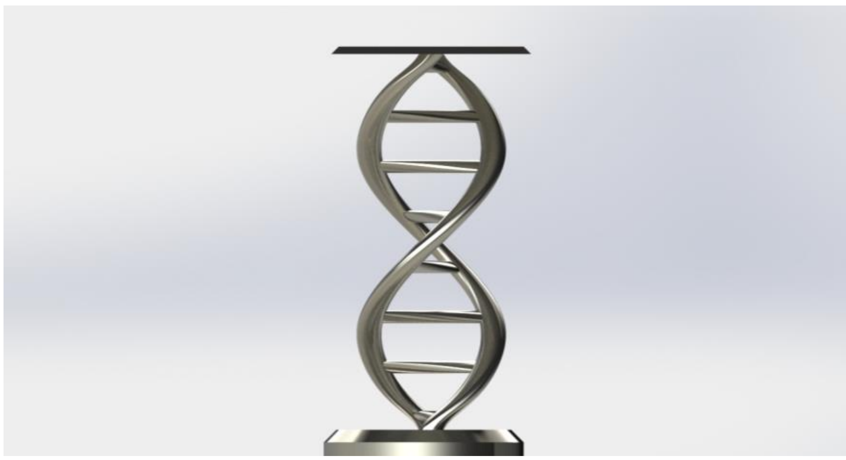

Figure 1b - mechanical engineers rendition of the helical structure, which will be used to support the solar panels and the graphical waterfall display.

The finalized installation will look very similar to the structure in *Figure b.* On the upper crossbar of the helical structure a fixed solar panel will be mounted. There has been some discussion in the team about possibly adding bifacial solar panels on the cross bars that make up the twisting helix. Currently the team believes the added solar panels would cause far too high a rise in the installations cost however further discussion of this matter with the sponsor is required.

At the edge of the upper platforms overhang, the graphical waterfall display solenoids will be installed. Thus the waterfall effect will be on one side of the structure only. The installation will have two primary ‘modes’ one for evenings and one for sunny afternoons. The afternoon mode will trigger water solenoids in response to passerby motion in front of the optical sensor. The evening mode will have all solenoids dispersing water in a continuous waterfall effect. Observers of the installation in the evenings will be able to trigger a series of colored variable-brightness LEDs that will illuminate the waterfall.

2 Project Description

The following section provides a generalized description of the project idea, explaining the components that will make up the solar sculpture installation prototype. The engineering specifications and constraints of the project will be listed. Additional constraints of the project prototype due to the nature of the team's relationship to the sponsor and the senior design class requirements will also be discussed.

2.1 Block Diagram

Displayed below in *Figure 2.1a* is the block diagram for the installation, showing the various inputs and outputs of the electrical components that make up the solar sculpture. All hardware components are either acquired or in development at the time of this writing. The 'in development' status of some of the power components conveys that the team is currently pursuing the possibility of a custom solution for this component to decrease the overall cost of the project.

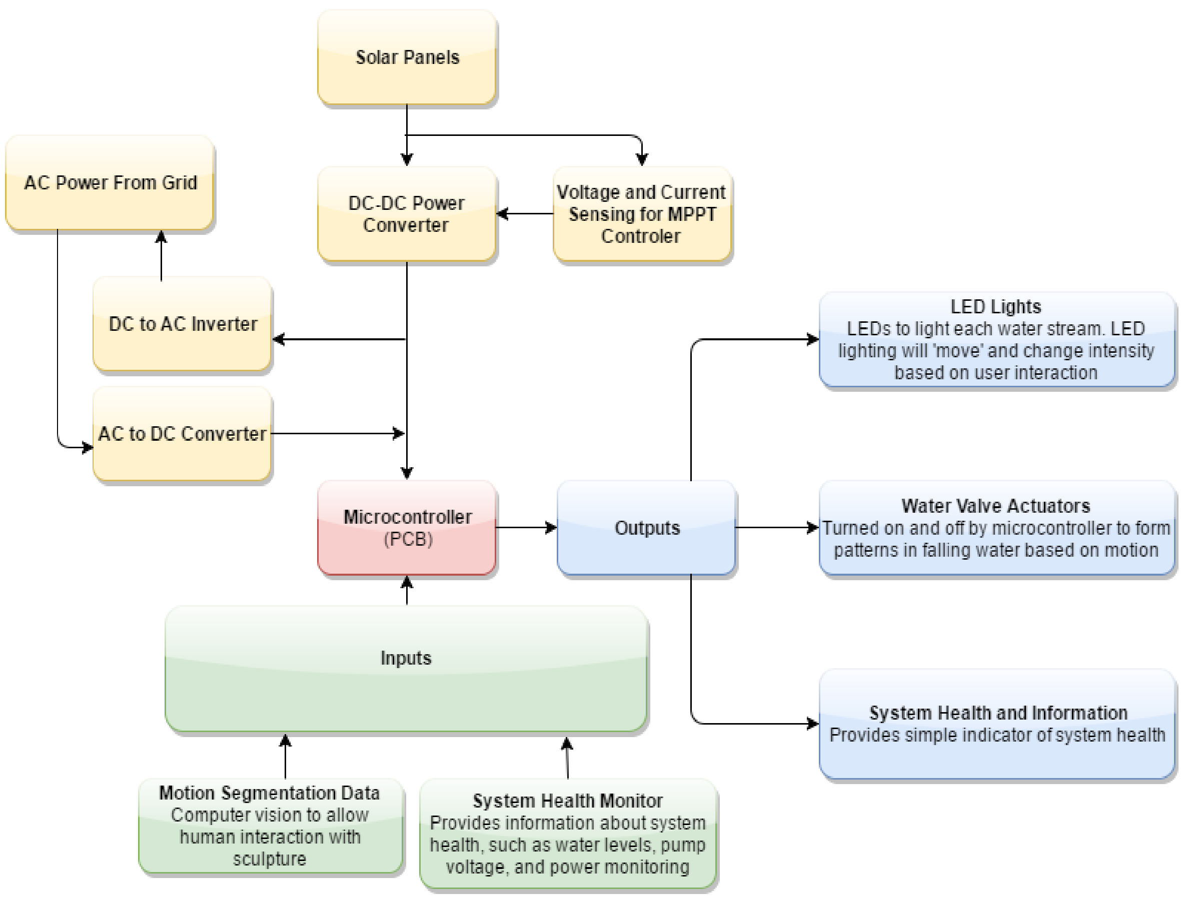

Figure 2.1a – block diagram showing all the inputs and outputs of various electrical components involved in the installation.

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Table 2.1a – shows status of each electrical component along with which team member is responsible for the acquisition of that component.

Block Description	Group Member Assigned	Block Status
Solar Panel	Robert Perkins	Acquired
DC to DC power optimizer	Robert Perkins	In Development
AC to DC Converter	Jack Gray	In Development
DC to AC Converter	Robert Perkins	In Development
PCB Design	Jack Gray	Complete
Microcontrollers	Connor Heckman	Acquired/Tested
System Health Monitor	Connor Heckman	Acquired/Tested
Vision System	Connor Heckman	Acquired/Tested
Water Valve Actuators	Ben King	Acquired/Tested

2.2 Project Specifications

- Location
    - Laureate Park Lake Nona
- Dimensions
    - Full Scale- Maximum 15' tall x 8' wide, Minimum 5' x 2'
    - Final Deliverable- 1/8th scale model
- Cost
    - Full Scale- $25k-30k
    - Final Deliverable- $2,000
- Solar Panels
    - Quantity-8 (full scale)
    - Individual Panel Size- 1580mm x 808mm x 35mm
    - Power Output: 200 W (full scale)
- Input Sensor
    - Quantity- 1 Pixy Cam
    - Size- 50mm x 54mm x 2mm
- Output Feature
    - Quantity- 16 Solenoid Valves
    - Size- 4 ft x 4 ft array
    - Output: User Interaction via Computer Vision
- Power
    - Total Consumption: 120 W
    - Total Production: 1,600 kWh/year

2.3 Project Constraints

- Interaction with the installation is complicated with multiple observers
- Ability to maintain power on overcast days
- Concerns regarding weather conditions, including waterproof operation of electronics for cylinder and pendulum variant
- Concerns regarding maintenance costs to prevent rusting and erosion of structural components

2.4 Economic Constraints

There are numerous economic constraints on this project that need to be taken into consideration during the design of this product. OUC, the project sponsor, has endowed the team with a budget of $2,000 dollars for the installation prototype. Their full-scale model budget is $70,000 dollars for the solar sculpture. Although this seems substantial this budget is split between the three teams, electrical, mechanical and art. For the electrical team the most costly components will be the photovoltaic module, electrical power equipment, water feature equipment and finally computer vision equipment. All of these systems were designed with cost and functionality in mind.

Our sponsor OUC suggests photovoltaic bifacial monocrystalline panels. They offer high performance and are visually appealing even from below. However these panels are quite expensive and the full-scale model will require around eight of them. This is not practical for our ⅛ scale model because the panels alone would be several thousand dollars. Instead the ⅛ scale model will use one monofacial 200W 24V monocrystalline panel. This will allow the team to demonstrate the grid tied solar production that will be seen on the full-scale model.

OUC doesn't want the added maintenance of a battery array for the full-scale model and instead opting for a grid tied inverter solution. The ⅛ scale model will demonstrate this by using a micro inverter for our single panel. The microinverter that is currently being looked at is a developer kit from TI. At a cost of $850 other solutions are being looked for.

Ideally the electrical team would like to demonstrate the largest waterfall possible. However the solenoid valves and related hardware cost at least $8 per unit. This cost limits the size of our waterfall. The group has settled on using sixteen solenoids in order to demonstrate the interactive nature and limit cost to a reasonable level.

For the computer vision system a camera is needed to produce raw data. A FLIR camera would be the best solution but for one that would be viable is around $300. Because of this a Pixy Cam will be used instead at a cost of $70. The Pixy

Cam has the added hurdle of usually being used for color recognition but that is an obstacle that can be overcome through modification of the vision system's source code.

Economic constraints are numerous because the electrical team's goal is to construct a model that reflects the full-scale $70,000 sculpture as accurately as possible on a $2,000 dollar budget. The team hopes to achieve this by scaling down aspects of the project that do not demonstrate engineering knowledge such as high end photovoltaic modules and utilizing an appropriate number of solenoid valves for the water display. With these changes a $2,000 model will accurate represent the $70,000 full-scale project.

2.5 Time Constraints

The construction of the ⅛ model will have to be completed in about 15 weeks. In that time all systems must be built, tested and ready for the senior design showcase. Because of this several systems of the project were designed with a tight time frame in mind. These systems include the photovoltaic module, water system and finally the power system.

OUC is bringing solar power to sculptures around Orlando in order to raise solar awareness and to also demonstrate they can be much more than a public eye sore. Initially there were designs that included custom-built photovoltaic modules that would be constructed at a cell level. This would allow for shapes other than the commercially viable rectangular shape. However soldering a large number of solar cells into a module doesn't show an understanding of engineering concepts this will not be included in the project. Instead a standard commercial rectangular 200W 24V monofacial photovoltaic module will be purchased.

The electrical team would like to demonstrate the maximum size waterfall display possible. However with more solenoids there is increased wiring that is necessary and also more circuitry including shift registers. For this reason along with financial reasons sixteen solenoids will be demonstrated.

The power system was designed to take all the energy from the grid and feed all the energy from the solar panels to the grid. This is a simpler solution that will need less circuitry than having the waterfall and other systems switch from drawing power from the solar array during periods of high production and the grid during low production times. This will not affect OUC's goal of having the sculpture produce a net positive amount of power.

The electrical team's main objective is to demonstrate as much engineering knowledge as possible in the limited time available. Artistic appeal and circuitry that doesn't help achieve our client's goal will not be pursued. Therefore there will not be a custom made solar array, unnecessarily large solenoid array, or complex power circuitry that does not help realize our client's goals. In the electrical team's limited time frame we hope to accurately represent the electrical system of the full-scale project in the ⅛ scale deliverable model.

2.6 Safety Constraints

The main concern for this project is safety. With the combination of electricity and a water feature there is a risk for short circuits and electrocution. To mitigate these risks several steps have been taken in regards to the photovoltaic array, power system.

With a larger photovoltaic array a system that more closely resembles that of the full-scale model could be achieved. However having several 200W 24V panels in an array would produce enough voltage and amperage to potentially kill someone. Because of this and other factors only one photovoltaic panel will be used.

The power system that takes energy from the grid and will power our project will use low voltage rails no higher than 12V. This will increase safety especially considering the water element of the project. The power system will also be as waterproof as possible to guard against potential leaks and spills.

2.7 House of Quality

Pictured below is the project house of quality along with numerical estimations for engineering requirements. Implementation time refers to the time needed to construct the prototype that will be presented at the conclusion of senior design II. Durability refers to the time the solar sculpture should be able to operate without maintenance.

		Output Efficiency	Solar Panel Coverage	Implementation Time	Durability	Size	Cost
		+	+	-	+	+	-
Engagement	+	↓		↓↓		↑↑	↓
Power Usage	-	↑				↓↓	↑
Aesthetics	+		↓	↓		↑	↓
Structural Complexity	-		↓↓	↑	↓	↓	↑↑
Cost	-	↓	↓↓	↑	↓	↓↓	
		> 15%	< 4500 in^2	< 1 Month	> 1 Week	12" x 18"	< $1800

2.8 Objectives

The solar power sculpture project has many objectives set by the design team and also by the client OUC and the Tavistock Group. These objectives include having an electrically robust design, safety for the public and maintenance crews, interactive, element with stranding, quick response times and to be green and net energy positive. All of these objectives will make the solar power sculpture a positive influence on the Lake Nona community. Leading to more discussion about the viability of solar power and its uses in unconventional applications.

The client requests a minimal amount of maintenance. Therefore a robust initial design will be crucial to this project. This is the driving factor for making the sculpture grid connected rather than battery powered. The use of a grid connected string inverter rather than micro inverters also leads to a more robust design because it reduces the number of failure points and makes the sculpture more easy to troubleshoot and repair if there is an inverter failure. A systems health monitoring circuit and microprocessor will constantly look for anomalies in voltage and current in key locations as well as monitor water levels and pump health. This system will mitigate further failures by catching problems early and shutting down subsystems to preserve their health.

Safety for the public and maintenance workers is of the utmost importance. Earlier versions of the project had kinetic components that had to be scrapped due to safety concerns. The final version has no moving parts but does have a water element and will generate large amounts of electrical power. Electrocution is the primary safety concern. Isolation between the electrical and water systems is a main design element. All power electronic systems will be built with compliance with NEC for ease and of maintenance and for the safety of maintenance workers.

The sculpture should draw in the public in order for them to develop more interest in solar power. An appealing aesthetic and interactivity will hopefully lead to this. Our goal is to have the public drawn in and then to discover the interactivity through the gesture controlled water feature. This will hopefully generate more interest in the sculpture, which in turn will lead to more interest in green solar energy.

Florida weather is extremely harsh, the sunlight is very intense, there is over 53” of rain annually and there's the threat of hurricane force winds for nearly half of the year. The strong sunlight leads to faster deterioration of polymers and some other materials. These materials will not be used when possible to improve the longevity of the sculpture. Large rainstorms can damage electronics and can damage water circulation systems. All precautions will be taken to insulate the electrical systems from precipitation in order to avoid corrosion and short circuits.

The installations graphical waterfall array should be highly responsive to observer movement. Extensive testing will be run on each individual solenoid in the waterfall feature in the hopes of detecting any troublesome units (solenoids with a noticeable delay when switching states) early on. The motion segmentation algorithms running within the vision system control software must be robust enough to avoid propagation delays throughout the system.

Generating green solar energy is key to this project because the overall goal is to heighten public awareness of solar energy and its uses. The implementation of solar panels on an art installation will demonstrate that solar panels can be aesthetically pleasing which counters that conventional opinion of them being an eyesore. The solar sculpture will generate large amounts of energy during the day that will be put back into the grid. At night and on cloudy days energy from the grid will be taken to power the sculpture. It is an objective set out by OUC that the sculpture remains a net positive energy source for the power grid. This means a close look at projected solar energy outputs will be taken and all energy conserving methods will be looked at in order to make the sculpture as energy efficient as possible.

Hopefully this installation will draw public attention towards solar energy as an alternative or supplementary power source that is both economical and visually appealing. This project sets out to build a robust, safe, interactive, responsive and green sculpture that will be a great addition to the Lake Nona community and will further the awareness of green renewable solar energy at a consumer or residential level.

3 Research

The following section details the team's research into related senior design projects, technologies relevant to the solar sculpture installation, and methods and procedures that may assist the team in the construction of a robust and responsive solar sculpture installation.

3.1 Research Methods and Related Projects

After the finalization of the project idea, the team then needed to realize how it would be implemented. The research for the project consisted of gathering information from similar projects and consulting university faculty to assure the initial design concepts are realistic and deliverable. Referencing old senior design projects from the University of Central Florida helped the team understand how specific requirements are met and how other groups were able to implement parts of their design related to the solar sculpture.

3.1.1 Dynamic Liquid Light Fountain

The purpose of the Dynamic Liquid Light Fountain is to add aesthetic value to home and garden. The fountain is powered from 120 V_{ac} and uses a wireless remote to control the LED drivers and light display used to illuminate the liquid stream. In addition to the remote control the DLLF uses motion sensor to activate and deactivate the fountain when motion is present. This project uses an AC to DC converter, 12V water pump, and switching circuit similar to the aspects of the design being used in this project.

3.1.2 Pressure Reactive Electronic Solar Stones

The P.R.E.S.S. is a solar powered stepping-stone that illuminates in different patterns based where the user steps. This can be controlled directly by the user interacting with the stepping-stone or remotely to display a pattern based on a Bluetooth module. This design was well written and had meaningful schematics, but the power was significantly less in total power consumption.

3.1.3 Solar Powered Window Blinds

This project is designed to harness the energy from the sun that inevitably comes through the window, providing shade and storing the solar energy. The solar energy is stored in rechargeable batteries to be used by devices in the home. The system displays the efficiency of the solar panels and power remaining in the batteries. The limitation of not using batteries differs from the waterfall solar sculpture but they are both harvesting energy to replenish energy resourced from the utility grid. The linkage to external devices to monitor the system will not be necessary for the solar sculpture because of the maintenance by the utility companies.

3.1.4 Solar Powered Golf Cart

Utilizing the sun’s power to charge the golf cart’s batteries, run the GPS monitoring system, and monitor the efficiency of the system is the motivation behind this project. The first component of the project was the user interface touch screen GPS and system monitoring display. This controlled the route guidance and power to life time relation of the batteries. The second feature was the motor control feature, eliminating a variable resistor across the pedal decreased the power consumption. An additional motor control feature was the pulse width modulator to increase the battery efficiency and prevent power spikes when accelerating. The final feature was the solar panel charge controller feeding into the 36V battery bank. This device used max power point tracking to increase the efficiency of the golf cart and solely rely on solar energy to run. This project and the solar sculpture both are using the max power point tracking to gain the greatest efficiency from the solar panels.

3.1.5 Progress Fly High Energy

The objective of this project is to make a portable solar tracking station that can be used to power 120V AC devices. Using a single solar panel, a solar tracking system is implemented to follow the sun assure solar efficiency in any location. The power output from the panels is fed into a charge controller, using a personally developed max power point tracking algorithm the battery bank is charged. The team then designed a DC/AC inverter to converter the stored energy to usable AC device power for an estimated reasonable amount of time. The device also displays the power inputs, outputs, temperature, and panel status. This project and the solar sculpture both use an Arduino interface, this project displays on LCD the information processed.

3.1.6 eMpower

The use of solar energy to power water pumps is not the only use for this project, the company Water Missions International reached out to this team about creating a reliable phone charging ports at the water pump stations. The solar panel arrays generate more energy than the water pump filtration is needed, so this team designed a phone charging station. The main objective of this project was to create an energy efficient charger that is safer and more reliable than the previous developer. The secondary objective is to create an interface panel that allows users to interface with the water pump filtration system. The similarity between this project and the solar sculpture is the possibility for a phone charging station. Similar to previous solar sculptures designed by OUC the unused power generated by the solar panels are consumed by the general public in need of charging stations for mobile device.

From these projects inspiration for ideas as well as unsuccessful ideas and the catastrophic flaws other senior design groups suffered. Understanding the capabilities of what a senior design group can accomplish in two semesters time is important when determining the design schedule and the goals to be accomplished. Further research is discussed below to outline the specifics not taught in the classroom necessary for the specification of the hardware for the project.

3.2 Solar Energy

Solar panels are driven by a series of solar cells whose basic construction consists of crystalline silicon sandwiched between conductive layers. This crystalline silicon is made up of two parts, a P type part and an N type part. P type silicon is doped, infused with, elements that can accept an extra electron. Boron is the most common P type dopant. N type silicon is doped with elements that have extra electrons. Phosphorus is used as an N type dopant for solar cells due to its fast diffusion, which leads to higher efficiencies.

The basic concept of the solar cell is that photons from the sun that carry enough energy can break an electron free from its bond in the N type silicon. This free electron and free hole, lack of electron, will now move. The electron will leave the N type layer and enter the conductive outer layer as the hole moves into the P type silicon layer. The free electrons in the conductor are now able to do work and power an electrical system and then return through the conductive material to the P side of the solar cell where they fill excess holes.

There are several different ways to construct solar cells that all have their advantages and disadvantages. The three major types of solar cells are monocrystalline silicon, polycrystalline silicon, and thin-film solar panels. There are more rare types of solar panel construction such as translucent cells and super high efficiency cells. Some efficiency rates are as high as 40%. These products are more rare because they are not yet commercially viable. However the price of ultra efficiency panels is dropping due to improvements on manufacturing practices.

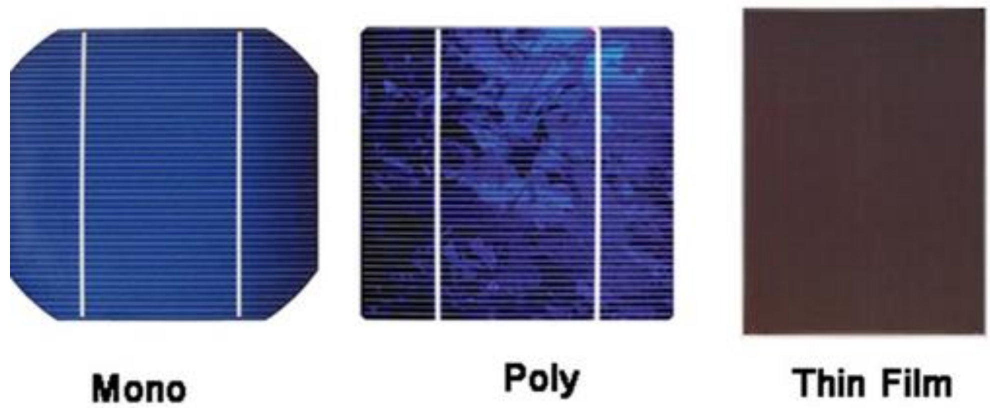

Figure 3.2a - Photovoltaic cells.
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Monocrystalline silicon solar cells are created from a sheet or wafer of a silicon ingot, this process is also used for silicon chips. This type of cell is more expensive than the others because it requires the production of a silicon ingot which is made using the Czochralski process. This is a long, technical and costly process. These cells also have the highest efficiency with some of the top of the line products reaching efficiencies just above 20%. This makes the panels highly space efficient as well. Monocrystalline silicon solar cells have lower failure rates and better performance in low light conditions.

Polycrystalline silicon solar cells are made up of multiple smaller crystalline structures. These cells are produced without using a silicon ingot or the expensive Czochralski process. These cells are therefore cheaper than their monocrystalline counterpart. The trade off for this cheaper price point is less efficiency, around 15%, which also makes them less space efficient.

Depositing multiple thin layers of photovoltaic material onto a substrate creates thin-film solar cells. There are four common types of thin-film solar cells; amorphous silicon, cadmium telluride, copper indium gallium selenite and organic photovoltaic cells. Thin film technology is relatively new and rapidly developing. These are the least efficient of the major solar cell technologies coming in with around 10% efficiency but this technology is being heavily researched so they may sees a drastic improvement in efficiency. This low efficiency makes them impractical to use in home applications due to a lack of space. These cells also have shorter lifespans when compared to crystalline-based cells. However these cells are the cheapest photovoltaic option on the market.

3.2.1 Advantages

Solar energy offers many advantages over its major competition, fossil fuels, and also over other forms of renewable energy. Solar energy is a clean renewable resource that can be utilized in most places, is long lasting and has low maintenance. As energy demands continue to rise and the effects of global warming put pressure on our planet solar energy is being turned to more than ever to produce power at the home and industrial level.

Solar energy offers numerous advantages over conventional fossil fuel energy production. Solar energy is clean and renewable. In 2015 the US power sector generated 1,925 million metric tons of C02 which is about 37% of the total 5,271 million tons the US produces. This fact coupled with the ever-decreasing price of residential solar modules predicted to fall to $2.00/W in the second half of 2018 from $3. 57 in the first half of 2016 are making solar energy a necessary and viable option for energy production.

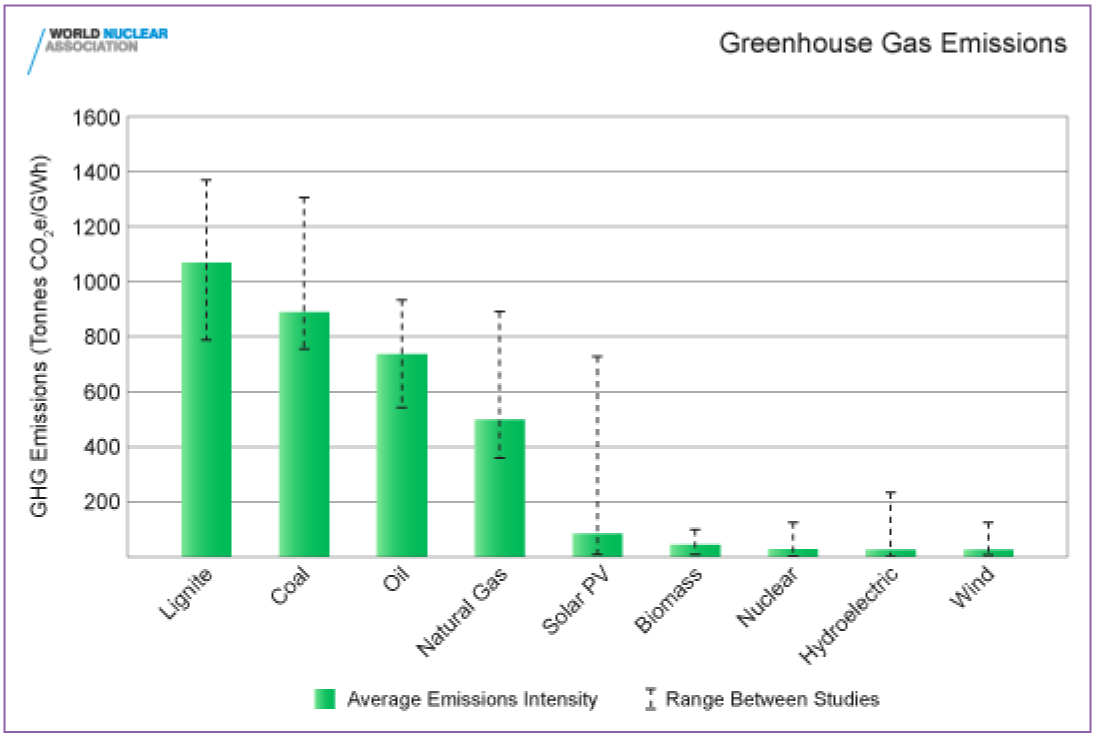

Figure 3.2.1a - Graph showing GHG emissions of various energy sources
Reprinted with permission from World Nuclear Institute

Solar energy can also be decentralized, off grid and also low maintenance often involving no moving parts. These make it vary appealing options for developing markets due to unreliable electrical grids and more volatile power prices. Many of these types of developing markets also happen to be near the equator, which makes them great areas for solar power generation. Solar energy is also taking off in large-scale production. There are currently over 4,000 major solar projects in operations generating over 72 GW of capacity and there are projects in construction or development that total over 53.3 GW of production. Solar energy is also insulated from volatile commodities markets and large price variations unlike fossil fuels. Because of these advantages that solar and other renewables have over fossil fuels they are predicted to double worldwide in the next 20 years.

There are many options for renewable energy besides solar. The two most notable renewable options beside solar are wind and hydroelectric. Hydroelectric power makes up the majority of the renewable energy accounting for 25% of total production. However hydro electricity in generally produced from damming rivers and there are a limited amount of locations for such facilities and they have major ecological impacts. Wind generated electricity accounts for 19% of renewable production but has similar pitfalls to hydroelectric power due to the limited areas it can be implemented and its negative effects on wildlife, in particular birds. Both of these technologies also have complicated construction and maintenance. Solar energy is easy to install and has very little maintenance due to the lack of moving parts. Solar energy also does not pose any environmental concerns and can be implemented in most areas. One of the biggest advantages solar energy offers over other types of renewable energy sources is that it can be implemented on a residential level and can be separated from the grid. This also allows solar to be implemented in areas with unreliable grids as mentioned before.

As global energy demand rises and more pressure is brought politically and socially for clean renewable energy sources solar will poised for rapid expansion. Solar power is also becoming more efficient and cheaper with the advancement of solar cell technology and production practices. As of 2012 about 15% of the world's population still has no access to power. This will be a great market for solar energy due to its decentralized nature.

3.2.2 Disadvantages

Solar power has numerous positive traits but it is also facing some challenges and disadvantages in a very competitive energy market. On a large scale solar is only economically viable in arid sun intense regions and takes up large areas of land. Solar energy can also only be collected in the day so it makes production predictable but sporadic. Although the price of solar panels is dropping quite rapidly panels are still expensive and many thousands of them are needed for the construction of a solar plant, which leads to high upfront costs.

The high land and strict climate requirements limit solar energies use in some markets. Large-scale solar production just isn't viable in some markets like the UK where there are too many cloudy days and the sun lacks intensity. For the US largest scale solar production takes place in the deserts of the South West. The difficulty in transmitting power over long distances means most of the US won't see large-scale use of solar power.

A drawback to solar energy is it can only produce power during daylight hours. Energy storage is extremely costly and bad for the environment due to large amount of batteries needed. A research solar facility, Andasol Solar, is investigating a thermal energy storage system to work around these problems. Andasol uses a novel system of heating up large tanks of molten salt during the day and then later uses that stored heat to drive turbines at night for up to 7.5 hours.

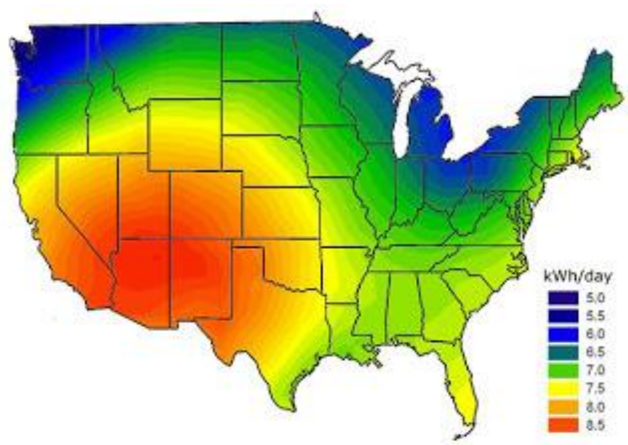

Figure 3.2.2a - Solar intensity map .
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Above is a map showing solar intensity across the US. It can be seen that solar power is much less effective in the North East and North West that more arid southern climates like the South West.

3.2.3 Solar Footprint

The driving force of our project is the sun. Understanding the capabilities and limitations from gathering solar energy is essential to making an efficient and reliable design. The location of our solar sculpture is at the Lake Nona Town Center (13615 Sachs Avenue, Orlando, FL 32827), surrounded by minimal shade and obstructions. Using Orlando International Weather Data and PVwatts.gov, the annual solar output of this location is 1,200 kWh annually. This is based off a 0.8 kW output using 8 panels of 100 W output, averaging an area coverage of 6 m^2. This exceeds of required 850 kWh annual output required by the sponsorship, and allows for power supply to the additional interactive features.

3.3 Sensing Circuits

3.3.1 Voltage Sensor

The Voltage Sensor is connected in series with the solar panels and in parallel with the MPPT controller. The two parallel resistors created a voltage divider used to read the solar panel voltages. With high resistance in these two resistors of R1=1.07MΩ and R2=165kΩ the maximum current drawn by the MPPT controller is considered negligible. The voltage across the R2 is fed into an analog-to-digital converter (ADC) driver circuit (op-amp in a voltage follower configuration that feeds into a low-pass filter) before being delivered to the ADCINA0 channel of the MPPT controller. The maximum input voltage to the ADC channel of the MPPT controller is 3Vdc. From the resistor values in *Figure 3.3.1a* the maximum voltage is 2.81V.

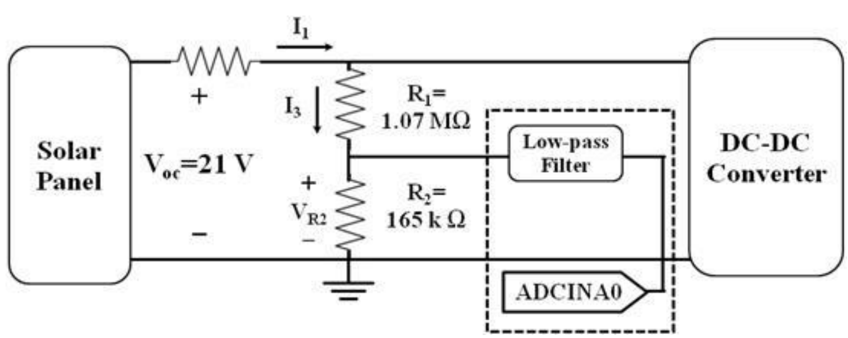

Figure 3.3.1a - voltage sensor circuit.
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3.3.2 Current Sensor

The Current Sensor consists of a single resistor in series with the solar panel. The voltage across the sensor resistor is fed into the ADC driver circuit, followed by the ADC1NA1 channel of the MPPT controller. The sensor resistor uses a very small resistance to cause minimal voltage drop. The maximum voltage input for the MPPT controller is 3V.

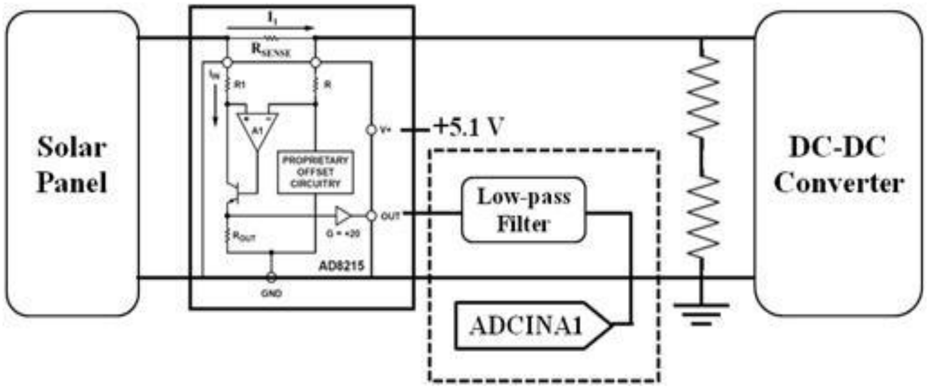

Figure 3.3.2a - current sensor circuit.
Reprinted with permission from Bryan W. Buckley

3.3.3 Analog-to-Digital Converter (Voltage Buffer)

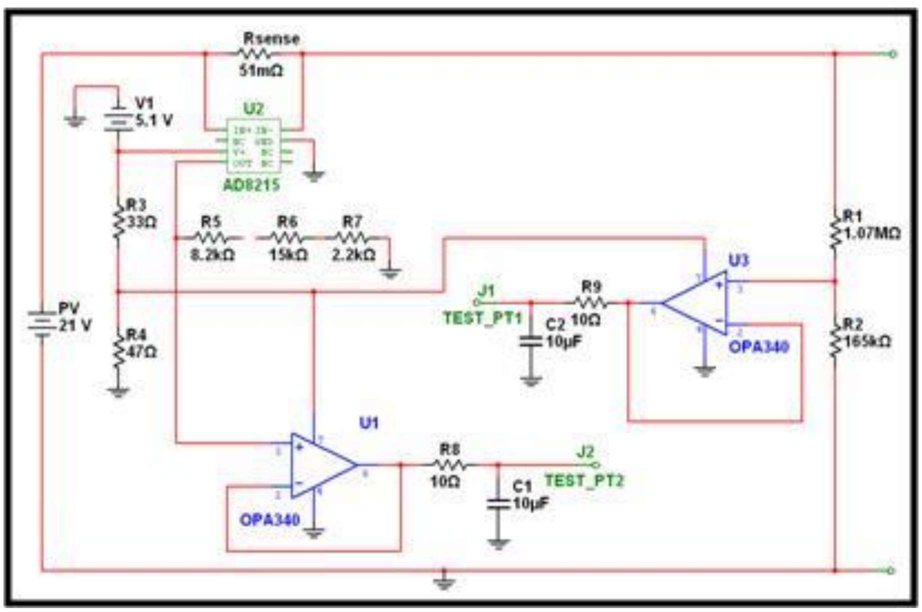

Figure 3.3.3a - System monitor circuit.
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In order to prevent the sensing circuits from receiving a voltage above its threshold of 3V an analog-to-digital converter is need. To condition the voltage Texas Instruments OPA340 op-amps are used in a voltage follower circuit, these outputs are then fed into a low-pass filter. The voltage follower circuits use the high input impedance and low output impedance to preserve the input voltage without over loading the MPPT controller input. Setting the terminal voltages of the op-amp to 3V clips any potential voltage spikes that would damage the ADC channel inputs. The voltage and current sensors combined with this ADC driver circuit fed into the MPPT controller makes up the entire sensing circuit shown below.

3.3.4 Digital-to-Analog Convert

A Digital-to-Analog Convert may be needed to independently power the components of our design. This DAC utilizes an on-chip pulse width modulated (PWM) signal generators to create an output signal used to control the DC-DC converter. A second order analog low pass filter shown in *Figure 3.3.4a* **i**s used to remove the high frequency input of the PWM signal. The PWM signal is controlled via software. This in combination with the analog low pass filter is a cheaper alternative to a dedicated off-chip DAC.

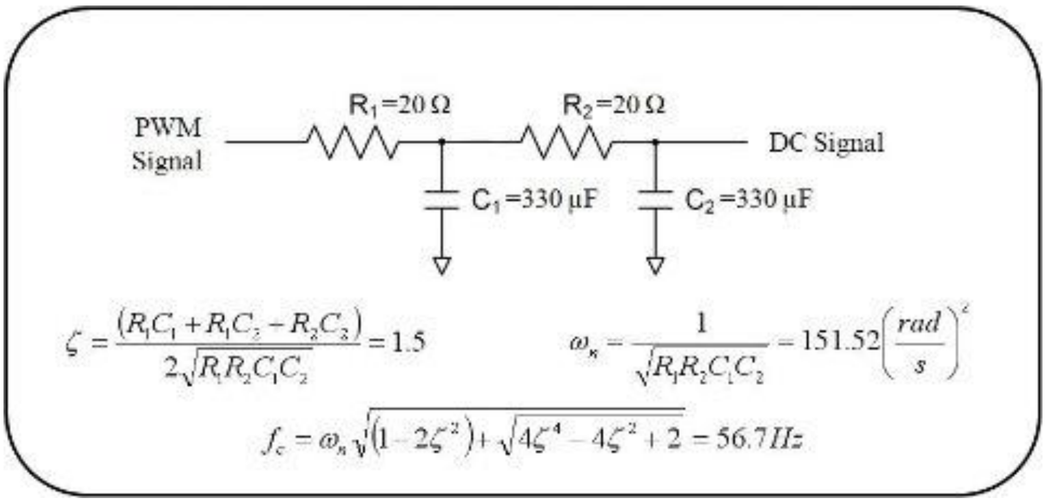

Figure 3.3.4a - Digital-to-Analog Converter Circuit
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3.4 Grid-Tie Solar System

3.4.1 Grid Interconnectivity

Solar panels generate DC, direct current, which is what will power our project. However the excess energy we will be making needs to be sent back to the grid. In order to do this we will need to use an inverter to change our DC power to AC power. There are several types of inverters that solar panels usually use. There are micro inverters, string inverters and finally grid connected inverters. Although grid connected inverters would either be microinverters or string inverters. The basic concept of an inverter is to take a DC input and then switch the direction of the current rapidly by using transistors and to smooth the sharp changes in current direction using capacitors and inductors. This will be covered in more detail below.

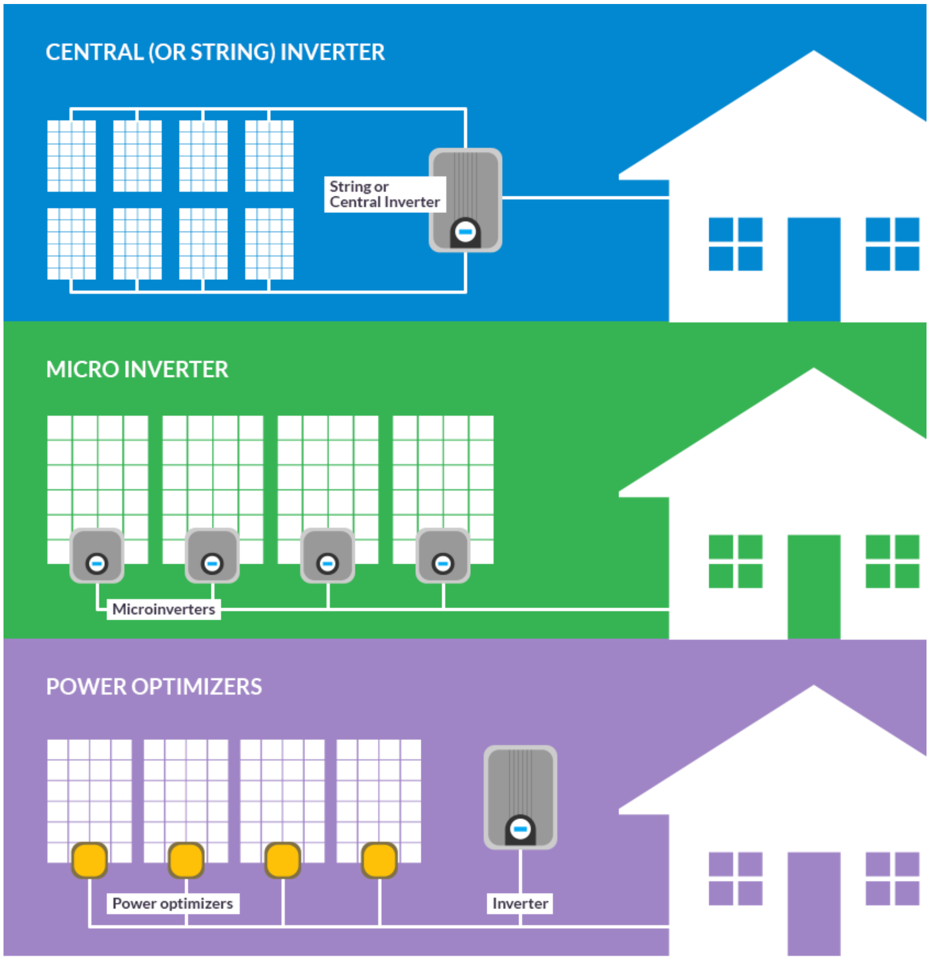

Figure 3.4.1a - string vs micro vs power optimizers.
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Micro inverters invert each panel individually using many micro inverters together. The greatest advantage micro inverters have is that each panel and can be optimized by its own inverter. This leads to much higher efficiency. Micro inverters also make solar systems easily expandable because eliminates the large cost of replacing a single string inverter for the increased output. Each microinverter will only handle a low amount of power meaning they will be exposed to less heat and lower voltage, which will give them a longer lifespan and improved safety. The 100's if not 1000's of DC volts string inverters handle can be fatal. Due to the dispersed nature of microinvertor systems any one failure will not cause the entire system to fail.

String inverters invert the entire string of panels at once usually using a single inverter. This has major advantages when it comes to cost and complexity. However this is not an option if at any point even a single panel is shaded or if the panels do not face the same direction. If a panel is shaded just 9% the entire system could see a power loss of 54%. String inverter systems are also far less complex which makes them much easier to troubleshoot and repair.

A grid tie inverter is a type of string or micro inverter specifically designed for connection to the power grid. Grid tie inverters have added complexity when compared to basic string inverters because grid tie inverters need to output the correct voltage amplitude and frequency to synchronize with the grid perfectly. The inverter also needs to switch off instantly if the grid voltage fails. In other words this inverter will fail if the grid does so this will prohibit the system from operating separately from the grid in the event of an outage. A grid tie inverters added benefit is that it can add excess power from the panels back to the grid and it also eliminates the need for costly batteries that require basic maintenance.

3.4.2 Rectifier

Our project will at times use more energy than our solar panels will be able to supply, especially at night. The most common way to solve this problem is to utilize a battery bank that can be charged in times of overproduction. However this adds more maintenance needs so for our project we will be connected to the grid. In times of underproduction energy from the grid will be taken to power the solar sculpture. Power from the grid is AC and our project is exclusively DC. A rectifier will be used to take the AC grid power and convert it to DC for the solar sculpture.

Many types of rectifying circuits exist. Each of the most basic examples will be touched on and their pros and cons will be assessed. There are three basic rectifier circuits, half wave rectifier, full rectifier and the bridge rectifier. These three circuits also have a single-phase ac and three-phase ac design.

A single-phase half wave rectifier utilizes a transformer and a diode. The three-phase rectifier uses three diodes. This rectifier is the least efficient but most simplistic using a minimal amount of components. The diode works to allow current to pass for half of the AC signal and rejects the other half. This produces a unidirectional output that has severe rippling. This circuit has very few if any real world applications due to its inefficiency and pulsing output. Below is an example of a half wave single-phase rectifier.

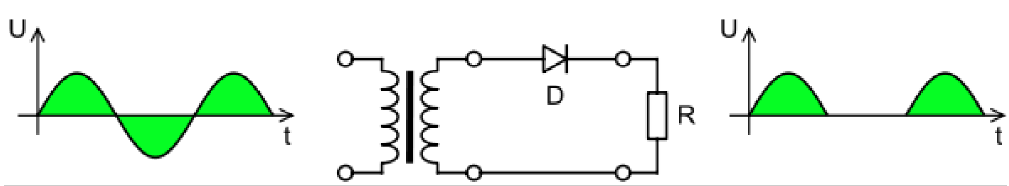

Figure 3.4.2a - half wave rectifier
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A full wave rectifier is similar to the half wave but utilizes twice as many diodes in order to use the other half of the AC signal. This gives the full wave rectifier the advantage of being twice as efficient and also produces an output that has less rippling when compared the half wave rectifier. The full wave rectifier has many real world uses but because of the transformer higher voltage full wave rectifiers become exceedingly expensive. Because of this most full wave rectifiers are used in low voltage applications. Below is an example of a full wave rectifier.

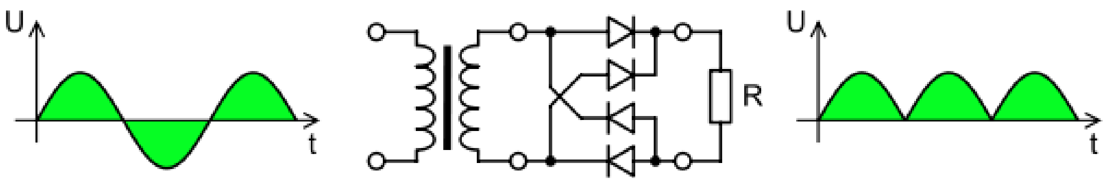

Figure 3.4.2b - full wave rectifier.
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The full wave bridge rectifier is the most common rectifier for real world examples. I uses no transformer so doesn't suffer from exponential price increases with higher voltage applications. The single phase full wave bridge rectifier in its simplest form uses four diodes to capture both halves of the AC input. For a three phase full wave bridge rectifier six diodes are used in order to utilize the other phases. Thyristors are commonly used instead of standard PN junction diodes because of their bistable switching and stability in high power applications.

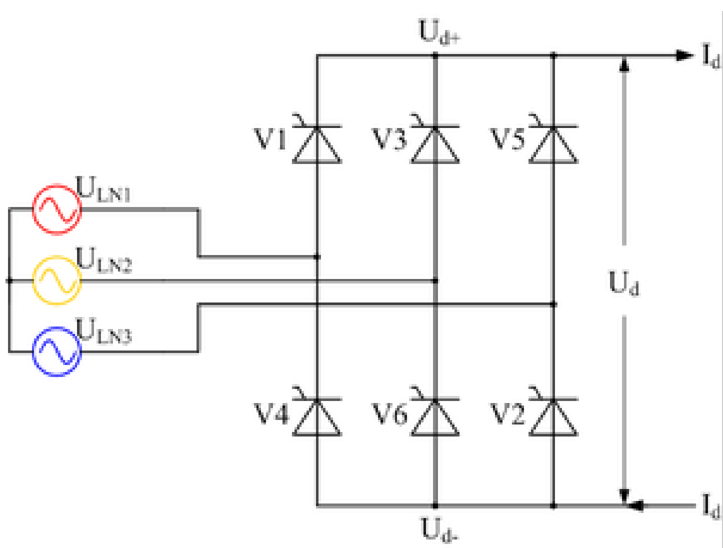

Figure 3.4.2c - three-phase full bridge rectifier.
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Considering the power and efficiency needs of the solar sculpture a full wave bridge rectifier circuit made of thyristors will be the best suited for this project. This is fairly standard in the industry for high power rectifiers. In considerably high power applications multiple thyristors can be run in parallel for each arm of the rectifier.

3.4.3 Inverters

This project full scale deliverable will implement a grid connected string inverter. For this project a single-phase grid connected inverter will be used. Power generation will be low enough that a three-phase inverter will not be necessary and the added cost and complexity can be avoided. The general components for a grid connected power inverter will now be discussed but the final design may vary slightly from this. A grid-connected inverter usually has an input filter, DC to DC step up, current controlled power inverter, output filter and current and voltage sensing module. A basic inverter diagram like the one that will be used in the solar sculpture installation prototype is pictured below in *Figure 3.4.3a*.

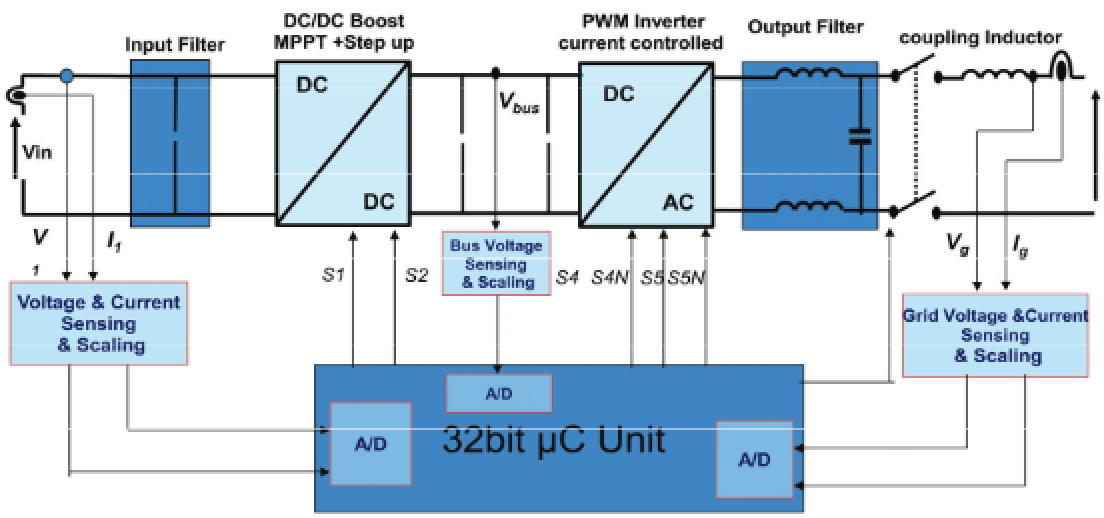

Figure 3.4.3a - inverter diagram.
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The input filter is used to filter out unwanted input signals that could potentially harm the system further down the line. This filters main goal is to make sure the input is within the operating range of the inverter.

After the input filter a DC to DC converter, generally a step up inverter, is responsible for supplying the right DC voltage and is also responsible for the maximum power point tracking. Generally high voltage gain, efficiency and step ratios are desired characteristics in this stage. This high voltage gain can either be achieved through one of two ways: by capacitor multiplier circuits or through a high frequency transformer. Capacitor multiplication is when a small capacitor can act like a larger capacitor by using the gain of a transistor as a multiplier. HF transformers are used when galvanic isolation is needed. Transformers can lead to leakage flux, which negatively affects efficiency. The higher the turn ratio in the transformer the higher the leakage flux. This poses an issue when large step ratio is needed so to realize a high step up ratio with low turn ratio a voltage boosting circuit can be used on the output stage. Below is an example of a pulse width modulated DC-to-DC converter that doesn't utilize any capacitor multiplication.

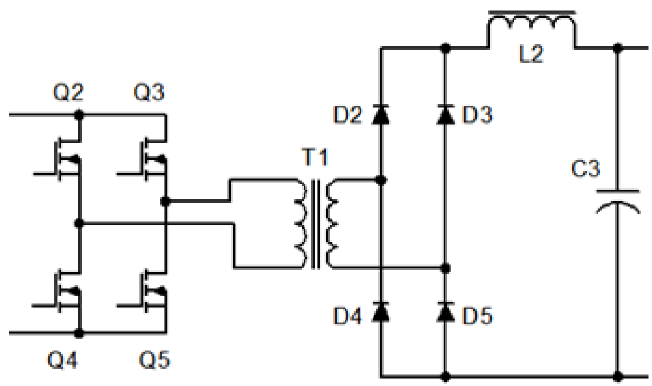

Figure 3.4.3b - DC to DC Pulse Width Modulated Converter.
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The DC-to-DC convertor output feeds the input for the DC to AC convertor. The DC to AC inverter is generally a pulse width modulation inverter that is current controlled. The basic schematic for this inverter is an H bridge made of mosfets with anti parallel diodes providing protection from freewheeling. The H bridge mosfets will are fed a signal to activate at the frequency to match the power grid. An example of an H bridge with anti parallel diodes can be seen below.

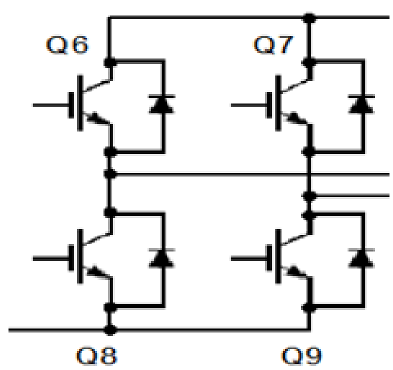

Figure 3.4.3c - H Bridge with Anit Parallel Diodes.
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The output filter for a solar inverter is most commonly an LCL filter. This LCL filter acts to eliminate the unwanted harmonics created by the H bridge inverter. One drawback to LCL filters is that they will amplify frequencies around their cutoff frequencies so dampening resistor is needed. This resistor decreases efficiency so an actively damped approach can be taken using a virtual resistor.

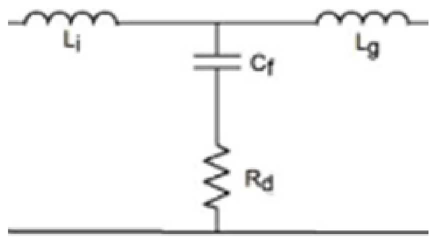

Figure 3.4.3d - LCL Filter.
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Voltage and current sensors are needed to match the output of the inverter with the grid. These sensors are placed at the input from the solar panels and also at the grid. This information is then processed and the relevant information is passed to the DC-to-DC converter and DC to AC inverter so the proper voltage and frequency is produced.

For the ⅛ scale model a string inverter is not practical so a microinverter will be used. For the ⅛ scale model only one solar panel will be used because of budget constraints and safety concerns, due to high voltages, with larger systems. This single panel will not be able to drive a larger string inverter.

3.4.4 Disconnects

Connecting to the utility grid to both draw and distribute power requires that the power capabilities of this project are up to the National Electrical Code for both the input and output of the system. Drawing power from the grid means taking 120 Vac and converting it to 12V DC necessary to power the electronics of this project. The highest potential of this electricity relay is from the source distributing the power, in this case the wall outlet. There are two types of disconnects capable of protecting the electrical components, a fuse box or an AC disconnect breaker. The fuse box limits the current from exceeding the maximum limit, for the 200W system being developed a 3 amp fuse rating is recommended based of the voltage and resistances in the design. The secondary option is to have a AC disconnect breaker, this is a physical switch that allows users to manually reset the connect between the load and the grid if the current previously exceeded the maximum range. This device increases the longevity of operating the project but increases footprint and cost of the project that may not be necessary for the prototype.

Inputs into the grid must be handled carefully as to not harm the electrical components relied upon by the public. Common with solar panel photovoltaic systems specifically, DC disconnects are needed to buffer between the output from the solar panels and the AC receiving end that is the utility grid. The solar panels have a high operating voltage although their labeling is typically half the open circuit voltage. Estimation for the proper DC disconnects size must be over estimated to assure the safety of the users. These rating depend mainly on the voltage and current capable of being handled by the inverter used by the system. The AC and DC disconnects are placed on opposite ends of the inverter as to buffer each side from a malfunction in either system. Necessary for safety standards it is likely these design parts will be purchased rather than design to assure safety.

3.5 Microcontrollers

This section details the specifications of the microcontrollers used throughout the solar sculpture installation. Three microcontrollers are used in total, the Arduino Uno R3 as the Pixy Cam Control Unit, the Microchip MSP430G2553 as the Solenoid Control Unit, and the Raspberry Pi 3 as the System Status Unit.

3.5.1 Arduino Microcontroller

The Arduino microcontroller controls all inputs and receives all outputs from the Pixy Cam vision system. The Pixy Cam has been specifically built to interface with the Arduino microcontroller making the meshing of these two a natural process. A custom RTOS solution will run on this microcontroller in an attempt to reduce the power consumption of the unit and to increase the challenge of the overall project.

The Arduino microcontroller’s primary function is to serve as the main processing unit for the installation. Thankfully, the Pixy Cam being used as the solar sculpture’s vision system contains an onboard processor and is capable of taking on some of the processing work involved in the realization of this project. However the Pixy Cam is limited by its relative newness and its inflexible firmware paradigms. Therefore a significant portion of the intensive work involved in image processing (positional data interpretation, clustering algorithms, etc.) Will need to be performed by the external Arduino microcontroller.

The Arduino Uno R3 is capable of running at an exceptionally fast 16 MHz, however in the context of this project it will likely only need to run at 2MHz, a far reach from its top speed. The reason for this reduction in speed is to reduce the power consumption of the microcontroller and prevent exceeds the capabilities of the Arduino microcontroller’s less sophisticated dependent, the MSP430G2553. A major constraint in throughout this project is the reduction of power usage, as all savings contribute to the solar sculpture's net gain for the power grid. Extensive speed tests will be conducted to determine if the reduced clock rate has a noticeable effect on the responsiveness of the graphical waterfall array. If this is the case, the Arduino's speed can be increased while limiting the rate at which data is sent to the MSP430G2553 to acceptably sparse intervals.

The Arduino microcontroller will communicate with the Pixy Cam through a USB connection, it will communicate with the MSP430G2553 through an I2C communications interface. Similarly, communications between the Arduino and the Raspberry Pi 3 System Status unit will utilize I2C communications interface. I2C communications are used primarily for the low pin count they require and their capability for error handling. Handling errors in inter microcontroller communication will likely be a pronounced feature of the installation due to concerns over the possibility of pins being damaged by excess water from the graphical waterfall array.

3.5.2 MSP430G2553 Microcontroller

The solar sculpture requires a device to control the output of its large array of water solenoids, a "Solenoid Control Unit". This job was initially intended for a microcontroller with 32 output pins whose only purpose would be to decode input commands from the Arduino "Pixy Cam Control Unit" and configure the graphical waterfall array appropriately. However, with both budget and power concerns in mind the MSP430G2553 was selected instead, a microcontroller with only 24 I/O pins. The management of the graphical waterfall array would be handled through the usage of two 8-bit serial input to parallel output (SIPO) shift registers controlled by the MSP430G2553. The details of this solution are discussed further in section 4.8 Solenoid Control Unit.

SIPO shifters no longer see wide use in modern circuits, primarily due to the availability of a larger amount of I/O pins on contemporary microcontrollers. However, a major consideration for the solar sculpture is the net power gain it can provide to the grid. With this in mind, it is ideal to keep the power consumption of all devices internal to the installation as low as possible. The MSP430G2553 is one of Texas Instruments famously ultra low power microchip options, requiring only 230 uA @ 3.6V running at 1MHZ.

The MSP430G2553 is architected for reliability and extended product life, factors that are both important to the team when it comes to hardware components of the solar sculpture. The device can produce 16-bit serial output, which will be perfect for managing a daisy chain configuration of SIPO shift registers. For achieving the evening mode discussed in the executive summary, a single bit internal to the microcontroller can be used to distinguish between evening and afternoon modes.

While in the evening a continuous active high signal will be sent by the MSP430G2553 to the graphical waterfall array, and it will instead manage the array of variable brightness LEDs.

The MSP430G2553 is able to communicate with other microcontrollers through its universal serial communication interface, and will do so with the Arduino Pixy Cam Control Unit in order to receive observer positional data from the vision system of the installation. The MSP430G2553 has a total of five separate low power modes that the team can experiment with if conserving power becomes an even more crucial factor. The MSP430G2553 is also capable of going into a power conservative sleep mode during long periods of inactivity, during which it is capable of being woken up by the digitally controlled oscillator in less than one microsecond.

It remains an encouraging factor as the Solenoid Control Unit's speed may be increased during testing to allow for discrepancies between solenoids in the graphical waterfall array.

3.5.3 Raspberry Pi 3

The solar sculpture installation requires a unit to monitor its subsystems. This subsystem status is for the retrieval and display of the installation's efficiency figures and solar power statistics. However it is also used as a system health monitor and can, if need be send interrupt signals to the Arduino or MSP430 in the event of critical system failures.

The Raspberry Pi will also be used to control the installation's water pump. The Raspberry Pi will monitor the water level in the water basin utilizing a HC-SR04 Ultrasonic Sensor. The ultrasonic sensor measures the time required for a ultrasonic wave to bounce off the bottom of the basin and return. Hence the water level (in centimeters) of the installation's water basin can be effectively evaluated and provided as input data to the Raspberry Pi. Once the water level crosses a predetermined "high" threshold value, the Raspberry Pi can signal the water pump to activate. If the water level decreases below a given "low" threshold value, the Raspberry Pi will then signal the pump to deactivate.

The Raspberry Pi being used is the Raspberry Pi 3B. It has onboard Bluetooth capabilities, which may be used to control the installation's water pump activation. The Raspberry Pi is capable of running as fast as 1.2 Ghz. For the installation's purposes, it will run checks on the solar sculpture's subsystems at a much slower rate. However its speed capabilities will be comfort since the Raspberry Pi will have to respond quickly to the water needs of the installation, and if a wireless connection is used, some delays are expected between the ultrasonic sensor's observance of the system's need and the water pump's activation.

3.6 “Pixy” Cam (CMUcam5)

The solar sculpture is intended to be interactive first and foremost. To incorporate interactivity into the sculpture, a motion-tracking element was required in order to trigger events based on observer actions. Due to team members’ interest and prior experience, a computer vision element was chosen to satisfy the project’s motion tracking needs.

The Xbox Kinect was initially considered for the vision system. The Kinect was particularly attractive because of its IR depth sensor. This IR sensor bathes the Kinect’s field of vision in infrared light and then observes the reflected IR in order to make distance calculations. The Kinect can thus render a complex 3D image of a scene in its view (about 1 to 4 meters). The 3D point cloud for each image is accessible to the user, however distinguishing and tracking objects of interest from frame to frame must all be done externally. In the solar sculpture’s case, this would mean the microcontroller in charge of interpreting the Kinect’s output would require large amounts of processing power. Additionally, the Kinect is not well suited for capturing motion in a large outdoor scene. It has been primarily designed to function from a fixed point within a well-lit and enclosed room. The Pixy cam was then proposed as an alternative vision system.

The Pixy cam, or CMUcam5 is an inexpensive DIY vision sensor used for object recognition purposes. It contains a NXP LPC4330 dual core onboard processor and hence can independently perform the intensive processing required to recognize objects frame by frame, sending only useful position data to the microcontroller in charge of the Pixy Cam. For added capability the Pixy cam comes with OpenCV libraries installed and ready for use. OpenCV is a library of functions used for programming solutions for various real-time embedded system computer vision scenarios.

This was a major benefit, since several team members already had exposure to OpenCV libraries in previous coursework and it was desirable to utilize their functionality on this project. The Pixy Cam is built to run in concert with an Arduino microcontroller and has a variety of options for conveying its output data (everything from UART serial communications to a simple USB connection).

The only issue encountered while researching the Pixy was its dependence on color based filtering algorithms to detect and track objects of interest. The Pixy cam learns what the objects of interest are for a given system by analyzing example objects presented to it in its “teaching” mode. While examining an object in “teaching” mode the Pixy cam calculates the hue and saturation of each pixel of the object, storing this information away so that the object of interest can be detected in the future.

This is known as a “supervised” object recognition system, since a human user is indicating objects of interest in the environment by “tagging” them (color tagging in the Pixy cam’s case). The proposed object recognition system was an “unsupervised” case, i.e. the vision system had to be capable of detecting and tracking “untagged” objects of interest. Nothing in the Pixy cam’s existing source code allowed for general motion tracking (tracking the movement of an “untagged” human body), so alternative options to the Pixy cam were briefly considered.

Chiefly among these was the FLiR Lepton thermal imaging module. Identifying human observers as objects of interest through the use of thermal vision was considered a viable option by the team. However, the price jump from the Pixy cam to the FLiR was enough to discourage this idea, seeing as budget constraints were already a concern due to the large number of water solenoids needed to realize the solar sculpture. In addition to the FLiR’s cost it had the added disadvantage that all object detection and tracking software would have to run external to the vision sensor (much like the Kinect). Thus, the team returned to the cheaper option in the Pixy cam, and discussed how best to resolve the issue of detecting and tracking untagged humans.

Vision System Analysis				
System	**Vision Method**	**Outdoors/Low-Light Performance**	**Comms**	**Pricing**
Xbox Kinect	Uses 3D point cloud rendering by bathing scene in IR light. Has capablility to make depth calculations.	Performance suffers when outside of a closed room due to IR light interference.	USB connection, will need appropriate drivers to control kinect.	$99.99
CMUcam5	Uses "color tagging", tracks motion by analyzing the hue and saturation of pixels in view.	Auto-exposure correction and auto-gain to prevent image from "washing-out" while outdoors. Special lowlight settings for night.	SPI/I2C/UART/USB	$69.00
FLiR Thermal Imager	Uses Longwave Infared Imaging to segment human observers from the enviroment.	The FLiR has a relative thermal detection capability which allows it to adapt to the heat signatures of a given enivroment. However its low resolution could cause problems in estimating the observer position.	SPI/I2C	$259.95

Figure 3.6a - analysis of various vision system options.

After doing further research online we decided our best course of action would be to move forward with the Pixy cam, simply modifying its open source software to suit our needs for the solar sculpture. The source code for both Pixymon (software interface for debugging Pixy Cam projects) and the Pixy cam itself are provided on Github by the developers of the device.

The proposed approach to general motion tracking would be something of a hack of the existing Pixy firmware. Our approach was to use the Pixy cam's capability to distinguish the RGB color signature of a given pixel to detect regions of charging color i.e. (moving objects, or people in our case). By this method the Pixy cam could signal to our system when and where motion was happening in relation to the installation by analyzing the change in pixel color over time for the Pixy cam's field of view.

The team's desire for this project was to implement this general motion-tracking algorithm on the Pixy's microprocessor itself, hence isolating all of the object recognition processing to a single device and preserving the modularity of our system. However, we are restricted by our inability to modify the Pixy cam's firmware, hence we've ensured there is significant processing power available on the microprocessor controlling the Pixy cam, in case further image processing is needed after receiving the Pixy cam's output.

3.7 Max Power Point Tracking

Necessary to maximize the efficiency of the solar panels a Max Power Point Tracking (MPPT) algorithm is needed. MPPT uses a Perturb and Observe method to monitor the voltages and currents to maximize the power output. The operational voltage increase or decreases due to temperature and irradiance the algorithm, then the system checks in the power increases and repeats the operational voltage adjustment accordingly. Multiple algorithms were researched to find the best fit in our design, key factors determining our selection includes ability to detect multiple maxima, costs, and convergence speed as the irradiance and temperature levels vary the maximum power point changes.

The challenge of programming efficient MPPT systems is to distinguish between the true maximum power point and the local maximum. The majority of the costs of the MPPT system is from the hardware used to monitor and control the system, the software algorithm determines which hardware components to use. The convergence of a high-performance MPPT ideally takes minimal time to find the maxima operating voltage or current sensors. Maximizing the convergence speed is dependent on the combination of hardware and software implemented in the MPPT design.

3.7.1 Perturb and Observe

One method considered for the MPPT algorithm is the Perturb and Observe (P&O) method, which modifies the operating voltage or current of the solar panel to oscillate around the true power point maximum. The algorithm increases the operating voltage, and then measures the power output. If the current power is greater than the previous operating voltage, the operating voltage continues to increase and measure until the power output decreases. This method as seen in the algorithm flowchart *Figure 3.7.1a* repeats indefinitely, continually oscillating around the maximum power point.

This system requires inexpensive hardware and the software algorithm is simple, reducing operating costs. The disadvantage of the P&O method stems from the continual oscillation around the max power point, with rapid changing irradiance levels the algorithm can quickly track in the wrong direction. It is important to choose a step size that will recover from this rapid change in irradiance, but small enough to minimize the speed of convergence and range of oscillation.

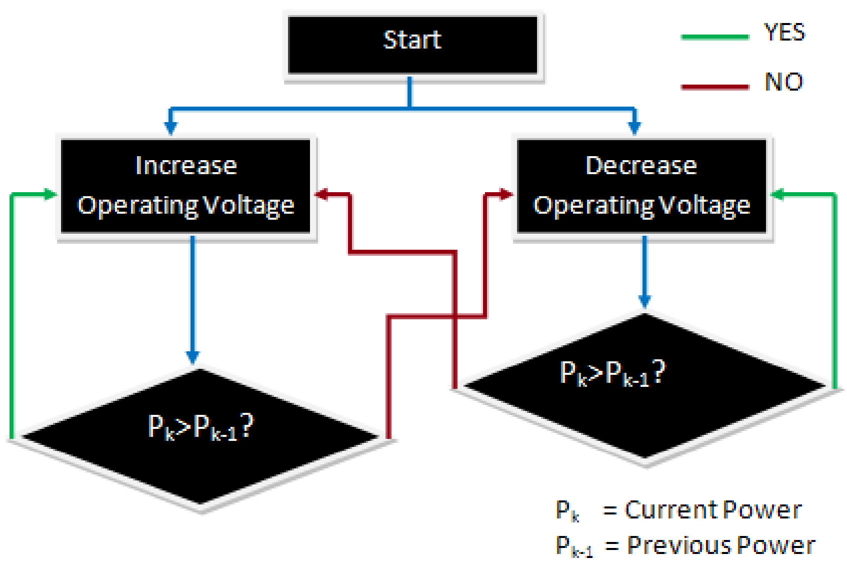

Figure 3.7.1a – Perturb and Observe Algorithm Flowchart.
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3.7.2 Incremental Conductance

The second method considered for MPPT is Incremental Conductance that works on the fact that the MPP is along the zero slope of the power-voltage curve as seen in *Figure 3.7.2a*.

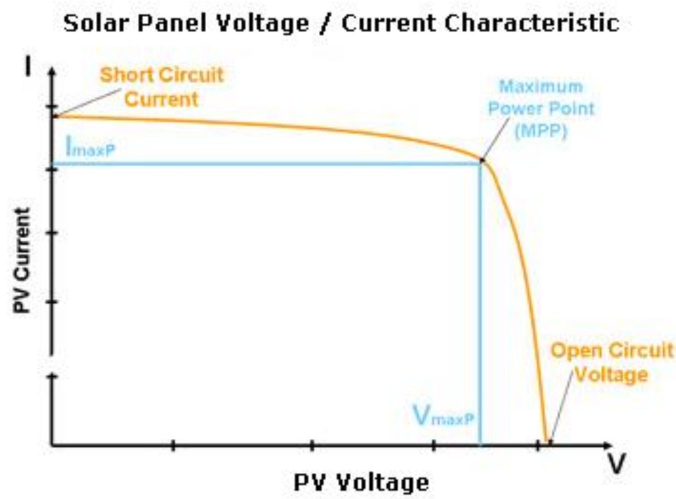

Figure 3.7.2a - MPPT Curve.
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Comparing the instantaneous conductance (I/V) to the incremental conductance (ΔI/ΔV) the algorithm measures whether the MPP moves positively to the left, or negatively to the right. The system maintains this MPP until a significant change in irradiance or temperature causes the conductance to increment. This technique is advantageous because it can track and maintain the MPP, reducing any loss due to the constant oscillation of the P&O method. This method also recovers rapidly from changing conditions. The disadvantage of this method is the complex computation decreases the response time of this tracking method outlined in *Figure 3.7.2b*.

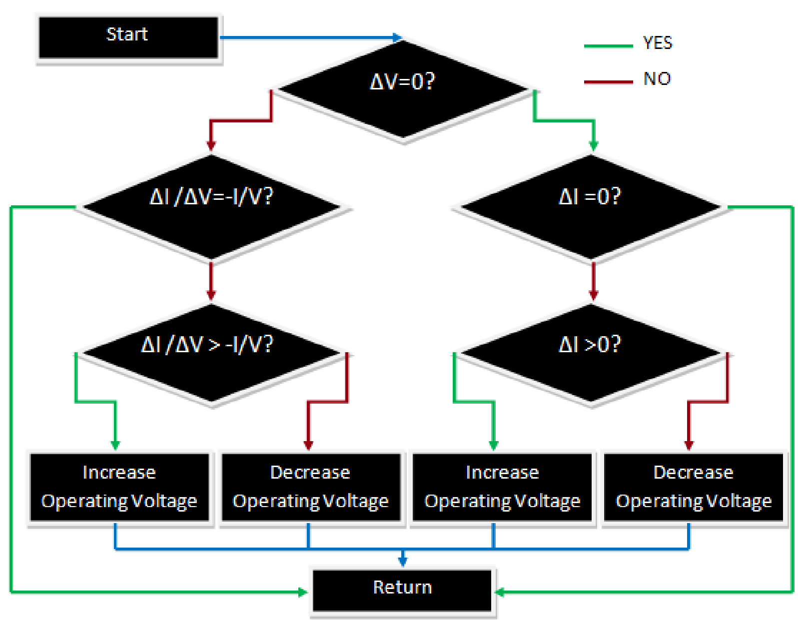

Figure 3.7.2b - Incremental Conductance Algorithm.
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3.7.3 Embedded Software

Using the MPPT controller the algorithm implemented is the P&O method. This method is implemented in an infinite for loop. The simplicity of the P&O method allows for continual operation under low power and computation requirements. Initiating the loop the controller measures the current power output from the ADC channel, then increases or decreases the operating voltage until the power output exceeds the previous power output. The PWM signal increases or decreases relative to the voltage incrementation. Decreasing PWM duty cycle decreases with the operation voltage decrease.

3.7.4 Impedance Matching

To maximize the power output of the solar panels impedance matching in needed. When the impedance of the source is the same as the load impedance there is minimal current and voltage lose, outputting the most efficient power. A DC-DC converter can accomplish impedance matching and a PWM if regulated by a microcontroller. In this implication a synchronous buck converter is used to step up or down the operating voltage of the solar panel.

This buck converter uses a combination of complex impedances, a diode, and a transistor as seen in *Figure 3.7.4a*. Switching the transistor from OFF to ON charges the inductive load, causing a voltage drop across it terminals and in turn decreasing the net voltage across the load. The switching of the transistor is controlled by the duty cycle of the PWM, which is controlled by the microcontroller P&O algorithm.

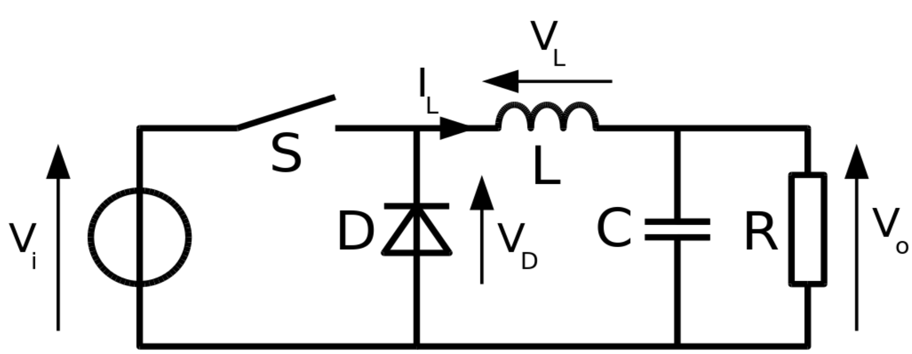

Figure 3.7.4a - Synchronous Buck Converter.
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3.8 Power Distribution

Understanding the National Electrical Code (NEC) is important to ensure the safety of this residential grid-tied solar electric circuit. These requirements include Combiner box, DC disconnect, Overcurrent Protection, ground fault protection, net meter socket, AC disconnect, and DP circuit breaker all outlined in *Figure 3.8a*. To determine the necessary component features and values the following measurements must be record or calculated. Circuit voltage and current levels, number of conductors (wires), size of conduit, required breaker sizes (ampacity), enclosure locations, highest estimate of the ambient temperature given location, and whether or not the inverter is transformer less, and all measurements considered for entering and leaving the components.

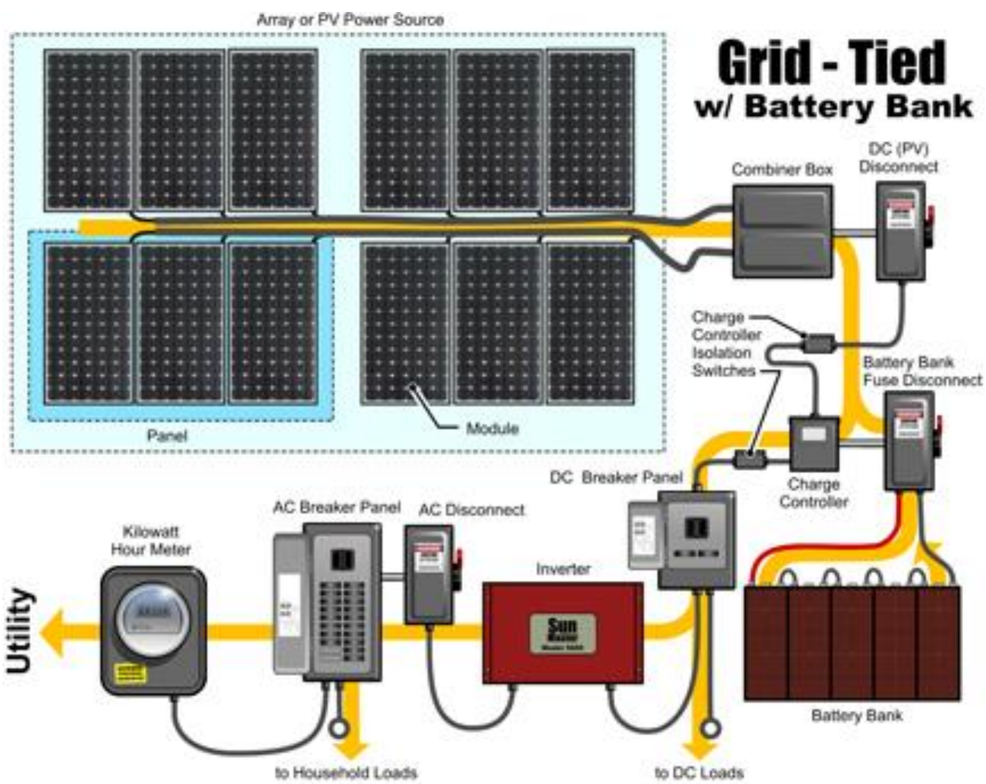

Figure 3.8a - Grid-Tied Power System
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3.8.1 Power Measurements

Due to Florida's extreme heat the voltage, current, and watt variations are important to consider when purchasing components. With the increase in temperature the voltage will decrease, causing the power to decrease is the current is not properly adjusted. The primary measurement need to base the rest of the system off is the open circuit voltage of the PV panels. This is defined in *Equation 3.8.1a*.

$$V_{max} = V_{o.c.} \text{ X}$$

EQ 3.8.1a - number of modules per string X low-temp voltage correction factor.

This equation will also size the inverter used, and largely depended on the series or parallel configuration of the panels. The value for the Low-temp voltage correction factor is determined from *Table 3.8.1a* provided by the NEC.

Table 3.8.1a Low Temperature Correction Factor
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Ambient Temperature (°C)	Correction Factors for Ambient Temperature Below 25°C (77°F)	Ambient Temperature (°F)
	(Multiply the rated open-circuit voltage by the appropriate correction factor shown below.)	
25 to 10	1.06	77 to 50
9 to 0	1.10	49 to 32
-1 to -10	1.13	31 to 14
-11 to -20	1.17	13 to -4
-21 to -40	1.25	-5 to -40

3.8.2 Combiner Box

Current and amperage calculations are crucial to maintaining the system health and preventing any power overloads. The Combiner box is needed to measure the ability of the conductors to handle the current size, and disconnect the fuses is the current exceeds this threshold. To combine a string of multiple solar panel modules without exposing the active terminals to the elements a junction box is needed.

This combiner box placed near the solar array will have single positive and negative output terminals traveling to the inverter as seen in Figure 3.8.2a. Rather than the red and black wires leading to the charge controller our design will involve an inverter, with microinverters the AC current will be combiner and run through a circuit breaker rather than a fuse box. This combiner box provides surge protection, notice all components are tied to ground through the green wire to assure overcurrent protection. Due to exposure to the elements and high temperatures it is important to adjust circuit factors to account for this. To calculate the maximum circuit ampacity the following *Equation 3.8.2a* is used.

$$\text{Circuit ampacity} = I_{max} \times 1.56$$

EQ 3.8.2a – maximum circuit ampacity

The short circuit current is used for the Imax and the multiplying factor is a combination of the continuous current received by the PV circuit.

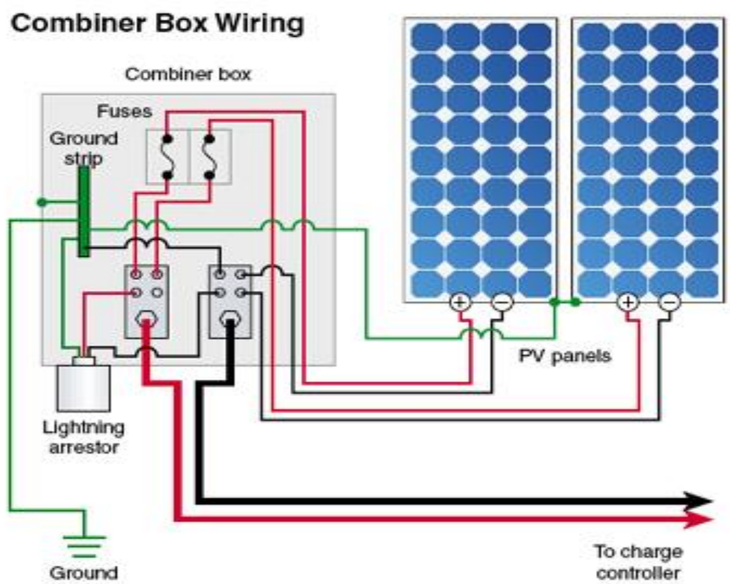

Figure 3.8.2a - Combiner Box Wiring Diagram.
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3.8.3 DC Disconnect

In addition to the combiner box a DC disconnect will be need to manually power off the relative PV circuit sections. The ampacity rating for this is similar but will have a multiplying factor based on the number of solar panels used in the combiner box shown in *Equation 3.8.3a*.

$$\text{O.C. ampacity} = I_{max} \times \text{\#Module Strings in the array} \times 1.56$$

EQ 3.8.3a – O.C. ampacity calculation

3.8.4 AC Disconnect

Necessary to safely draw current from the grid to our circuit an AC disconnect is needed. The AC disconnect consists of 3 inputs, 2 “hot” conductors and 1 neutral lead, each of the two conductors carries half of the 120V grid output. To calculate the circuit ampacity needed by the AC disconnect the *Equation 3.8.4a* is used.

$$\text{Circuit Ampacity} = \text{Inverter AC output current} \times 1.25$$

EQ 3.8.4a – circuit ampacity needed for AC disconnect

Different from the DC disconnect this formula uses the continuous output current from the inverter and a smaller max current cushion of 1.25. Running the AC disconnect to our circuit we will need a two-pole (DP) backfed circuit breaker. This provides a physical barrier between the utility grid and inverter, preventing short-circuiting and any chance of arcing.

3.8.5 Net Meter

A Net Output Meter is needed to measure the power outputting to the grid. This assures the system meeting the OUC requirement of Net Zero+ power. Mentioned previously by OUC the requirement for 850 kWh/year is a positive value after considering the power being leached by the project devices.

3.8.6 Wiring

Determining the correct wires needed for the design is based off voltage, current and external variables. Wire sizes need to account for overcurrent devices and conduit of the circuit, specifically wiring distances, insulation needed and local temperature. Safety constraints are necessary to consider for the hydroelectric interaction of these components.

3.8.7 Power Supply

The energy harvested from the solar panels will be converted to AC and sent to the grid. The electricity used to power our system will be drawn from this same grid. Our project uses both AC and DC power, the AC power is 120V and 3 phase, while the DC power must be converted from the grid to 12V solenoids and 5V step down for the microcontroller. To implement this inversion our design consists of a full-bridge rectifier and voltage regulation circuits. This will step down the circuit to power our DC components. *Figure 3.8.7a* displays a linear realization of the power supply.

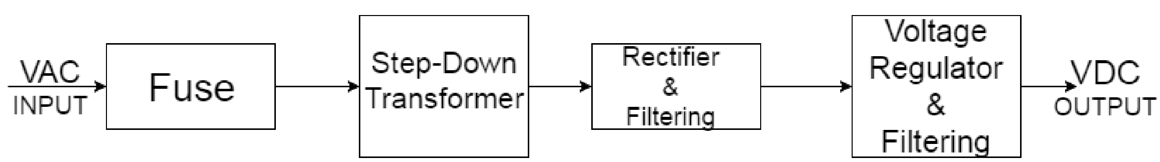

Figure 3.8.7a AC-DC Power Supply.

3.8.8 Voltage Regulator

A Voltage Regulator receives any input voltage and outputs a constant and limited output voltage dependent on a reference voltage. Necessary to operate our microcontroller a constant 5V will be supplied. Used in the circuit is a 3 terminal fixed voltage regulator, shown in *Figure 3.8.8a*. Comparing the reference voltage to the series passed input voltage the amplifier outputs a fixed voltage.

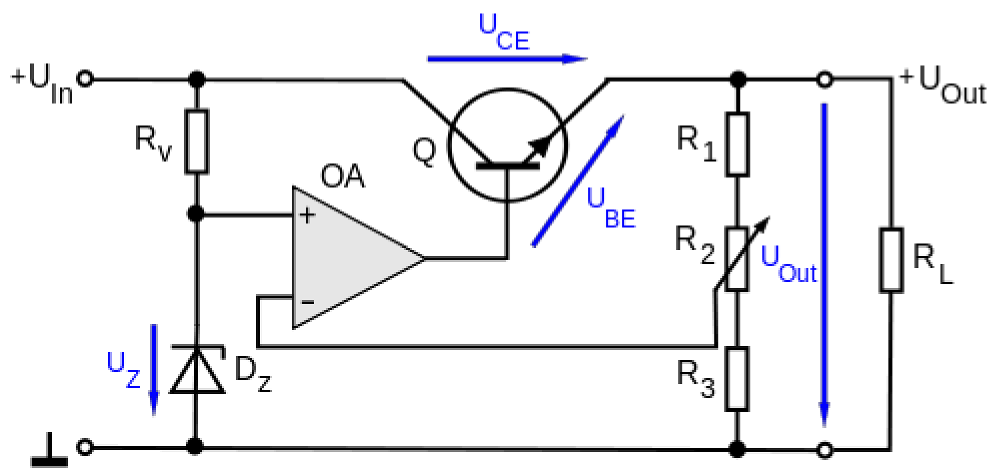

Figure 3.8.8a – Regulator with an Operational Amplifier.
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3.9 Computer Vision Research

One of the central challenges of the proposed solar sculpture is the accurate detection of observer interaction with the installation. Observer motion must be detected and contextualized by the vision system in real time. To achieve this the Pixy Cam being used as the solar sculpture's motion detector will utilize a variety of the functionality available to it via its native OpenCV libraries. OpenCV (The Open Source Computer Vision Library) is an open source collection of functions used to realize solutions for common real-time embedded system computer vision scenarios. OpenCV functions are used practically anywhere that vision sensors are being used and will certainly see use in this project.

The following section will detail the team's research into computer vision scenarios relevant to the solar sculptures unique unsupervised general motion detection.

3.9.1 Image Difference

Motion segmentation is one of the core fundamentals of object tracking in computer vision. It basically consists of separating by some means the objects being tracked from the background environment. Implementing a means of motion segmentation via the installation's pixy cam will be essential to the successful detection and tracking of observer motion. There is a vast collection of algorithms and methods that perform real-time motion segmentation, however one of the simplest and most effective methods is the concept of image difference.

Image difference seeks to construct a map of differences between two contiguous frames from a video snippet. It identifies these differences by comparing the intensities of each of the frames corresponding pixels. This technique is extremely sensitive to image noise (random variations in brightness and color that can be thought of as "digital background noise") and is practically unusable when the camera capturing the images is moving.

Due to the fact that the installation utilizes a fixed camera solution and does not require fine-grained object recognition, this primitive but effective technique is viable solution. Image difference is best at tracking blobs of motion moving through a series of frames. Typically these motion blobs are then used as input to more advanced computer vision techniques, which might attempt to identify specific objects or produce a more fine tuned structure for the objects of interest. However in the case of the proposed solar sculpture, observers can very well be thought of as vague regions of movement. Considering that the resolution of the graphical waterfall responding to observer movement is made up of only 16 solenoids.

To reduce the rate at which the Pixy Cam observes a "false positive" (instructs a solenoid to turn active when no observer is present in front of the solenoid) a high threshold can be applied to filter final output of the image difference solution. This would further reduce the definition of the regions of motion but should effectively eliminate any response to "background movement" and help to manage the effects of image noise on the system.

3.9.2 Optical Flow

Optical flow techniques will likely be utilized by the installation's vision system. Optical flow is the tracking of "object of interest" pixels from frame to frame in order to track the apparent motion of an object in a constant series of images. Optical flow calculations can be complicated by the motion of the camera in relation to the object, but thankfully in the proposed solar sculpture the Pixy cam will observe a fixed scene from a fixed point on the installation, making it a great deal easier to track the motion of objects of interest (observers in this project's context) passing through the scene. Optical flow calculations are based on two initial assumptions. First that the intensities of an object's pixels remain constant from frame to frame, and second that pixels neighboring one another are likely to have similar apparent motion.

Optical flow can be best described at the micro scale. Imagine a singular pixel on an object in motion across a series of frames. This pixel has a constant intensity as described by the initial assumptions of optical flow. From frame to frame the pixel travels a distance (dx,dy) over a given period of time, (dt between frames). Hence when describing the optical flow of a pixel, one can derive Equation 3.9.1a. Where U represents the change in the pixel's horizontal position with respect to time, and V represents the change in the pixel's vertical position with respect to time.

he Lucas-Kanade method is a popularly estimation for optical flow. The Lucas-Kanade method assumes a constant optical flow in small groups of local pixels. By combining the flow of several neighboring pixels, Lucas-Kanade method reduces the complexity and ambiguity of finding the optical flow for certain objects. Also, since the flows of several pixels are being grouped together, it has the added advantage of reducing error due to image noise. OpenCV provides the functionality to make Lucas-Kanade estimations with a single callable function.

However before optical flow estimations can be made, first points o objects of interest, or rather the specific pixels whose motion is being estimated, must be identified. OpenCV provides a function to identify these points using Shi-Tomasi corner point's method. This method uses the intensity of image gradients in comparison to the second derivative of the image to find "good features to track".

$$f_x u + f_y v + f_t = 0$$

Equation 3.8.2a - Optical flow derivation. Reprinted with permission from OpenCV.

While Lucas-Kanade is all about tracking a small set of features (a few pixels on objects of interest tracked across a series of images), another option is utilizing dense optical flow functions. Dense optical flow evaluation skips the process of determining specific points to track in a given series of images and simply tracks all pixels in a series of images. This requires a higher degree of processing on the part of the microcontroller in charge of the vision system but provides a clear delineation between the static environment that the fixed Pixy Cam is watching and the "hot spots" in the image where motion is taking place. This approach is more about tracking a streak of changing pixel intensities in relation to time. Examples of sparse optical flow estimation and dense optical flow estimation using OpenCV supported functions are provided in *Figure 3.9.2a*.

Figure 3.9.2a - comparison of sparse optical flow (left) with dense optical flow (right). Reprinted with permission from OpenCV Libraries

However in the case of the proposed solar sculpture it is not enough to simply follow the direction of movement across multiple frames. The vision system for the installation must be able to catalog the history of an object moving through a series of frames. In other words for a given snippet of video, the Pixy Cam must be able to understand the direction of an observer's motion and the current position.

Fortunately, there is support for just such functionality in the OpenCV libraries. Generally, a point or pixel on the object of interest or object being tracked is chosen as the proverbial center of the object for purposes of position calculation. The point being tracked is assigned x and y coordinates based on the location of the “center” pixel in the frame. As the object moves through a series of frames a “buffer” of previous x and y coordinates is kept for reference. This stored positional data is essential to the successful operation of the graphical waterfall array. The Positional data of an object of interest in motion will be interpreted by the Pixy Cam Control Unit and used to trigger or deactivate specific units in the water solenoid array. The details of this solution will be discussed further in section 4.6 Pixy Cam Control Unit.

3.10 PCB

A printable circuit board is an essential aspect to our solar system circuit design, the PCB holds the internal components of the circuitry as well as leads to external components. PCBs typically consist of one, two, or three layers with multiple schematics all printed onto the same board at different layers. Considering which hardware components that will be added to the PCB it is import to consider the quantity, reference designators, impedance values, manufacturer part number and PCB footprint. These features determine the size, output pins, and temperature consideration of the PCB. Designing the schematic in EagleCAD, a DC-AC inverter, voltage and current sensing circuit, and the microcontroller leads will be implemented onto the PCB.

3.10.1 PCB Design

The schematic for the PCB is similar to the schematic in Figure 3.10.1a, which is a boost converter, in series with a PWM DC-DC converter and a low frequency transformer.

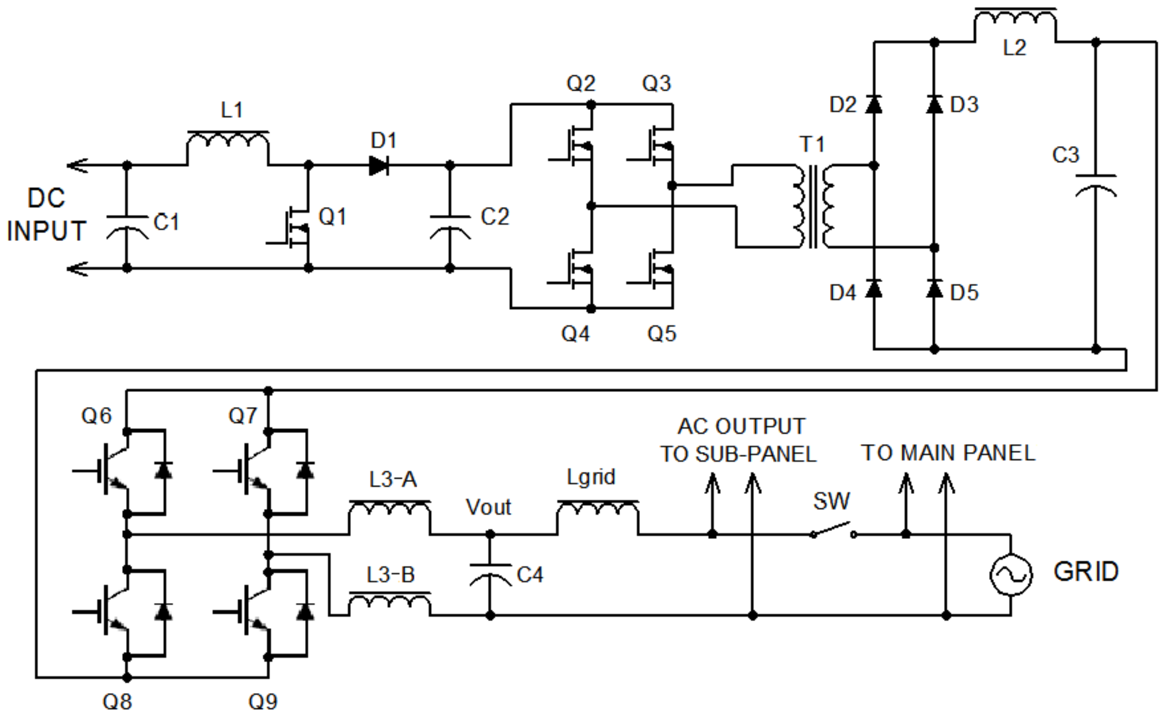

Figure 3.10.1a - Grid Tie Inverter Schematic.
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3.11 Water System

The water system will consist of a reservoir at the bottom of the structure for holding water, a filtration system to filter the water in order to reduce maintenance, a submersible water pump, water supply and return tubes to provide water to the top of the structure, the solenoid valves that control each individual water stream, and the solenoid switching circuit which drives the solenoid using the signals from the solenoid control unit.

After viewing previous waterfall designs utilizing solenoid valves, it was determined that a spacing of 32 valves per meter should produce an acceptable horizontal resolution for the waterfall display. Due to budget constraints and the cost of solenoid valves, the scale model will use a half-meter wide array consisting of 16 solenoid valves.

3.11.1 Solenoid Valve Selection

In order to precisely control the falling water streams, a solenoid valve is needed. A solenoid valve is a valve that is electromechanically controlled by use of an electric current passing through the solenoid. The solenoid itself is a coil of wire that is wound around a metallic core. When current is passed through the coil, it creates an electric field, which moves the core pin. In a solenoid valve, this movement is used to control the opening and closing of the valve. It is noted that the nature of solenoid being a coiled wire makes it an inductive load, which must be taken into account when creating the switching circuit for the solenoid valves.

Solenoid valves can be used for many mediums, such as air, water, and other liquids. Solenoid valves are also made of various materials, such as plastics and metals like brass, aluminum, or steel. Many solenoid valves found that are approved for use with water are made from plastic or brass, but due to cost constraints, the main focus for this project is on plastic solenoid valves.

The solenoid valves have several other specifications to compare, such as response/opening time, normally open (NO) or normally closed (NC) operation, valve diameter, and of course their operating voltage and current draw. For response time, a fast response is needed for the opening and closing of the valves in order to produce a decent resolution from the falling water. An acceptable response time for this application is less than 200ms, but lower response times would improve performance, as the vertical resolution quality relies on the valve response time.

Normally open (NO) operation means the valves are open until voltage is applied, however this means that power must be used whenever the system is not operating, due to the voltage that must be applied in order to close the valves. Normally closed (NC) operation means the valves remain closed until voltage is applied, which would allow our valves to remain closed when not in use without drawing drawing additional power. In addition, normally closed valves appear to be more common with a larger selection than normally open valves, making normally closed operation ideal for this project. The valve diameter is crucial in this application in order to create the desired effect of falling water streams. By viewing previous waterfall display devices, it was determined that the valves should have ¼” inch openings for this application.

Given that this project will be run with solar power in mind, the lower 12-volt DC operating voltage solenoids were considered rather than AC or 24 volt DC valves. Based on these specifications, it appears an ideal water solenoid valve for this waterfall display application has a normally closed (NC) operation, ¼ inch diameter, 12 volt DC operation with a fast valve response time.

As many valves are needed for this project, one of the largest constraints is cost. The least expensive water valve readily available was part #997 by Adafruit Industries, shown below in Figure *3.11.1a*.

Figure 3.11.1a - Adafruit Part 997 ½” Plastic Solenoid Valve

This valve by Adafruit is actually a ½” valve, which is twice the size of our desired specification of ¼”. However, due to the lower price, using this larger valve with a reducer or splitter would be acceptable. The technical details for this valve were listed as follows:

- Working Pressure: 0.02 Mpa - 0.8 Mpa
- Rated Power: 4.8W
- Working Temperature: 1 ℃- 75 ℃
- Response time (open): ≤ 0.15 sec
- Response time (close): ≤ 0.3 sec
- Actuating voltage: 12VDC

The Adafruit valve, however, only operates in one direction. This is not directly an issue for the waterfall display application, as the water only needs to flow in one direction through the valve. However, this one-way liquid flow is controlled by a gasket arrangement inside, which requires a minimum pressure in order to operate of 0.02 Mpa. A simple test with this part was performed that confirmed gravity alone would not provide enough water pressure to open the valve and allow water to flow. Using a pressurized system for the water supply would add additional cost and difficulty to the design, and negates the cost benefit of this low-price valve. Due to its minimal operating pressure, this valve is not suitable for the waterfall display application without a considerable amount of redesign.

With minimum operating pressure in mind, two other valves are considered which both have no minimum operating pressure, and are still fairly inexpensive. The Digiten ¼” quick connect plastic solenoid valve is shown in Figure 3.11.1b. Like the Adafruit valve, this valve is fairly inexpensive for a solenoid valve, at roughly $8 each. The other valve considered is the ¼” nylon solenoid valve made by US Solid, shown in *Figure 3.11.1c*.

This valve costs slightly more, at roughly $12 each. The US Solid valve also requires the purchase of brass fittings for the valve in order to supply water via a nylon hose, as well as create a steady output stream by acting as a nozzle. The Digiten brand valve, however, uses quick connect fittings and does not require the purchase of additional fittings, since the water supply tube is connected by pushing it directly into the valve input. Another small length of tube is then used as a nozzle for the output of the Digiten valve. The additional cost of the brass fittings makes the total cost of the US Solid valve in *Figure 3.11.1c* to be $15 per valve, compared to the Digiten brand valve in *Figure 3.11.1b*, which costs $8 per valve.

Figure 3.11.1b - Digiten ¼” Quick Connect Plastic Solenoid Valve

Figure 3.11.1c - US Solid ¼” Solenoid Valve and ¼” Brass Adapter.

The Digiten brand valve *Figure 3.11.1b* is typically used for consumer applications, such as drinking water dispensers or ice making machines. The following technical specifications were given for the Digiten valve:

- Working Pressure: 0 - 0.8 Mpa
- Rated Power: 4.8W
- Actuating voltage: 12VDC

The US Solid Valve Figure *3.11.1c* is produced by US Solid Company, which makes many solenoids for various applications.

The specifications for the US Solid brand solenoid valve were given as follows:

- Working Pressure: 0 - 1.0 Mpa
- Rated Power: 4.8W
- Working Temperature: -5 ℃- 80 ℃
- Actuating voltage: 12VDC

Neither the Digiten nor the US Solid brand valves provided exact valve response times in specifications, but tests confirmed that the response time was low enough to seem almost instantaneous and thus suitable for the application. When the Digiten valve was tested, it appeared to open at voltages as low as 8 volts, although the response time seemed slightly slower than at 12 volts. Surprisingly, the US Solid valve was able to open at inputs as low as 5 volts, despite it's 12 volt rating. Both valves seemed less responsive at the lower voltages than at 12 volts. Although the ability to run the valves at a lower voltage would conserve power, an important consideration given our reliance on solar generated power, the lower operating voltage causes a slower response time and may lead to issues with reliability and performance.

With this in mind, the solenoid valves will be driven at the rated voltage of 12 volts to ensure fast performance and reliability. The current draw for the Digiten brand valve was measured to be ~400mA at 12 volts, for a measured power draw of around 4.8 watts. The US Solid valve current draw was measured to be ~320 mA at 12 volts, for a measured power draw of around 3.8 watts. The lower power usage of the US Solid brand solenoid valve is ideal in this application, given our constraints of power usage from solar power generation. The US Solid brand valve also appeared to provide a cleaner cut-off in the water stream when the valve closed. The superior performance and lower operating amperage of the US Solid valve indicated that it was the best valve for this application. Despite it's higher cost when compared with the Digiten brand valve. The comparisons of the considered solenoid valves are shown below in *Table 3.11.2a*.

Table 3.11.2a - Solenoid Valve Comparison.

Solenoid Valve	**Rated Power Draw @ 12V**	**Minimum Operating Pressure**	**Relative Water Stream Appearence**	**Relative Response Time**
Adafruit	4.8 W	0.02 Mpa	N/A	N/A
Digiten	4.8 W	None	↓	↑
US Solid	4.8 W	None	↑	↑↑

3.11.2 Solenoid Switching Circuit

While the microcontroller of the Solenoid Control Unit will be providing the binary representation of 'ON' or 'OFF' in 1's and 0's represented by ~3 volts and ~0 volts, this voltage is insufficient for driving the solenoid coils for the water valves. The 12 volts provided to the solenoids will therefore need to be controlled by a 'switching' circuit, which uses the 3-volt output from the shift registers as the switching signal.

There are several choices to look at when attempting to drive a higher voltage load using a lower voltage signal. This application requires fairly high switching times, which eliminates mechanical relay switches, so various transistor-switching circuits are considered. Bipolar junction transistors (BJTs) and metal-oxide field-effect transistors (MOSFETs) are commonly used as switches for such applications. A hybrid of these devices, known as an insulated-gate bipolar transistor (IGBT) is also available for higher-current switching circuits.

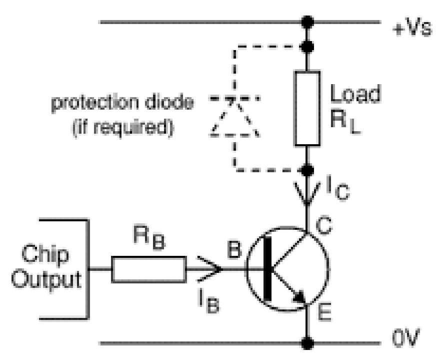

Figure 3.11.2a - NPN BJT Switching Circuit.
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In *Figure 3.11.2a* above, a typical switching circuit using an NPN BJT is shown. It is noted that a protection diode would be required in a switching circuit for the solenoids, as they are an inductive load. The equation for the voltage across an inductor is portrayed in *Equation 3.11.2a*.

$$V_L = L \frac{di}{dt}$$

Equation 3.11.2a – voltage across inductor.

This indicates that when the transistor is switched off, the drop in current will be very fast, resulting in a voltage spike across the inductor, which is the solenoid valve for this application. The protection diode, also referred to as a flyback diode, allows the inductive load to discharge current through itself when this voltage spike occurs, rather than risking damage to the transistor.

It is noted that BJTs are typically cheaper than MOSFETs and IGBTs, and are good at providing the current we desire, however BJTs require a small base current in order to turn on, given by $I_C = \beta \times I_B$, where I_C is the collector current (the current that will be driving the solenoid load), I_B is the base current provided by the digital output pins, and β is the current gain factor provided by the device manufacturer. Taking an example of max current needed by the solenoid load being 500mA, and the gain β equal to 200, this would still require a base current, I_B, of 2.5mA provided by the shift registers. This may not be much current to drive a single solenoid valve, however when multiple valves are opened at once, this may reach limitations of the current that can be provided by the control pins from the Solenoid Control Unit. Even if the control pins are able to provide sufficient current, this extra current draw is not ideal for power saving, which is especially important given that the design is based on solar power and must take efficiency into account.

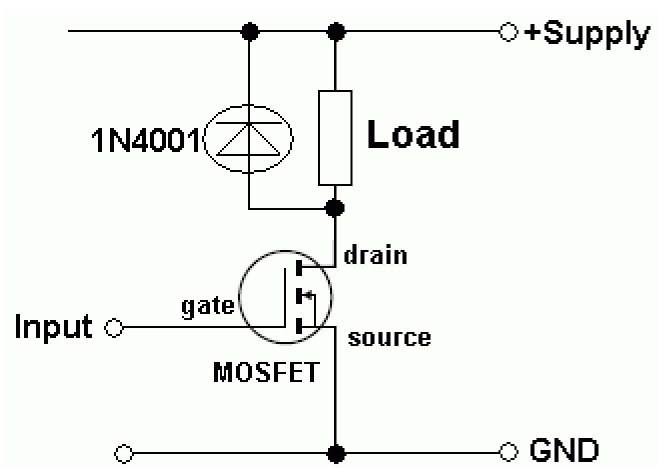

Figure 3.11.2b - N-Channel MOSFET Switching Circuit
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Above in *Figure 3.11.2b*, an N-Channel enhancement MOSFET Switching Circuit is shown, which is a commonly used MOSFET to drive loads using an input as the control for a switch. The 1N4001 diode represents a protection diode, with the same purpose as the protection diode shown in the BJT circuit of *Figure 3.11.2a*. In enhancement mode MOSFETs, a voltage across the oxide from gate to source creates a conducting channel between the source and drain contacts via the field effect, allowing current to flow when the voltage is applied to the gate. Due to the fact that this current is driven by a field effect rather than a direct connection, and is physically isolated using an oxide layer at the gate, there is actually no current drawn from the input controlling the gate.

This means that current will not be drawn from the pins of the solenoid control unit. No current flowing from the control unit means less energy used, which is ideal for the power saving aspects of our design and it's reliance on solar power. It is noted that regular MOSFETs typically do not support current above a few hundred milliamps. However, power MOSFETs are designed to support higher current, and typically have a built in flange that acts as a heat sink, to help prevent overheating, which would be ideal for this application.

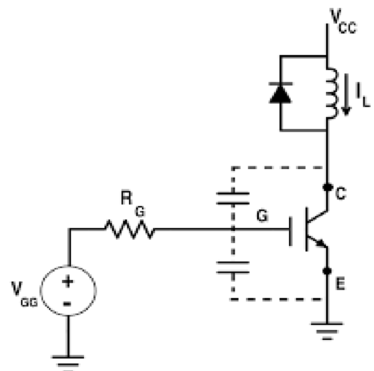

Figure 3.11.2c - IGBT Switching Circuit.
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Another device that can support a higher current, while also providing an isolated gate, is the insulated gate bipolar transistor, or IGBT. A typical IGBT switching circuit is shown above in *Figure 3.11.2c*. The IGBT combines the isolated gate of the MOSFET design, with the bipolar nature of the BJT, to allow for higher current flow than typical MOSFET devices. IGBT devices can handle hundreds of amps at voltage levels near 1,000 volts. Such devices would be overkill for this application, and unnecessarily higher cost. While lower amp and voltage rating IGBT devices do exist, they also cost significantly more than a MOSFET device. With the ability to obtain power MOSFETs that can handle 500mA at 12 volts, it seems that using an IGBT device would be an unnecessary additional cost.

With all these considerations, it seems the best device for this application would be an n-channel enhancement mode power MOSFET, which is capable of handling at least 500mA at 12 volts.

3.11.3 MOSFET Selection

For the MOSFET, several devices are suitable for this application, such as: NXP Semiconductors PSMN022-30PL, Fairchild Semiconductor FQP13N06L, Fairchild Semiconductor FQP20N06L, and International Rectifier IRLB8721PbF. All of these options use a TO-220 package, shown below in *Figure 3.11.3a*, which is a common package for discrete transistors. This package is a through-hole mount device with 3 pins, rather than a surface mount chip. The through-hole package will take up slightly more room on a PCB, but allows for easy testing of circuits on a breadboard. Another notable characteristic of the TO-220 package is the metal tab with a hole on the back. This tab acts as a built-in heat sink, and can be attached to a larger heat sink if needed. This added feature would alleviate any concerns of possible overheating in the Florida heat or with extended use.

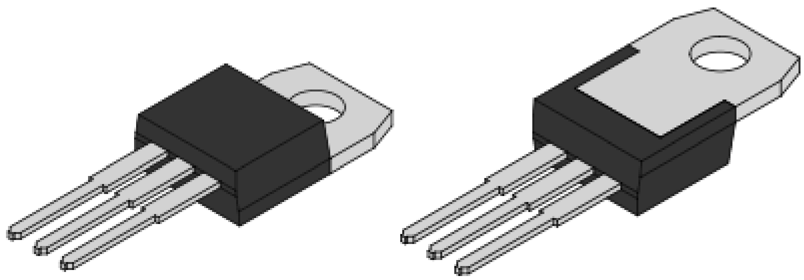

Figure 3.11.3a - TO-220 Transistor Package
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Most power MOSFETs in this package can handle currents and voltages well above the maximum of 12 volt and ~500mA requirements for the solenoid valves, and could be considered ‘overkill’. However, this overkill gives the added benefit of not needing to worry about overheating or pushing the limits of the device, as well as being widely available at relatively low cost. The main concern about using a higher rated MOSFET than necessary for the application would be power loss, however this is based upon the on-resistance, or R_{DS}, which is still relatively low for TO-220 package power MOSFETS, ranging from 0.01 to 0.1 Ω. The power lost through the MOSFET device, is giving by $P = VI = I^2R$. Using max values of 0.1 Ω and 500mA provides an overestimate amount of 0.025 watts of power lost by the MOSFET device when it is switched on.

Table 3.11.3a - MOSFET Comparison

Mosfet Device	**Max V_{DS}**	**$V_{GS(Th)}$**	**R_{DS} @ V_{GS} = 4.5**	**Max I_D**
NXP Semiconductors PSMN022-30PL	30 V	1.70 V	27 mΩ	30 A
Fairchild Semiconductor FQP13N06L	60 V	1.75 V	110 mΩ	13.6 A

Fairchild Semiconductor FQP20N06L	60 V	1.75 V	55 mΩ	21 A
International Rectifier IRLB8721PbF	30 V	1.80 V	13.1 mΩ	62 A

In *Table 3.11.3a* above, select specifications from 4 suitable MOSFET devices are shown. The max V_{DS} is the maximum voltage that the MOSFET can handle between the drain and source pins.

In this application, the voltage between the drain and source would not be capable of going above 12 volts, as that is the voltage of the power supply. $V_{GS(Th)}$ is the threshold voltage between the gate and source pins required for the MOSFET to turn on. Given that shift register pins provide a voltage of ~2.8 volts, the threshold V_{GS} voltage for the MOSFET device must be lower than 2.8 volts for the MOSFET to turn on.

The R_{DS} is the resistance between the drain and source pins when the device is turned on. While this value is typically in milliohms (mΩ) and should not affect the operation of the solenoid valve, a higher resistance will result in power lost by the MOSFET device. The max I_D is the max current that can flow through the drain pin. As the solenoids will draw less than 0.5 A, these values are all more than enough current, however it is noted that a higher max I_D does seem to correlate with a lower R_{DS}.

All of these listed MOSFET options appeared to be fairly inexpensive, around 90 cents each, making price the least important factor when choosing the device. While all of these options are suitable for this application, the lower R_{DS} rating of International Rectifier's (now owned by Infineon Technologies) IRLB8721PbF MOSFET stands out as ideal, given that it will result in lower power consumption. The reputable vendor, adafruit, also recommended this mosfet for driving a 12v inductive load, and has tested the device in driving an equivalent 4.8 watt 12v solenoid valve. Given all of this information, it seems like the IRLB8721PbF is well suited for this application, and is further researched.

3.11.4 IRLB8721PbF MOSFET Device Research

In *Table 3.11.4a* below, the several maximum ratings from the IRLB8721PbF datasheet is shown, provided by International Rectifier. Each of the voltage and current maximums are well above the requirements previously mentioned for the solenoid switching application.

Table 3.11.4a - Absolute Maximum Ratings for IRLB8721PbF MOSFET Device
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Absolute Maximum Ratings

	Parameter	Max.	Units
V_{DS}	Drain-to-Source Voltage	30	V
V_{GS}	Gate-to-Source Voltage	± 20	
I_D @ T_C = 25°C	Continuous Drain Current, V_{GS} @ 10V	62	A
I_D @ T_C = 100°C	Continuous Drain Current, V_{GS} @ 10V	44	
I_{DM}	Pulsed Drain Current ①	250	
P_D @T_C = 25°C	Maximum Power Dissipation ⑤	65	W
P_D @T_C = 100°C	Maximum Power Dissipation ⑤	33	
	Linear Derating Factor	0.43	W/°C
T_J T_{STG}	Operating Junction and Storage Temperature Range	-55 to + 175	°C
	Soldering Temperature, for 10 seconds	300 (1.6mm from case)	
	Mounting torque, 6-32 or M3 screw	10lb·in (1.1N·m)	

Table 3.11.4b below shows additional static parameters for the IRLB8721PbF MOSFET device. Several of these parameters are worth noting when using the MOSFET as a switch as in this application: $R_{DS(on)}$, the drain-to-source resistance of the device when it is on, $V_{GS(th)}$, the threshold gate-to-source voltage required to turn on the device, $t_{d(on)}$, the delay time for the device to turn on, $t_{d(off)}$, the delay time for the device to turn off.

Table 3.11.4b - Additional Static Parameters for IRLB8721PbF
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Static @ T_J = 25°C (unless otherwise specified)

	Parameter	Min.	Typ.	Max.	Units	Conditions
BV_{DSS}	Drain-to-Source Breakdown Voltage	30	—	—	V	V_{GS} = 0V, I_D = 250μA
$\Delta BV_{DSS}/\Delta T_J$	Breakdown Voltage Temp. Coefficient	—	21	—	mV/°C	Reference to 25°C, I_D = 1mA
$R_{DS(on)}$	Static Drain-to-Source On-Resistance	—	6.5	8.7	mΩ	V_{GS} = 10V, I_D = 31A ③
		—	13.1	16		V_{GS} = 4.5V, I_D = 25A ③
$V_{GS(th)}$	Gate Threshold Voltage	1.35	1.80	2.35	V	V_{DS} = V_{GS}, I_D = 25μA
$\Delta V_{GS(th)}/\Delta T_J$	Gate Threshold Voltage Coefficient	—	-7.0	—	mV/°C	
I_{DSS}	Drain-to-Source Leakage Current	—	—	1.0	μA	V_{DS} = 24V, V_{GS} = 0V
		—	—	150		V_{DS} = 24V, V_{GS} = 0V, T_J = 125°C
I_{GSS}	Gate-to-Source Forward Leakage	—	—	100	nA	V_{GS} = 20V
	Gate-to-Source Reverse Leakage	—	—	-100		V_{GS} = -20V
gfs	Forward Transconductance	35	—	—	S	V_{DS} = 15V, I_D = 25A
Q_g	Total Gate Charge	—	7.6	13	nC	
Q_{gs1}	Pre-Vth Gate-to-Source Charge	—	1.9	—		V_{DS} = 15V
Q_{gs2}	Post-Vth Gate-to-Source Charge	—	1.2	—		V_{GS} = 4.5V
Q_{gd}	Gate-to-Drain Charge	—	3.4	—		I_D = 25A
Q_{godr}	Gate Charge Overdrive	—	2.0	—		See Fig. 16
Q_{sw}	Switch Charge (Q_{gs2} + Q_{gd})	—	4.6	—		
Q_{oss}	Output Charge	—	7.9	—	nC	V_{DS} = 15V, V_{GS} = 0V
R_G	Gate Resistance	—	2.3	3.8	Ω	
$t_{d(on)}$	Turn-On Delay Time	—	9.1	—	ns	V_{DD} = 15V, V_{GS} = 4.5V③
t_r	Rise Time	—	93	—		I_D = 25A
$t_{d(off)}$	Turn-Off Delay Time	—	9.0	—		R_G = 1.8Ω

The $R_{DS(on)}$ source-to-drain resistance is listed as a typical value of 13.1 milliohms based on V_{GS} = 4.5V. This resistance is well below a single ohm, and is insignificant in the amount of power loss compared to the 4.8 watts used by the solenoid valves. The threshold gate voltage, $V_{GS(th)}$, is listed as 2.35 max, which is well below the voltage provided by the shift registers to control the solenoid valves. The turn-on and turn-off delay times, measured using the method shown below in *Figure 3.11.4a*, are both less than 10 ns. A delay measured in nanoseconds is insignificant when considering the millisecond response times of the solenoid valves.

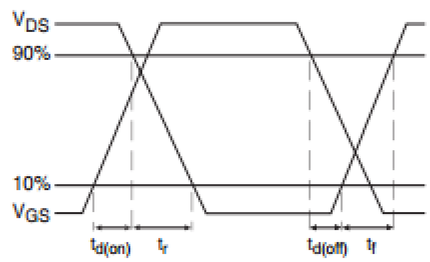

Figure 3.11.4a - Switching Time Waveforms for IRLB8721PbF
Reprinted with permission from Infineon Technologies

In *Figure 3.11.4b*, a graph from the datasheet is shown with the drain-to-source current, I_D vs the drain-to-source voltage, V_{DS}. Based on this graph, the lowest drain current shown is 2 amps, at V_{GS} = 3.0V and V_{DS} = 0.1 V. Given that the solenoid valves require less than half an amp, all the ranges of I_D shown on the graph are more than enough for this application.

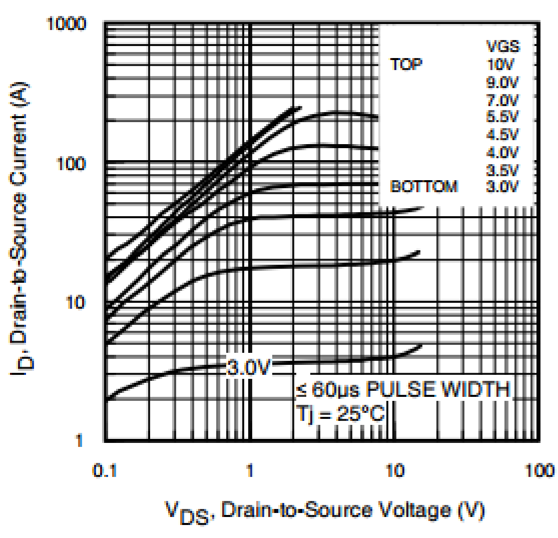

Figure 3.11.4b - I_D vs V_{DS} Graph for IRLB8721PbF
Reprinted with permission from Infineon Technologies

For a better consideration of the drain-to-source resistance $R_{DS(on)}$, *Figure 3.11.4c* shows the drain-to-source resistance, $R_{DS(on)}$ vs gate-to-source voltage, V_{GS}, in a graph from the IRLB8721PbF datasheet. While all of these values are less than 100 milliohms and will result in an acceptable low power loss from the MOSFET device, it is noted that the resistance R_{DS} increases exponentially below a V_{GS} of around 4.5 volts.

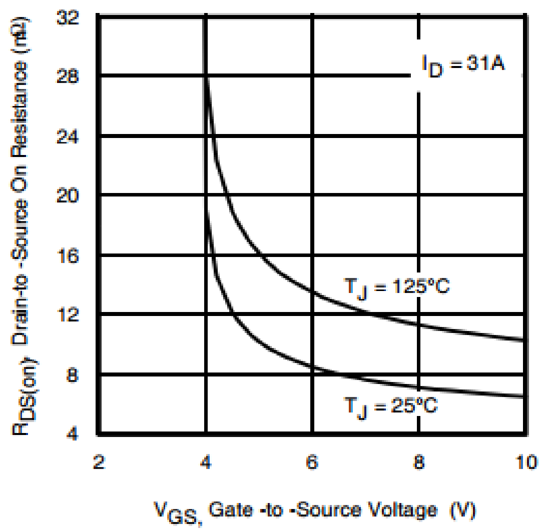

Figure 3.11.4c - I_D vs V_{DS} Graph for IRLB8721PbF
Reprinted with permission from Infineon Technologies

After reviewing the relevant specifications listed in the tables and various graphs of the datasheet, the IRL8721PbF MOSFET device produced by International Rectifier is sufficient for this application. The MOSFET specifications are more than sufficient for operating as a switch controlled by the low voltage shift register and driving the 12v solenoid load at 400mA (4.8 watts).

3.11.5 Diode Selection

As previously mentioned, a protection or 'flyback' diode is required in a switching circuit for the solenoids. This diode is used in order to eliminate the flyback, which is the sudden voltage spike that occurs across an inductive load when the current is suddenly changed. This effect is due to the equation for voltage across an inductor given by *Equation 3.11.5a*

$$V_L = L\,\frac{di}{dt}$$

Equation 3.11.5a - voltage across inductor.

Where V_L is the voltage across the inductor, which is proportional to the change in current, $\frac{di}{dt}$.

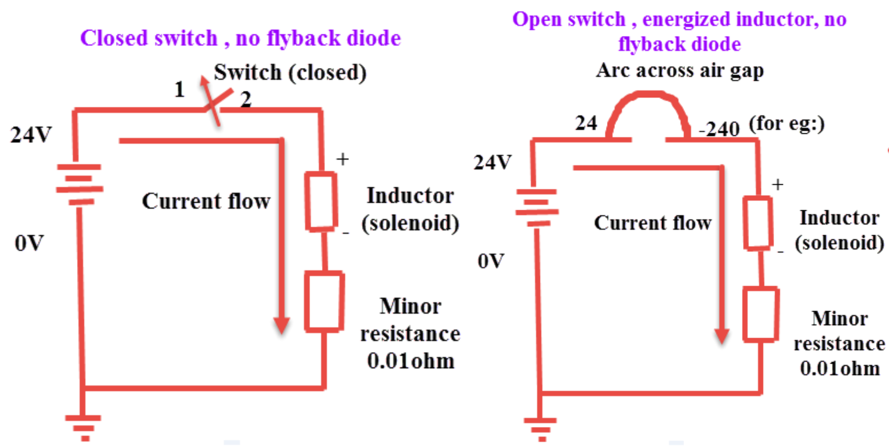

Figure 3.11.5a - Example Inductor Circuits Without Flyback Diode
Reprinted with permission from Tarun Agarwal

Figure 3.11.5a above shows an inductor being driven by a simple circuit without a flyback diode. In the solenoid switching circuit, the MOSFET acts as the switch seen in this example. When the switch is opened after being closed for a while, the sudden voltage spike, or flyback, across the inductor gives a large negative voltage spike due to the rapid change in current (large di/dt). This voltage spike can cause an arc across the open switch, or in the case of the solenoid switching circuit for the water valves, this voltage spike may damage the MOSFET devices or attempt to arc to a grounded connection.

Figure 3.11.5b below shows the same example circuit, only with a flyback diode in use. In this case, when the current suddenly stops and creates a large negative voltage in the solenoid, that negative voltage puts the diode into forward bias and allows the current to draw from itself in a loop, safely dissipating the energy spike through the inductor and diode rather than causing possible damage to other circuit components.

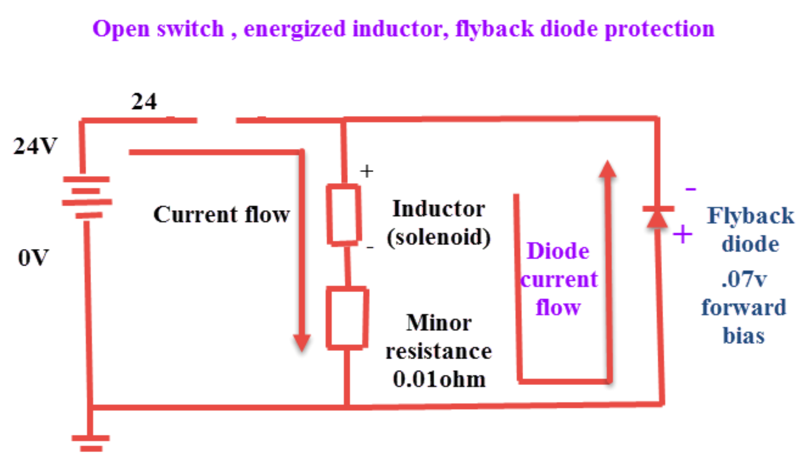

Figure 3.11.5b - Example Inductor Circuit With Flyback Diode
Reprinted with permission from Tarun Agarwal

Upon researching what type of diode is best suited for this application as a flyback protection diode, the 1N4000 series is found to be a popular rectifier diode for 1 amp applications. As the solenoid valves draw less than 1 amp of current, one of these diodes should be suitable to act as a flyback or protection diode in the solenoid switching circuit.

Table 3.11.5a: Maximum Ratings for MCC 1N4000 Series Diodes
Reprinted with permission from Micro Commercial Components

MCC Catalog Number	Device Marking	Maximum Recurrent Peak Reverse Voltage	Maximum RMS Voltage	Maximum DC Blocking Voltage
1N4001	1N4001	50V	35V	50V
1N4002	1N4002	100V	70V	100V
1N4003	1N4003	200V	140V	200V
1N4004	1N4004	400V	280V	400V
1N4005	1N4005	600V	420V	600V
1N4006	1N4006	800V	560V	800V
1N4007	1N4007	1000V	700V	1000V

As shown in *Table 3.11.5a* above, the 1N4001 diode can block a maximum reverse bias of 50V peak or 35V RMS, which is well above the 12V DC voltage that it will need to block when the diode is off.

Table 3.11.5b - Electrical Characteristics for MCC 1N4000 Series Diodes.
Reprinted with permission from Micro Commercial Components

Average Forward Current	$I_{F(AV)}$	1.0A	T_A = 75°C
Peak Forward Surge Current	I_{FSM}	30A	8.3ms, half sine
Maximum Instantaneous Forward Voltage	V_F	1.0V	I_{FM} = 1.0A; T_J = 25°C*
Maximum DC Reverse Current At Rated DC Blocking Voltage	I_R	5.0µA 50µA	T_J = 25°C T_J = 125°C
Typical Junction Capacitance	C_J	15pF	Measured at 1.0MHz, V_R=4.0V
Typical Reverse Recovery Time	T_{rr}	2.0us	I_F=0.5A, I_R=1.0A, I_{rr}=0.25A
Rating for fusing	I^2t	3.7A²s	t<8.3ms

Upon a negative voltage spike occurring across the inductor, the diode will turn on and allow current to flow. In Table 3.11.2e above, it can be seen that the average current draw will be 1.0 amps, and the maximum forward voltage is 1.0

volts. The 1 amp current draw is more than enough to dissipate the energy from the solenoid, and the Forward Voltage, V_F, indicates that the voltage spike, or flyback, from the sudden switching off of current through the solenoid will only be able to reach 1 volt before the flyback diode turns on to dissipate any higher voltage that may otherwise cause damage to the rest of the circuit.

Given these considerations, the 1N4001 diode specifications are suitable for this application of a flyback protection diode in the solenoid switching circuit. The device is widely popular and easy to find as well. Micro Commercial Components, or MCC, is a company that produces 1N4000 series diodes. The MCC 1N4001-TP is a thru-hole package style 1N4001 diode that is available for only $0.18 each. The suitable specifications and very low cost of the MCC 1N4001-TP devices make it an ideal choice for use as a flyback protection diode in the solenoid valve switching circuit.

3.11.6 Chosen Solenoid Switching Circuit Design

The schematic below in *Figure 3.11.6a* shows the chosen circuit design for a single solenoid valve driven from the output of an 8-bit shift register. After the previous research, this circuit contains an n-channel MOSFET device made by International Rectifier part IRLB8721PbF, which is driven by the shift register, and a 1N4001 diode made by Micro Commercial Components. The input to the 8-bit shift register is a serial input that will be sent from the MSP430 microcontroller located on a separate PCB board. Each of the 8 parallel outputs from the shift register (QA - QH) will connect to an individual MOSFET, with the MOSFET acting as a switch for the solenoid valve connection.

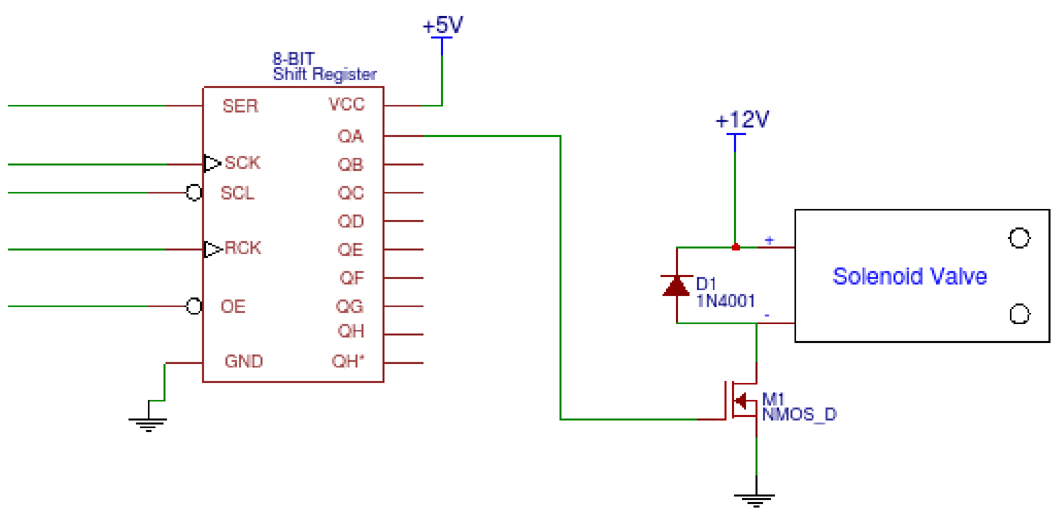

Figure 3.11.6a - Chosen Solenoid Switching Circuit Schematic.

3.11.7 Reservoir

The reservoir of the water system holds the water for the pump to deliver to the solenoid valves. An important aspect of this water reservoir is to reduce the additional maintenance requirements involved with the use of water as much as possible. This includes features to limit algae growth, preventing debris from entering the reservoir, and inhibiting corrosion.

The reservoir should be constructed with easy-to-clean and water-impervious surfaces that are resistant to bacteria, algae growth, and prolonged exposure to weather elements. According to the project sponsor, OUC, a water connection will be provided at the installation site. This connection will require a valve that is controlled by the system health monitor, allowing the reservoir to be filled if the water level is too low.

One main consideration for the reservoir includes blocking sunlight to inhibit algae growth. For this purpose, the reservoir will need to be made of an opaque robust material that will block sunlight from the standing water. Of course, an opening will be needed for the water falling from the display to re-enter the reservoir. By covering this opening with a dense foam material, it is possible to allow the water to re-enter the reservoir while blocking most sunlight that would otherwise enter through the opening. This dense foam will also have the additional benefit of helping eliminate the audible splash of the falling water, as well as acting as a preliminary filter to stop larger debris from entering the system.

3.11.8 Filtration

In an attempt to make this water sculpture require as little maintenance as possible, filtration is a key aspect. Filtration will not only prevent debris from clogging the system and interfering with valve operation, but will also help prevent algae and mineral buildup that would be aesthetically unpleasant.

The reservoir will be covered with a dense foam. While this dense foam is not specifically meant to be a filter, it will stop large debris such as leaves from entering reservoir. In addition, another filter will be located at the water pump intake within the reservoir. This filter will need to be fine enough to stop particles that may clog the valves, while not being too fine as to unnecessarily restrict flow. Medium to high flow submersible pumps typically use a filter, or are sometimes housed within a pre-filter, of approximately 80-100 microns.

In addition to a filter around the pump, a simple water filter designed to remove minerals and water sediments from tap water should be used at the water connection provided at the installation site. This filter will be used to remove hard water minerals that are typically found in municipal water sources, as they could lead to water stains on the structure from evaporation.

3.11.9 Water Pump

A key component in the water system is the pump required to move water from the reservoir to solenoid valves above. This pump will need to move water up approximately 1 meter of tubing and provide sufficient flow to run all 16 valves simultaneously. For applications that require good lift and flow rate characteristics, there are two common types of pumps used: positive displacement diaphragm pumps and centrifugal pumps. A positive displacement pump uses a rubber diaphragm to trap and expel water in a manner similar to a piston. A centrifugal pump uses an intake at the center of an impeller, which accelerates the water radially outward into a diffuser section of the casing, which then decelerates the flow in order to increase pressure.

In order to simplify system design and keep it centered on the use of solar power, a DC pump is considered rather than an AC powered pump. There are many submersible water pumps that are designed to run on solar power for remote water pumping applications that may be suitable for this design.

A similar project, the waterfall swing, used a 1 HP 1.5” water pump. This waterfall sculpture application will be smaller and require less flow than the waterfall swing project, however these specifications give a good starting point for the requirements of this application.

3.11.10 Water Supply/Return

They are the pipes necessary to connect the pump and water distribution modules. There is a supply and a return conduit, avoiding excessive pressure in the manifold when all the valves are closed.

Both the water supply and return tubes will be approximately the same size of 1.5”, however the distribution tube at the top will be significantly larger at 3-4”. The water supply and return tubes will both connect at the top of the larger tube, and the larger tube will act as a small water storage tank. With this arrangement, the water supply tube will fill the larger distribution tube from the top, and overflow will enter the return tube, which is at the same level at the top of the distribution tube but located on the other end.

4 Design

The following section details the design of the prototype solar sculpture installation. Circuit schematics, software logic, and PCB design will be discussed as well as various considered which have affected the design of the installation.

4.1 Design Modifications in Response to Sponsor Input

Shortly after the team's critical design review in Senior Design 2, our sponsor OUC met with the team to regrettably announce that they did not wish to use a water feature in the full scale solar sculpture. Having progressed far enough with the interactive waterfall design that turning back was not an option, the team decided to continue moving forward with the water feature purely as a conceptual prototype rather than a candidate for full scale implementation by OUC.

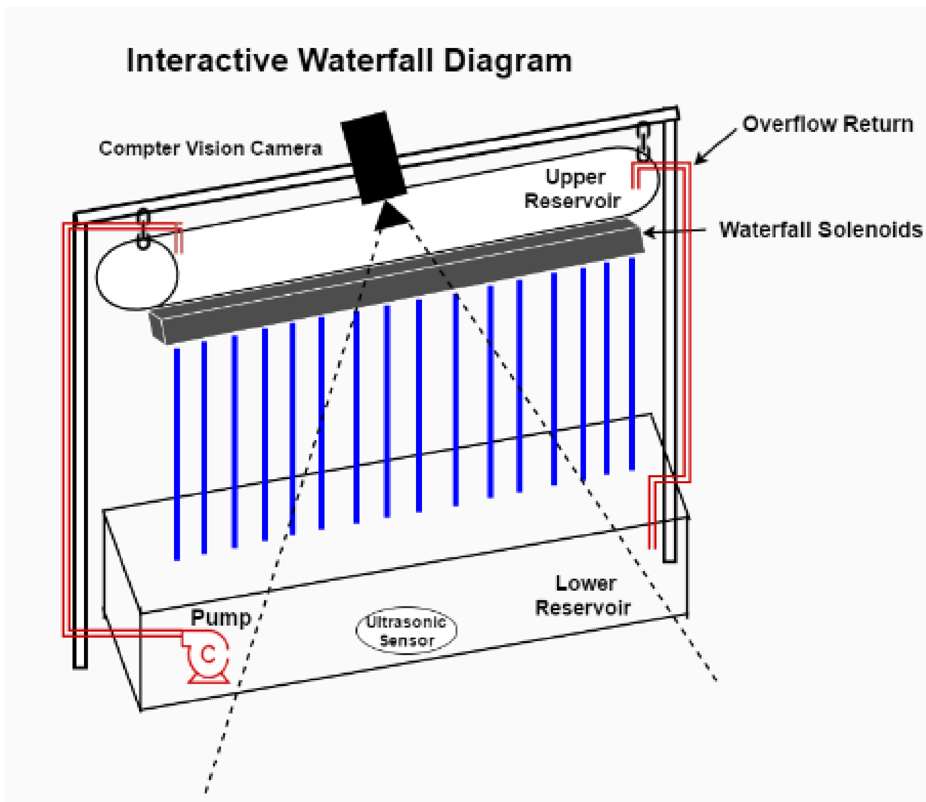

Figure 4.1a – new structural design concept for interactive waterfall prototype.

After discussing matters with our art and mechanical teams, an agreement was reached whereupon the art and mechanical team would produce a separate static solar sculpture to be considered for full scale implementation, while assisting our team with the structural design of the interactive waterfall prototype. In exchange, our team would assist the mechanical and art team in acquiring, mounting, and wiring the solar panels for their separate static solar sculpture. In this way, research and design decisions made previously in Senior Design 1 regarding the usage of solar panels on the sculpture would not be wasted. Additionally, the team could continue to take advantage of the art and mechanical team's structural and aesthetic insight. With this idea in mind, a new visualization of the interactive waterfall design was created as shown in *Figure 4.1a*, and progress on the final prototype progressed.

While this conceptual prototype would not be considered by OUC for their full scale solar sculpture implementation, the team continued to receive their welcome support and advice. The team decided that future design decisions would be made with the idea in mind that the conceptual waterfall prototype might at some point be utilized for a full scale solar sculpture visualization. Our art team members helpfully provided a visualization of what that full scale implementation might look like as seen in *Figure 4.1b*.

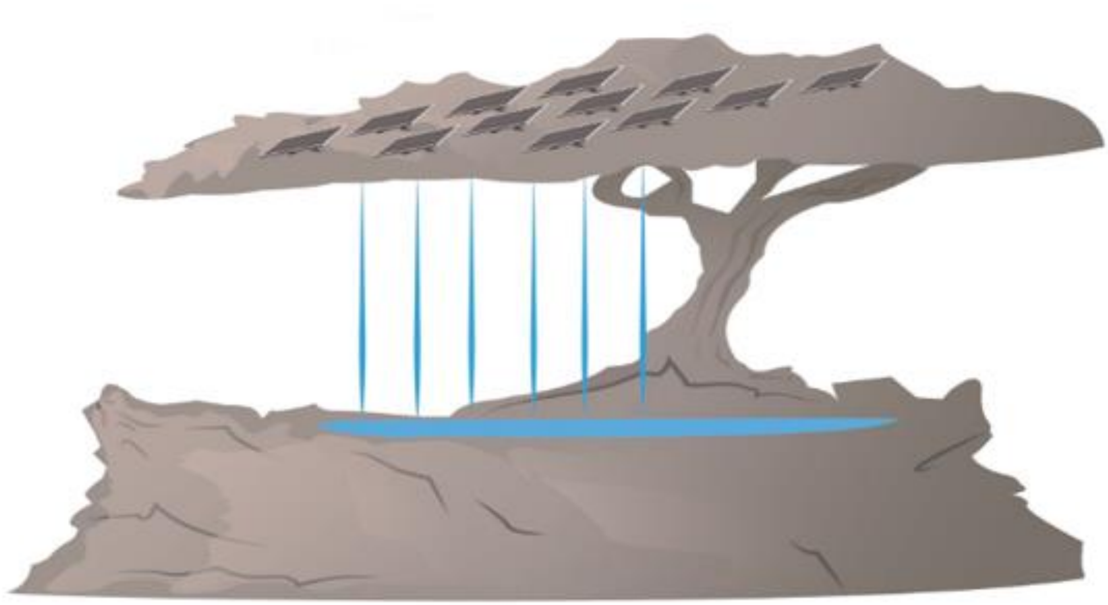

Figure 4.1b – Artist's interpretation of a full scale implementation of the proposed interactive waterfall installation.

4.2 Power Requirements and Production

A single 24V monocrystalline solar panel will be used in the ⅛ model in order to power the microinverter and demonstrate MPPT, DC/DC conversion and DC/AC conversion. In order to meet the voltage requirements of the micro inverter, input voltage of 28-45V, a 24V panel was necessary. For the full scale model a PV array of eight panels will be used. These can all be wired in series because the max output voltage of a panel, 45V, when multiplied by eight, 360V, is less than the 500V maximum of our suggested inverter. That being said there might be installation constraints or safety constraints that would make a mix of parallel and series wiring beneficial.

Figure 4.2a - Monocrystalline Solar Module. Reprinted with permission from Low Energy Developments

This module is ideal because it is monocrystalline giving it a relatively high efficiency of 12.2%. Higher end panels can generate up to 20% efficiency but this comes at an increased cost and is not necessary to demonstrate solar production. This panel has a optimum power voltage, V_{mp}, of 36.5 which is in the range of operation for the micro inverter developer kit that is planned to be used. The panel's open circuit voltage, V_{oc}, is also within operational range of the microinverter so there will be no conflicts between the two.

4.2.1 Power Requirements

There are three sections of power consumption in our design. There is a power requirement for the solenoid valves, the water pump and all the microcontrollers and microelectronics. The microelectronics and power loss because of electrical components will be assumed to be 150W. The pump and solenoid valves are very power hungry with the valves drawing 13A at 12V while all on and the pump drawing 30A at 12V while on, this is a large overestimate. This is 156W and 360W, this could be as low as 24W though, respectively. Our project goal is to be net power positive so the time the pump and the valves are on will need to be limited carefully.

The solenoid valves are normally closed so they will only draw power when activated by the motion sensor. The pump will only run when the water level in the reservoir above the solenoid valves is low. This combination will limit the pump and valves to running only when there is a motion sensor input from the user. The power consumption will be very dependent on how long the sculpture is actually being used by the public on average. Assuming 2hr of continuous operational time the pump and valves will consume 72W on average.

To draw attention to the water feature of the sculpture a pre-designed display will run on a timer. This display will be three minutes long and run once every 30 minutes. The sculpture will run in an extreme standby mode between 2am and 6am in which it will not look for gesture controlled inputs and will also not run the pre designed display. This will further limit power consumption at a time when there will be no solar energy production.

With these power-conserving features the sculpture will be more easily power neutral or even power positive. On average the sculpture will be using 72W for the pump and solenoid and about 125W for the rest of the electronics**.** This gives a combined average consumption of 197W. This is a number that can be comfortably produced by solar power alone.

4.2.2 Power Production

Power production will be accomplished with a solar array wired with three panels in a string series and each of those strings wired in parallel. The sculpture will consume 197W on average so the goal for solar production will be set to 277W. This overestimate will ensure a net positive energy gain.

Location and installation have a large effect on energy production from a solar array. In Orlando there are about 5 kWh/m^2/Day, this is commonly referred to as 5 sunlight hours a day. This is advantageous because it is a relatively high number. This will allow for fewer solar panels to be used in order to reach the 277W goal for production.

Table 4.2.2a - Table of Sun Hours vs Monthly production
Reprinted with permission from Affordable Solar

Sun Hours → Monthly Usage ↓	< 3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5
50kWh	0.7kw	0.6kw	0.5kw	0.5kw	0.4kw	0.4kw	0.3kw	0. kw
100kWh	1.4kw	1.2kw	1.0kw	0.9kw	0.8kw	0.8kw	0.7kw	0.6kw
150kWh	2.0kw	1.7kw	1.5kw	1.4kw	1.2kw	1.2kw	1.0kw	0.9kw
200kWh	2.7kw	2.3 kw	2.0kw	1.8kw	1.6kw	1.6kw	1.4kw	1.2kw
250kWh	3.4kw	2.9kw	2.5kw	2.3kw	2.0kw	2.0kw	1.7kw	1.6kw
300kWh	4.1kw	3.5kw	3.0kw	2.7kw	2.4kw	2.4kw	2.0kw	1.9kw
350kWh	4.7kw	4.1kw	3.5kw	3.2kw	2.8kw	2.8kw	2.4kw	2.2kw

The solar panels will have to be mounted at different angles depending on the season for maximum efficiency. The winter angle for Orlando is 38°, the Fall/Spring angle is 62° and the summer angle is 86°. Adjusting the panels for each season can yield up to an 18% gain in efficiency depending on the season. This adjustment has added maintenance requirements and if the client, OUC, deems them to be too high a fixed mounting angle can be used. Fixed mounting angle solar panels have zero maintenance requirements aside from being occasionally cleaned.

Extrapolating our 277Wh needs to kWh a month we get 200kWh. 1.6kW of solar panel production will be needed to produce 200kWh monthly or 277Wh. eight 200W panels will produce this 1.6kW. There will be a single string of eight panels that will all be connected to one central inverter. This inverter will be sized large enough to leave room for expansion if need be. However this is unlikely given the overestimate of 277W that is already being used.

4.3 Solar Panel Mounting

Solar panels vary in efficiency based on the angle they are mounted. A fixed solar panel will also vary in efficiency based on the time of day and the season. Solar panels have tilt tracking options that improve their efficiency day-to-day and also season-to-season. There are single and double axis tracking options however these have greater complexity and will be avoided in the Solar Sculpture Project due to concerns about reliability. Having manually adjustable tilt is simple and can allow for angle changes based on the seasons to greatly improve efficiency year round.

Fixed tilt panels have no adjustability and have the added convenience of an install and forget operation. However this is the least efficient method for solar panel tilt. Fixed panel arrays have around 70% efficiency when compared to their two axis adjustable array counter parts. It is important to note that these panels are facing true South. If a compass is used to orient the array magnetic declination must be taken into consideration.

Adjustable tilt panels are low tech and also low maintenance. They are more efficient than fix panels but still less efficient than tracking panels. Adjustable panels can either be adjusted twice or four times a year. Adjusting the panels just twice a year can improve efficiency to 76% of tracking panel. Adjusting four times a year will improve panel efficiency to 81-88% in the winter, 74-75% in the spring and fall and 68-74% in the summer. Tracking panels outperform tilt panels more in seasons where the sun traverses large distances in the sky.

Tracking panels have either single axis or dual axis tracking. Dual axis tracking is the most efficient but is costlier. Generally single axis tracking is done horizontally and dual axis includes vertical tracking. Vertical tracking is most beneficial at higher altitudes.

Solar panels are wired into arrays in parallel, series or combination. Panels wired in parallel have additive current but constant voltage. Different voltage rated panels wired in parallel will produce a voltage equal to that of the lowest voltage-producing panel, which is highly inefficient. Panels wired in series have additive voltage and constant current. Panels wired in series with different currents will produce a current equal to that of the lowest current panel drastically reducing efficiency. Most arrays use a combination of these two types of wiring. First a certain number of panels are wired in series to achieve the desired voltage and then multiple strings of panels in series are wired in parallel. Below is an example three panels wired in series and three wired in parallel.

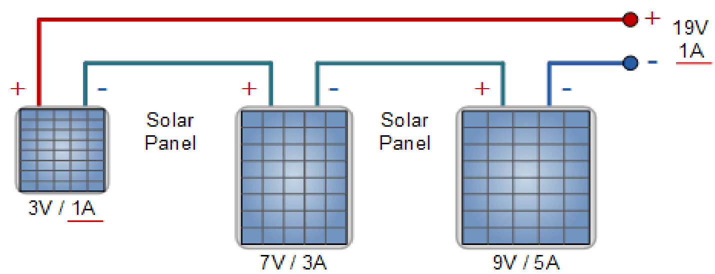

Figure 4.3a - Solar Array in Series
Reprinted with permission from Alternative Energy Tutorials.

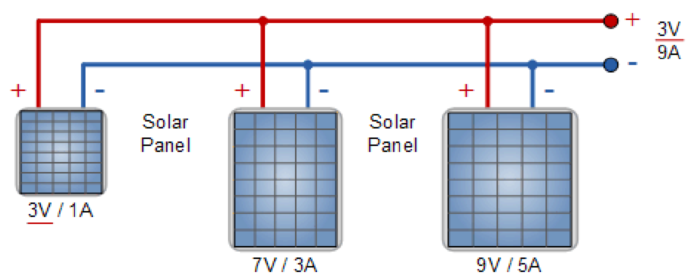

Figure 4.3b - Solar Array in Parallel
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4.4 LEDs

This project will use LEDs mounted in strategic locations in order to draw attention to the sculpture and particularly to the waterfall feature. An LED driver will control this LED array, particularly the STP24DP05 offered by STMicroelectronics. This driver will be talked about in more detail below. These

LEDs will need to be dimmed and brightened for artistic effect and based on the time of day. Pulse width modulation will be used to achieve this. Many LEDs will have to be controlled by the MSP430 microcontroller. These LEDs will have to be high power RGB in order to be seen clearly in the daytime and also allow for artistic flexibility.

The STP24DP05 is specifically made for RGB LED arrays. This will allow for a greater range of artistic effects. This driver operates with an input voltage of 3.3V to 5V. Can detect short and open circuit errors and has adjustable output current through external resistors.

LED brightness will need to be adjustable for visual effects and based on the time of day. There are two ways of achieving this. The first is through analog dimming which operates by changing the current through of the string. This method is not attractive despite its simplicity because it is inaccurate and can lead to changes that are unwanted in the LED color. For these reasons pulse width modulation of the string current will be used. This operates by changing the duty cycle of the constant current which essentially changes the average current. This method is more accurate and does not affect LED color.

The MSP430 microcontroller will give inputs to the STP24DP05 LED driver. To achieve an LED array with the STP24DP05 LED driver eight of the sixteen outputs will drive transistors, which will act as switches, one switch per row. The other eight outputs will connect eight columns of LEDs and will be used to sink current to the activated LEDs in that column. This matrix solution can be seen in *Figure 4.4a* below.

A 1W RGB LED, part number YSH-FRGBB-IA, was selected for its high brightness. Low maintenance is one of the critical requirements from our client OUC. Due to the high power nature of this LED special consideration to heat dissipation will have to be taken in order to maximize the lifespan of the LED.

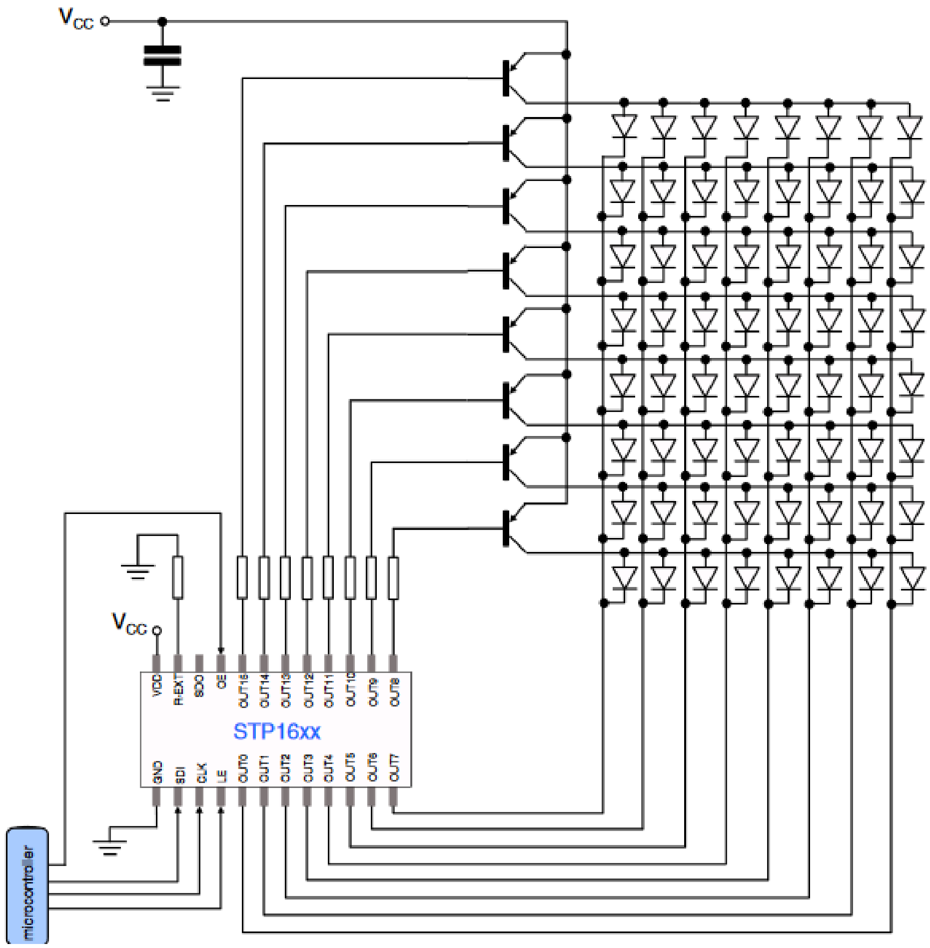

Figure 4.4a: Circuit showing how a microcontroller along with a led driver can operate a large LED array. Reprinted with permission from ST.

4.4.1 LED Array Design Modifications

The above mentioned LED driver was used on the initial prototype. The team found during the course of its testing that the driver was consuming more power than expected. In an effort to reduce the power usage of the overall installation in order to meet the low power specifications provided to the team by OUC, the LED driver was removed from the design and the LED strips used to backlight the graphical waterfall array were instead tied to the 12 volt rail from which the solenoid circuits receive their input power.

In order to regulate the brightness of the LED strips and achieve a desired effect where motion in the y axis would lead to a variation in LED brightness, digital pulse width modulation was used. A visualization of pulse width modulation is provided below in *Figure 4.4.1a*. PWM inputs fed to the LED circuits directly from the Raspberry Pi 3 or System Control Unit were used to regulate the LED strips to their desired brightness for a given pixel intensity shift on the y axis.

While the Raspberry Pi's ability to perform digital pulse width modulation using its GPIO pins was a powerful tool for the team, there was a noticeable limitation in the difference of brightness that could be achieved with the Raspberry Pi's PWM signals. It was observed that the majority of change in brightness on the LED strips occurred when their duty cycle was varied between 10% and 30%. With this in mind the team decided to vary not only LED brightness but color, adding 2 additional LED strips to the system each of a different color. Thus, a noticeable response to motion in the y axis could be performed by varying not only the LED strips' brightness but their colors as well.

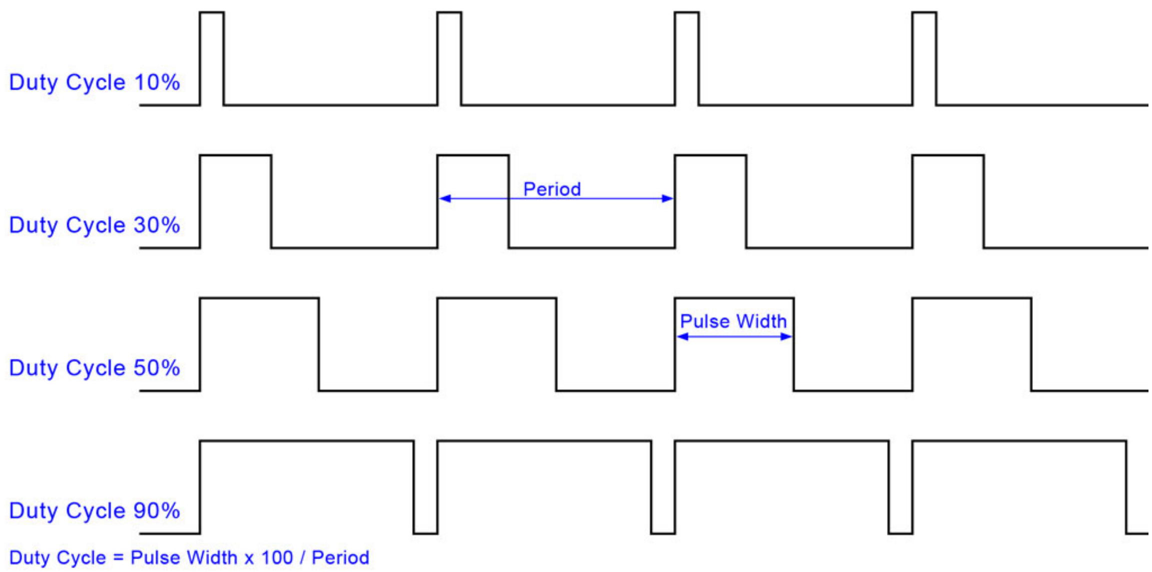

Figure 4.4.1a – Representation of pulse width modulation, reprinted with permission from Texas Instruments.

4.5 Pixy Cam Control Software

The Pixy Cam control software logic diagram is provided below in *Figure 4.5a* Primary features of the control software include image difference to discern regions of motion, hysteresis thresholding to eliminate image noise and background motion, and a clustering algorithm, which aggregates regions of motion into single objects that the Pixy Cam can track.

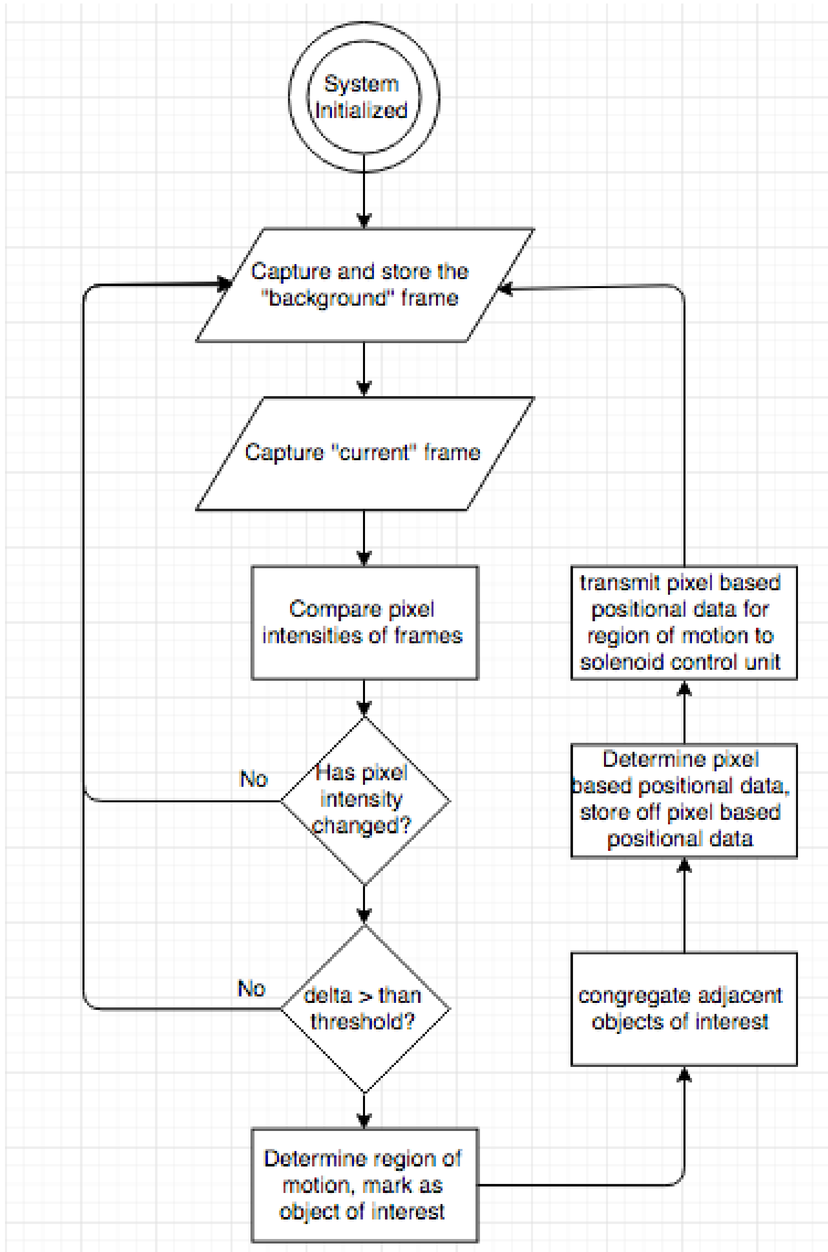

Figure 4.5a - Software Logic Flowchart for Pixy Cam Control Software.

4.5.1 Image Differentiation

The Pixy Cam captures fifty frames per second and can evaluate differences between the frames utilizing its onboard processor. Image difference calculations are carried out between every two sequential captured frames. Before image difference is calculated, an OpenCv gray scale filter will be applied to both images to eliminate color from consideration. Once the image is in gray scale, the pixel intensities for all pixels in each image are evaluated.

Foreground subtraction functions are then carried out, where every pixel intensity in the previous frame is subtracted from every pixel intensity in the most current frame. Thus the image difference is computed and stored in an intermediate image, this is the “gradient” image. An absolute value function is applied to pixel intensities in the gradient image so that every pixel is a value on a scale from 0 to 255, with 0 being black and 255 being white.

4.5.2 Double Thresholding

With the differences between the two frames captured in the gradient image, thresholding can take place. Applying hysteresis thresholding to the image will help reduce image noise and eliminate any change between the frames that is not the result of observer motion, such as movement in the background of the scene or brief changes in brightness. Hysteresis thresholding will also help segment regions of motion as separate objects from one another.

The thresholding is carried out first by applying a high threshold to all pixel intensities in the gradient image. This is the “first pass”. Any pixel that is above this initial high threshold is set to an intensity of 255 (white) and marked as a “peak”. Any pixel intensity that falls below the initial high threshold is passed over. For the second pass all pixels that passed the initial high threshold (the peaks) are reexamined. Any pixel that is adjacent to a peak pixel and has intensity greater than a second low threshold value will now be set to 255 (white) as well.

This method works by observing that pixels adjacent to pixels with a high intensity are likely to be a part of the same region of motion. It is important to recall that this thresholding is being performed on the gradient image, hence regions being set to white in this final image are the regions where motion is occurring in the frame.

With the final image computed (the thresholded gradient image where white represents motion in the observed scene), further calculation can be performed to determine what data to send to the solenoid control unit. The pixel intensities of the thresholded gradient image are converted to values which are stored in a two dimensional array. This two dimensional array has the same dimensions of the Pixy Camera’s resolution. It can be thought of as a dataset that contains the x and y coordinates of every pixel in the scene where motion is taking place.

4.5.3 Background Analysis

Background analysis was introduced late into the system software design during the prototyping process. Over the course of testing the final prototype, the team discovered that the low threshold value that is chosen as input for the hysteresis double thresholding algorithms is a key factor in overall motion recognition performance. Rather than chose a constant for this value and optimize the installation only for the senior design lab environment where testing was taking place, a new step was introduced in the motion segmentation software, the calculation of a dynamic low threshold constant through a process the team dubbed background analysis.

This background analysis is performed by introducing a 5 second delay upon system initialization whereupon a sequence of 10 frames are captured by the pixy cam, one at the start and end of each second long period. Average absolute pixel difference is calculated between each start and end frame producing a single average pixel intensity difference value for each second. These 5 values are then averaged together to produce a single average pixel intensity difference value which generally serves as a good low threshold constant for any given environment. If the calculated low threshold constant is found to be less than 15 (the minimum low threshold value for an enclosed environment), then the value of 15 is used for the low threshold constant. If the calculated low threshold constant is higher than the high threshold for an enclosed environment (30), then the high threshold value is increased to 60. If the calculated low threshold value is greater than 60, the program is terminated with an error statement indicating that there is too much motion in the given background.

4.5.4 Software Design Modifications

Over the course of developing the final prototype the software was modified to meet the needs of the final product. However, other than the introduction of dynamic low threshold calculation and the removal of the OpenCV filtering functions, the overall software logic present in the final deliverable remains for the most part unchanged. The primary difference between the team’s initial vision of the motion segmentation software and the final product is the use of custom motion segmentation functions coded in C++. Rather than use the OpenCV functions to perform motion segmentation the team decided that a manual approach would more challenging and rewarding. Members of the team had previously taken classes on image processing and had written similar projects, but nothing yet as powerful as the fully realized FLOW project.

4.6 Pixy Cam Control Unit

The primary purpose of the Pixy Cam Control Unit is to interpret the data communicated to it by the Pixy Cam into a form that is understood by the Solenoid Control Unit.

4.6.1 Addressing Processing Power Concerns

Initially, the Arduino Uno was intended to serve as the Pixy Cam Control Unit, however it was quickly determined during the course of prototyping that the Arduino microcontroller did not have the processing power to carry out the intensive image processing tasks required by the installation. The

Pixy Camera is designed to function in concert with an Arduino microcontroller and comes with many native functions that expedite communication between the camera and an Arduino microcontroller when it comes to the outputs of the camera's color tagging motion algorithms. In the context of this project however, the Pixy camera's native color tagging algorithms were not utilized. Instead a series of commands had to be sent to the Pixy Cam via USB which would capture frames using only the Pixy Camera's auto-exposure and auto-gain algorithms.

There was little support for sending commands to the Pixy Camera via an Arduino (the Arduino clearly intended to be serve only as a receiver of positional data). The Arduino additionally needed to use a dangerously high amount of its CPU to carry out the motion segmentation process even at a reduced rate of five frames per second. This level of performance was clearly unacceptable, and the

Arduino was therefore removed from the installation design, with the decision that the System Health Unit or Raspberry Pi 3 would pick up the workload of the Pixy Cam Control Unit and become a single System Control Unit. This appeared to be a step in the right direction as the Pixy Camera was capable of carrying out its own functions as well as the Arduino's with a max 10% CPU usage. Additionally, converting to the Pixy Camera gave access to the pixyusblib Linux library which opened up a much wider array of commands that could be sent to the Pixy Camera from the System Control Unit. Perhaps the only downside of switching to the Raspberry Pi was the speed gap between it and Solenoid Control Unit represented by the MSP430G2553. In order to allow for steady UART communication between the two microcontrollers, it was necessary to add several delays to the motion segmentation software in order to ensure the MSP430 was not bombarded by updates from the Raspberry Pi. Even with these

delays in place however, motion segmentation was able to take place at a desirable rate of 25 frames per second, with the only stop gap being the Pixy Camera's ability to transmit captured frames to the Raspberry Pi.

4.6.2 Motion Region Interpretation

Motion regions will be grouped into separate “blocks” with each separate motion region possessing a different Pixy Cam signature. For each Pixy Cam signature that is being tracked, an x coordinate, a y coordinate, a width, and a height are transmitted to the Arduino as positional data.

All of this data is measured in pixels, therefore the x and y position of a region of motion that the Pixy Cam is observing is the x and y coordinate of the center pixel of that region of motion on the observed frame. The Pixy Cam on the installation will run at 50hz, and therefore its resolution will be 640x480. Hence each X and Y coordinate is on a grid of this size. However, in some low light scenarios it may be advisable to run the Pixy Cam at a reduced rate to produce a better resolution. If the Pixy Cam is run at 25 hz in the context of a low light scenario, then the resolution of the frame will be 1280x800 affecting the scale of the frame's positional coordinates. The Pixy Cam Control Unit source code must be robust enough to handle these possible changes in scale. This is however, only an architectural precaution, as low light testing performed on the Pixy Cam has confirmed that it should be capable of recognizing motion with its default settings even in evening light.

4.6.3 Resolution Scaling

For determining which solenoid should be on or off, a rendering of the graphical waterfall array is superimposed over the pixy Cam's captured output image difference frame. In the case of 50hz default settings, the Pixy cam's horizontal frame axis is 640 and each solenoid is considered to be 40 pixels "wide". Hence in the default settings case, the brightness levels of each colored LED is considered to be 120 pixels "long".

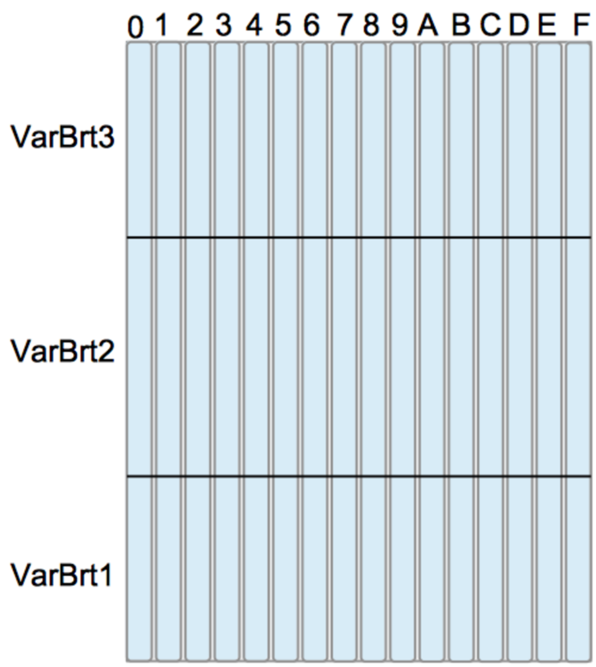

Figure 4.6.3a - Visualization of the 2dimensional position array transmitted from Pixy Control Unit to Solenoid Control Unit.

This means that if a region of motion that is 160x240 pixels is detected by the Pixy Cam, the Pixy Cam Control Unit will send positional data to the Solenoid Control Unit such that four solenoids are set to active high, LED brightness level for these solenoids would be set to two. In the special lowlight case of the Pixy Cam being run at 25hz to achieve a better active resolution, the horizontal frame axis would be 1280 pixels. Therefore, in this case each solenoid should be treated as 80 pixels “wide”, and each LED brightness level should be treated as being 280 pixels “long”. By building in the ability to adapt to changes in resolution, the team can be assured that a region of motion detected by the Pixy Camera will be scaled according to the camera’s resolution. Hence, a reaction will be produced in the graphical waterfall display, which is positional accuracy regardless of camera resolution.

The Pixy Cam Control Unit will transmit a two dimensional array to the Solenoid Control unit. This two dimensional array has columns which represent the graphical waterfalls solenoids, and rows which represent the various brightness levels for the colored LEDs used to illuminate the waterfall in evening mode. *Figure 4.6.3a* is a visualization of this two dimensional array.

4.7 System Health Unit

The System Health Unit for the installation is made of a Raspberry Pi 3 and an ultrasonic sensor. The primary function of the System Health Unit is to monitor water levels and determine whether or not to activate the 12-volt DC submersible water pump located in the installation's water collection basin. The System Health Unit will also be responsible for monitoring the power efficiency of the installation and determining if any power issues occur. In the event of a failure in the installation’s power system the System Health Unit will transmit interrupt signals to disable any the other microprocessor units as necessary.

4.7.1 Submersible Pump Regulation

The proposed installation has a unique problem in maintaining its water levels. Because the observer's motion will control the rate at which water is dispersed from the graphical waterfall display, it is be difficult to determine ahead of time the interval at which pumps to replenish the water reservoir should be run. The proposed solution to this dilemma is to control the activation of the water pump based on the level of water in the installation’s lower collection basin.

The water level in the installation’s collection basin will be marked with a low and high threshold value. When the water basin’s water level dips below the low threshold, the submersible water pump should be deactivated until the water level reaches the high threshold (open water solenoids are draining the upper water reservoir when the submersible pump is deactivated). When the water level in the basin rises above the high threshold, the water pump should be activated until the water level decreases to the low threshold. Hence water used by the graphical waterfall display can be replenished according to the installation's current need. This also assures that water pumps will not be running during long periods of inactivity where no observers are present.

This monitoring of the water level is performed by an ultrasonic sensor, which is connected to the Raspberry Pi 3 microcontroller. Looking down on the water collection basin the ultrasonic sensor can monitor the time it takes for an ultrasonic wave to propagate down to the bottom of the basin and return to it. By running a custom python script in the Raspberry Pi 3, this data provided by the ultrasonic sensor can be interpreted into a water level in centimeters, which the Raspberry Pi can then use as a gauge of when to activate and deactivate the submersible water pump in the basin. This custom python script is a modified version of the RaspiSump script created by Linux North for the purpose of monitoring water levels and producing alerts in a sump pump system.

4.7.2 Pump System Modifications

For the second semester of senior design, pumps were physically tested with the system to check if they deliver enough water to the system, rather than relying on flow and pressure calculations. The results of the testing showed that the system could easily be supplied by a single Aubig 12v DC pump. These pumps were small, with a flow rating of only 2.2 gallons per minute with no overhead height. Due to this, it was originally believed that two pumps would be needed to supply enough water to the upper reservoir to keep it full even when all 16 valves were open.

However, the testing showed that a single pump provided enough flow and both pumps were not necessary which left us a second pump to use as a backup if needed. It was also not necessary to control the pump with the Raspberry Pi unit, as the overflow return meant the upper reservoir was always full, and the pump would be allowed to remain on whenever the system was on.

4.8 Water System Design Modifications

A water filter was not necessary for the functionality of a prototype design. However, a synthetic mesh filter was used to cover the lower reservoir, which served a dual purpose of filtering large debris as well as eliminating the noise of splashing from the falling water streams.

At the beginning of the second semester of senior design, the water supply and return tubes were initially made the same size out of half inch tubing. However, this resulted in an excessive syphon effect force that was not accounted for. Once the upper reservoir was full, and water began to flow through the water return tube, the water return tube created a syphon effect that was actually sucking with more pressure than the pressure being provided by the supply tube. This resulted in some of the solenoid valves actually sucking in air when open, rather than allowing the water to stream out. This issue was corrected by using a restricting valve at the bottom of the water return tube, which slightly increased pressure in the water return tube and restricted the syphon effect.

4.8.1 Solenoid Valve Array Design Modifications

The US solid valves were chosen based partly on cost. The lower cost made our project come in under budget, as brass fast-response solenoid valves would have cost at least three times as much as the US solid plastic solenoid valves. However, in the second semester of senior design, it became apparent that the valves were very leaky with extended use, and at times refused to stay closed at all. This was occasionally fixed by taking the solenoid valves apart and reassembling them after cleaning the spring mechanism.

4.8.2 Solenoid Switching Circuit Design Modifications

In Senior Design 2, the IRLB8721PbF MOSFETs circuit was able to be used to control multiple devices due to its exceptional specifications. The low turn-on and turn-off delay times of 9 nanoseconds made it suitable for PWM control of LEDS. For the final project, three LED strips were added to the project to light the water streams. One strip was blue, one was green, and one was red. The Y-axis tracking of the user was coded to control the intensity and color of the LEDs. The intensity of the LED strip could be controlled with PWM modulation at 3.3 volts. We selected 12 volt LED strips, which made the IRLB8721PbF MOSFETs ideal to control the LED voltage using the 3.3v signal.

The circuit to connect the LED strips was the same as the solenoid switching circuit, with the exception of the fly back protection diode, which wasn't needed for the LED strips as they are not inductive loads. Rather than output pins from the shift registers controlling the gate of the MOSFETs, the 3.3 volt PWM signal for each LED strip was used to control the gate of the MOSFETs. This allowed for PWM modulation of the 12 volt supply to the LED strips in the circuit, which successfully varied the LED intensity based on the duty cycle of the PWM signal. By using the same circuit and MOSFETs to control the LED strips, an extra copy of the same PCB board was able to be used for controlling the LEDs, rather than trying to order a new board and hope it arrived in time.

4.8.3 Water Reservoir Design Modifications

Due to the fact that our project was a scale-model prototype, a simple plastic tub was used for the lower reservoir during the second semester of senior design. Rather than using a dense foam, a cheaper synthetic mesh air filter was used with the same purpose to block light, helping eliminate the audible splash of the falling water streams, and stopping larger debris from entering the water.

For the prototype construction in the second semester of senior design, water filtration over time was not a key concern. While a filter was placed over the lower reservoir, it is only able to stop large debris. For a long-term display, especially a full-scale outdoor design, water filtration using a micron screen filter and a paper water filter would be necessary.

4.9 Solenoid Control Unit

The Solenoid Control Unit is made up of the MSP430430G2553 microcontroller and 4 Addicore 74HC595 8-bit shift registers. The microcontroller will receive and interpret commands from the Pixy Cam Control Unit, determining what signals to send to the Solenoid Switching Circuit. It will also report status of the graphical waterfall array to the System Status Unit. If a malfunction occurs with the water or power system, the MSP430430G2553 is capable of receiving an interrupt signal that disables all graphical waterfall array activity.

4.9.1 SIPO Shift Register Usage

SIPO (serial in, parallel out) Shift registers like the ones utilized in the Solenoid Control Unit generally do not see much use in modern sequential logic design. This is due to the availability of microcontrollers with a wide range of output pins. However for this project's implementation budget and power consumption are major constraints. Hence, a cheap and efficient multiple component circuit was designed rather than investing in a single more powerful (and more pricy) microcontroller.

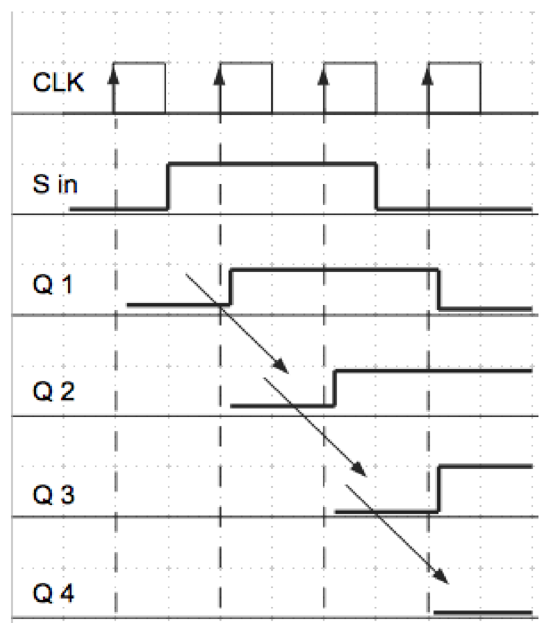

Figure 4.9.1a – clock cycle diagram for a 4-bit SIPO shift register, the value 0110 is the serial input.

One of the major advantages of using the SIPO shift registers is that they can be loaded in a short number of cycles, and proceed to have all parallel (Q) output lines read in a single cycle. This eliminates the possibility of a delay in the graphical waterfall array, whose impressive display is highly dependent on responsive solenoid switching. *Figure 4.9.1a* shows a clock cycle diagram for one of the shift registers, reduced from 8-bits to 4-bits for simplicity. Serial input data can be loaded in a number of cycles equal to data bus width (i.e. 8-bit serial input takes 8 cycles to load 8 1-bit output lines).

Utilizing 2 8-bit shift register units, the MSP430430G2553 microcontroller can control the state of 16 1-bit input water solenoids by transmitting 8-bit serial data signals to 2 of its output pins (each connected to an independent shift register). It takes a total of 8 cycles for all water solenoids to be “set”. Knowing that the parallel output lines are all read on the same cycle will assist the team in determining if any of the water solenoids have a “turn-on” delay that will need to be addressed.

4.9.2 Shift Register Daisy-Chain Configuration

In order to control all 16 of the water solenoids the Solenoid control unit will need to pump serial data to 2 8-bit shift registers. Since the MSP430430G2553 microcontroller only has one serial data output, the shift registers will need to be “daisy-chained” together to allow for a single 16 bit serial data signal to turn them on or off at will. Daisy chaining the shift registers is a scheme in which they will be connected in a linear sequence so that both the shifters are included in the same loop. Pictured below in *Figure 4.9.2a* is a daisy chain configuration of two 74HC595 shift registers. This same daisy chain configuration is tested on a breadboard in Test Case 4 in Section 6.3.

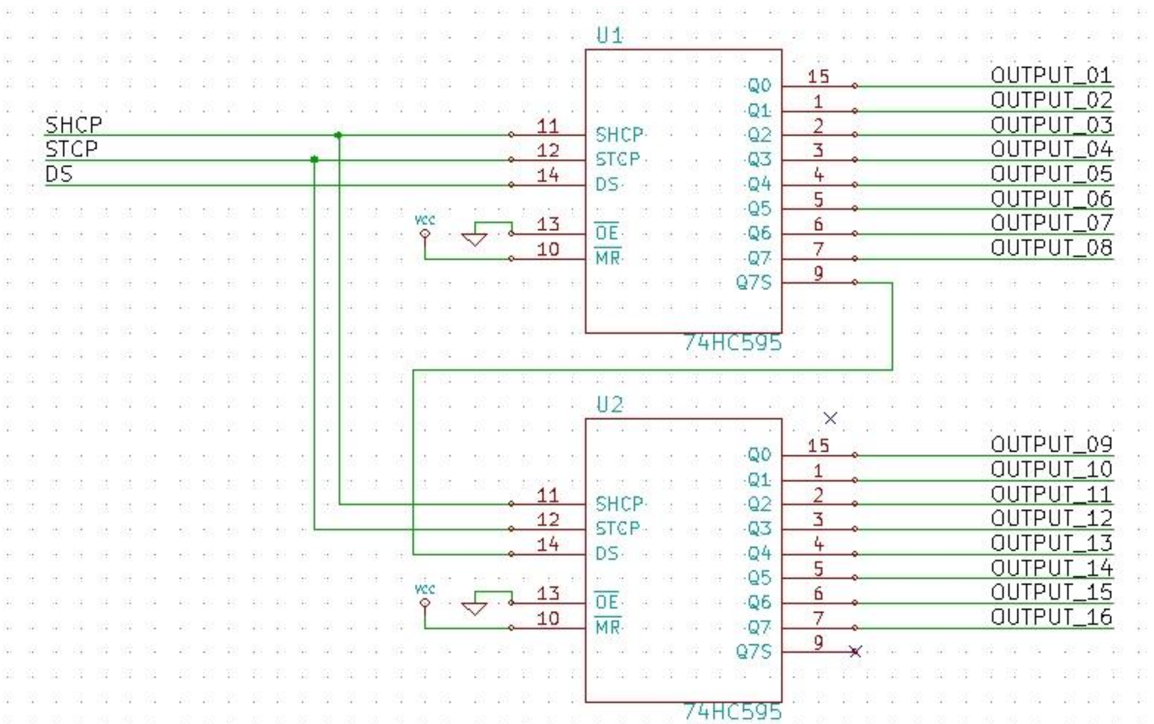

Figure 4.9.2a - Two-74HC595 shift registers in daisy-chain configuration.
Reprinted with permission from Michael Silverman.

With the shift registers in this configuration it is possible to transmit sequences of serial data as the MSP430430G2553 processes input from the Pixy Cam Control unit. These sequences inform the shift registers which outputs should be set to active high and which to active low. The interval for which the outputs are set can be controlled in the source code for the Solenoid Control Unit.

4.10 Audio Interaction

One of the stretch goals taken on by the team shortly after midterm demonstrations was the addition of some audio interaction by which observers might input music to the installation and see synchronized patterns play in response to their chosen songs.

To do this it was necessary to implement rudimentary spectrum analysis onboard the Raspberry Pi 3 or System Control Unit. The idea being that this digital spectrum analysis would listen for specific notes being played on the input music and would send signals to the solenoid array based on the frequencies of these notes. Thus observers could watch as a unique waterfall pattern was produced in synchronization with their chosen song, along with some LED light patterns as well.

4.10.1 Music Visualization Software

The team reused an old pair of computer speakers (Manhattan 2600 USB speakers) for the audio output device which was mounted atop the installation above the graphical waterfall array. With an input voltage of 5 volts, these speakers were ideal, as powering them was as simple as connecting them to the output node of the 5 volt power supply PCB. A single pulse width modulation GPIO pin was diverted from the Raspberry Pi 3 to serve as the input signal line. Software was then added to the Raspberry Pi 3 or System Control Unit which would trigger specific solenoids for given frequencies (ranging from 260 hz to 590 hz). With 16 Solenoids available in the graphical waterfall array the entirety of 4th and 5th musical octave could be represented. In addition to this, specific LED colors and brightness values were assigned to each of the given frequencies to add to the music visualization experience. Unfortunately at this point the team ran out of spare time with which to pursue this stretch goal and real time audio interaction was not achieved in the final prototype. However a music visualization routine choreographed to a single preprogrammed song was possible and the team chose the Super Mario Bros. Theme as the perfect song to demonstrate this future functionality.

4.11 PCB Design

The PCB design of our project will include the AC to DC converter, the solenoid switching circuit, the pixy cam, and the system-monitoring unit. EagleCAD is the software most familiar to our team and is our preferred option to design the printed circuit board. EagleCAD simplifies the process of designing a PCB by converting the schematic design into the most efficient PCB layout given the number of layers and dimensions desired. Using the schematic editor in EagleCAD we will realize the components accessible to the manufacturer and consumer. The reference design for the AC to DC converter was taken from TI Webench Power Design shown in *Figure 4.11a* is the schematic with the integrated circuit chip LM5023.

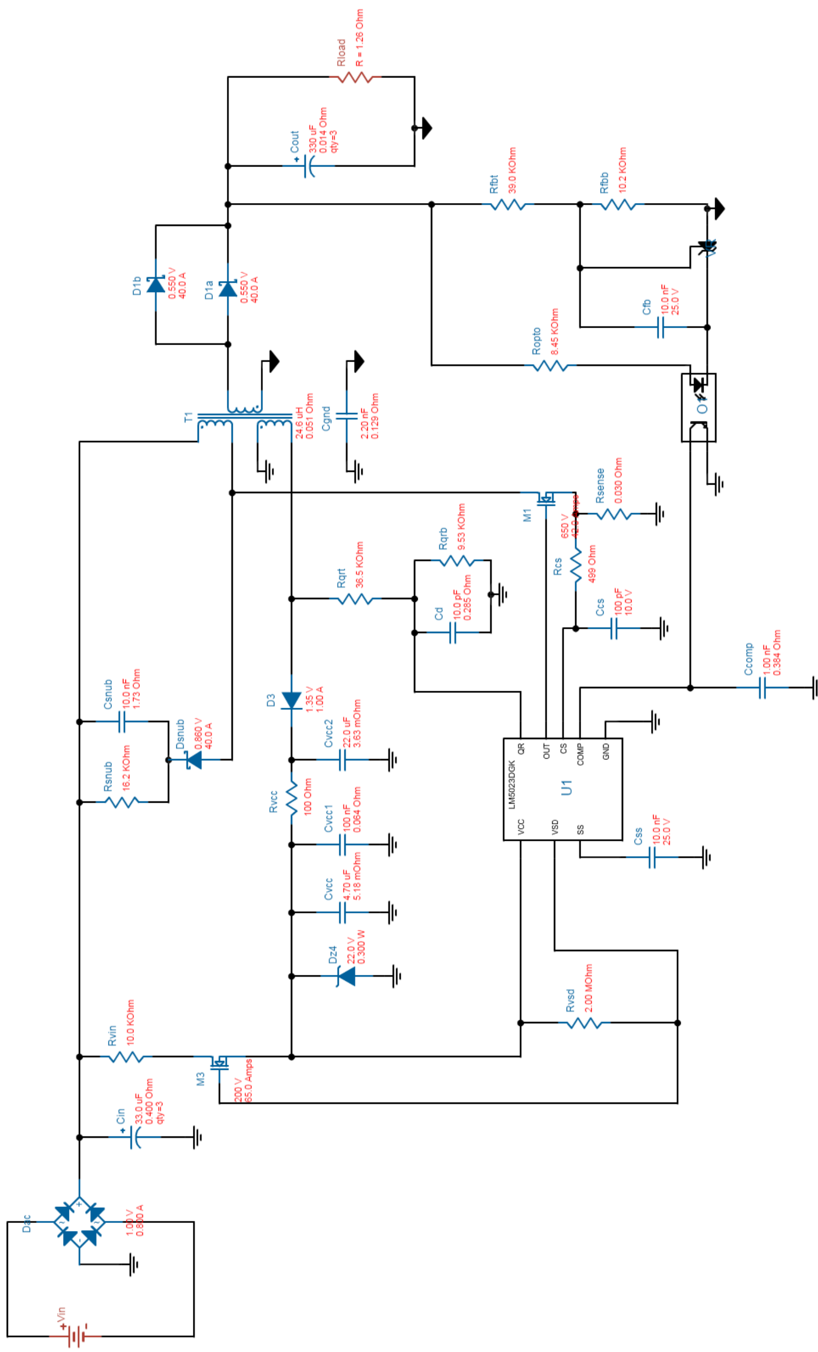

Figure 4.11a - AC to DC Converter Reference Design
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It is likely that transformer and IC will have to be externally soldered after ordering the printed circuit board because of their footprint. The estimated size of this PCB will be 4 sq in which will cost about $33 for the 2-layer PCB manufacturing. These price estimates are given by 4pcb.com, a PCB manufacturing company that provides discounted PCB's for students and education purposes. There is a possibility for a 3 layer pcb for $66, but the complexity of this design will our simple power supply will not be necessary.

To design the PCB for this project EAGLE 7.7.0 was used for the schematic and board editor. Thanks to a PCB design workshop presented by an employee from EAGLE CAD and element14 a fundamental understanding of the design process was explained using a low pass filter example. This design translated the necessary libraries and functions used in the design of the printed circuit board for this project.

Naming the value of each wire eliminates excess wiring and easily reference the connections between the shift register and which solenoid it will be paired with. This is especially useful because the solenoid labeling will be present on the PCB necessary from our through hole components such as the diodes and MOSFETs. The primary interaction between the shift register and the solenoids runs through the n-channel TO220X MOSFET that turns on and off the solenoid valve. Connected in parallel with the solenoid is the 1N4001 diode to assure the voltage spike from the switching will not cause voltage or current overload. The through hole devices were found in the Eagle library but a specific 1N4001 diode was not found, to solve this the value of the 1N4004 diode used was changed. Connect in parallel is two screw terminals needed for the solenoid connections. Two terminal screw hole connections were selected because of their versatility and ability to replace the solenoid easily if anything were to happen. After building the first solenoid hardware components of the schematic it was copy and pasted to have a total of 8 solenoids accounted for on the board. The schematic analyzed using the Electrical Rule Check feature in the Eagle CAD software. Any errors were adjusted and made compatible for the board editor.

Following the completion of the schematic the circuit board was ready to be developed in the board editor aspect of the Eagle CAD software. The first aspect of the board editor is to layout the physical components where needed on the circuit board parameters, making sure to minimize the distance of wiring as to reduce the number of layers and vias. Knowing the solenoids will all have external wires connecting to PCB the screw terminals were placed on the outside parameter, the diodes and MOSFETs were then placed in sequential order next to the solenoids to logically outline where they should be placed after receiving the printed circuit board and soldering the through hole hardware components. The input pins from the MSP430 were also placed near the exterior of the PCB but closer to the 8-bit shift register as to reduce the wire length needed. The 8-bit shift register was placed nearest the MOSFETs because that was the closest connection as outlined in the schematic. After all the components were properly aligned on the circuit board the auto router tool was used to find the most efficient wiring schema for this PCB. Five potential wiring networks were available but the one selected used only 2 layers, which would be the cheapest and dissipated the least amount of power. Consideration for future changes in the design is to make the input ports from the MSP430 as female pinheads because they are similar to the pinheads on the MSP430 and leave a small footprint on the PCB.

The largest PCB layout will be the solenoid switching circuits because 16 will be needed to make the waterfall feature, in addition to the computer vision controlled I/Os. The solenoid switching circuit runs off the 12V power supplied by the AC to DC converter PCB previously explained. A tertiary PCB may be added for the 5V and 3.3V components. The individual solenoid switching schematic is designed as in the *Figure 4.11b* showing the 12V inputs an MOSFETs used.

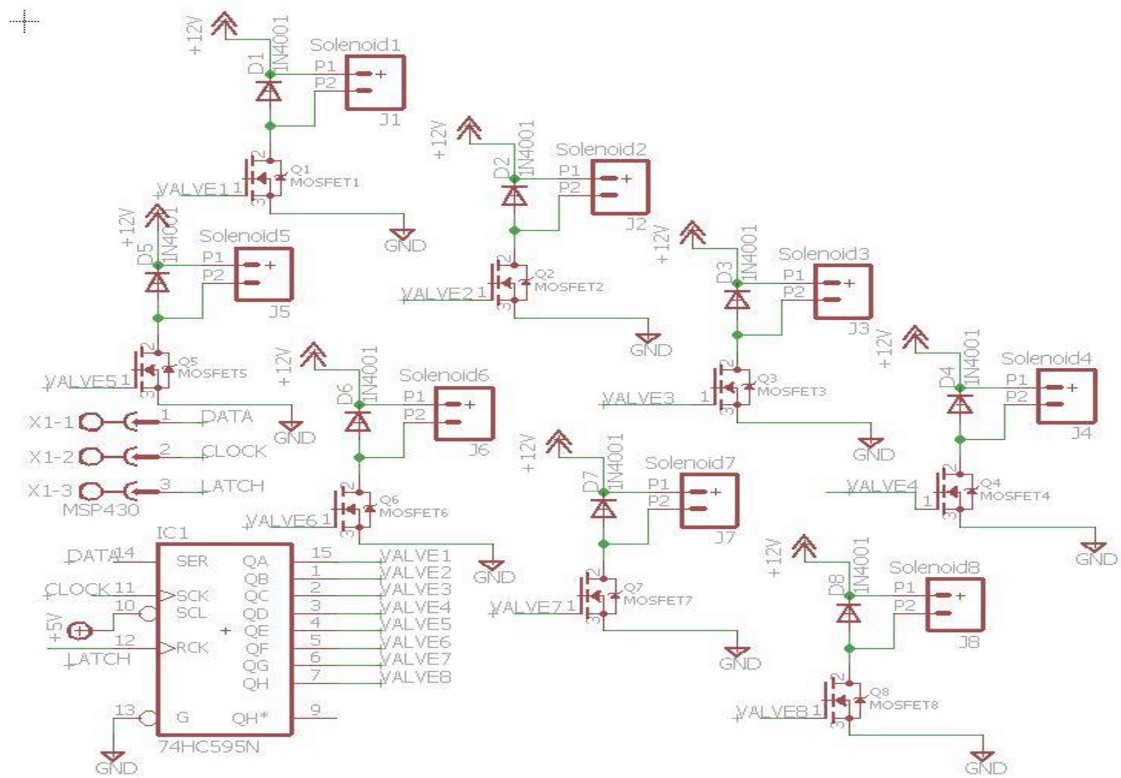

Figure 4.11b Solenoid Component Schematic

The current drawn from each solenoid is 400mA with a max power draw of 4.8W. The solenoid has a fast valve open and close time close to 10ms allowing for rapid switching between all 16 of the solenoid valves. Repeating this schematic 16 times for each solenoid does call for power and current draw considerations necessary for the PCB. With all the schematics on a single PCB the design will look similar to *Figure 4.11c* with the additional computer vision controller attached at the bottom.

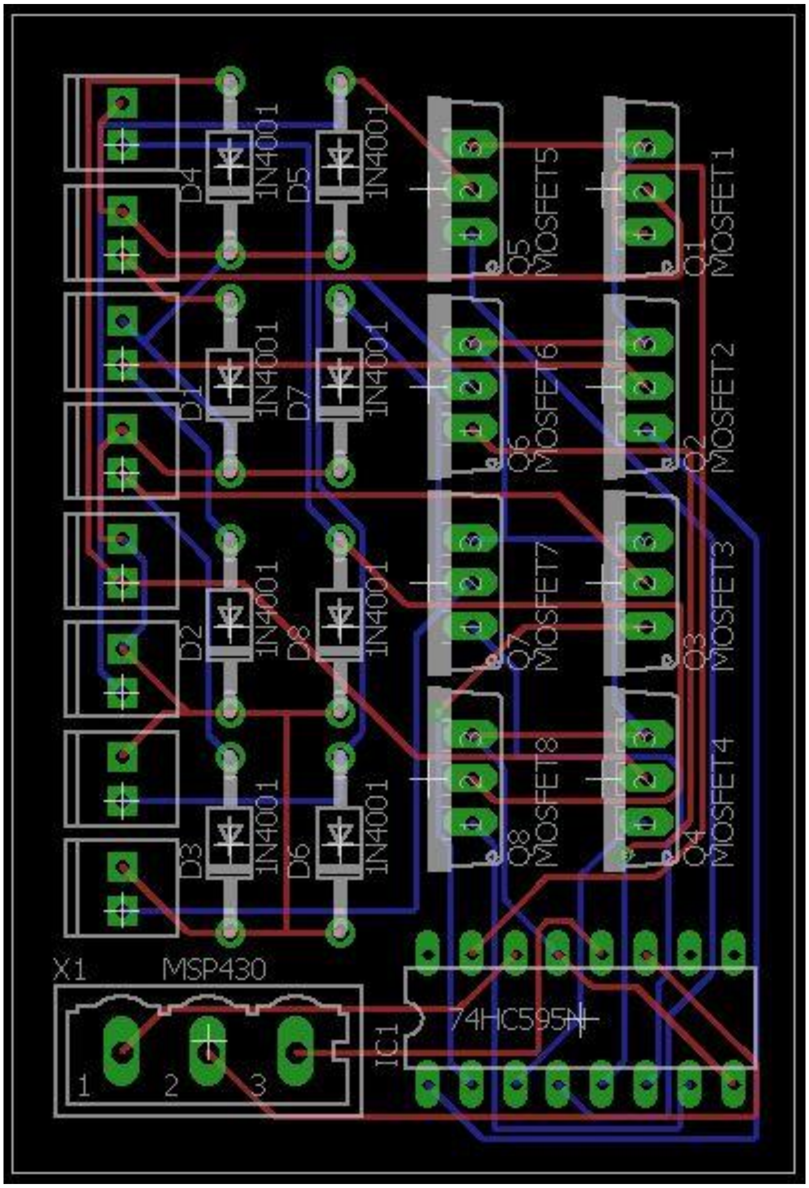

Figure 4.11c Solenoid Switching PCB Design

With a surface area of 14” x 10” this will be the largest PCB in our design assembly. To reduce unnecessary wiring a data bus was created to interconnect the shift registers.

4.10.1 Finalized PCB Design

The team's PCB design was finalized during the initial weeks of the Senior Design 2. The design of the printed circuit board was constructed using the schematic software EagleCAD. The PCB contains 4 main components: the solenoid switching circuit, the shift register, the MSP430 microcontroller, and the power supply rails. The solenoid switching schematic consists of an N-channel MOSFET, with a 1N4001 diode and the solenoid in parallel. These components all share a common 12V rail to supply power to the solenoid.

The switching of these solenoids are controlled by the output from the two 8-bit shift registers and there connection to the MOSFETs. These MOSFETs act as switches to regulate the 12 volts supplied to the solenoid, when the shift register outputs high to the gate on the MOSFET the 12V is able to turn on the solenoid. The diode is placed in parallel with the solenoid in order to prevent fly back voltage to the MOSFET when the solenoid induction current is dissipated. The two 8-bit shift registers are daisy chained together by connecting pin 9 to pin 14 as seen in *Figure 4.11.1a*.

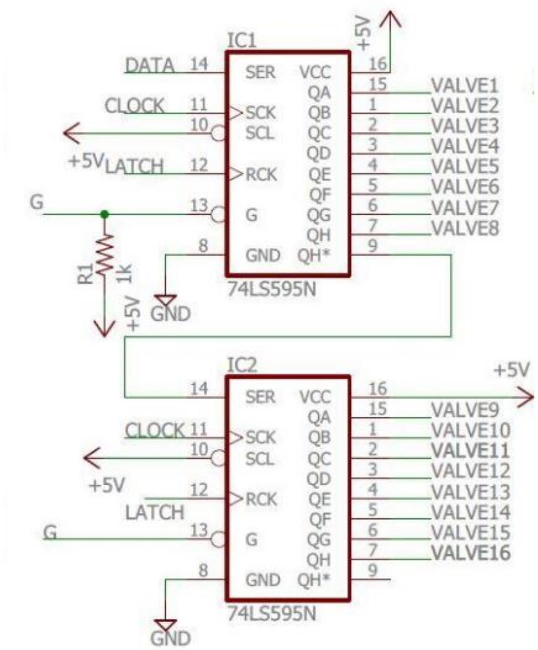

Figure 4.11.1a - Daisy chained shift register circuit with MSP430 input lines.

This allows the MSP430 microcontroller to be able to communicate to all 16 solenoids simultaneously. The MSP430 is mounted on the circuit board with a 20-pin socket and receives input commands from the Raspberry Pi. These external connections are made through female header pins mounted on the outside edge of the PCB. These data lines allow for transmission of information from the sensor camera through the processing components out into the selector lines controlling the state of the solenoids. All these components mounted on the printed circuit board share a common 12V, 5V, or 3.3V rail. The 12V rail is a direct connection from an AC to DC power supply with 20A, necessary for the large power draw from the solenoid array and LED lights. These 12 volts are then regulated down to 5V and 3.3V using external voltage regulating PCBs. The 12V is used to power the solenoids and water pump, while the 5V regulator is used to supply the power needed for the Raspberry Pi, CMUcam5, and Audio input sensor. Further voltage regulation down to 3.3V is necessary for powering the MSP430 microcontroller.

After completion of the final schematic design in EagleCAD, the circuit is ready to be transferred to the physical printed circuit board layout design. Considering the high functionality and power draw of the solenoid switching circuit consideration for heat dissipation were evaluated. Placing the MOSFETs in parallel position along the length of the circuit board allowed to optimal cooling and preventative over heating measures. The control components, MSP430 and shift registers, are placed in the middle of the PCB because of their centralized connection to all the components on the board. This centralization allowed for minimal wiring layers and vias need when printing the board.

The outer connections to the solenoid screw terminals are all placed in a row of 16 in order to consolidate the wires need between the PCB and the solenoids. The input and output pins used for communication with the other controllers are placed on the exterior of the PCB to allow for ease of access when debugging component interconnections. The layout of the final printed circuit board is shown in *Figure 4.11.1b*.

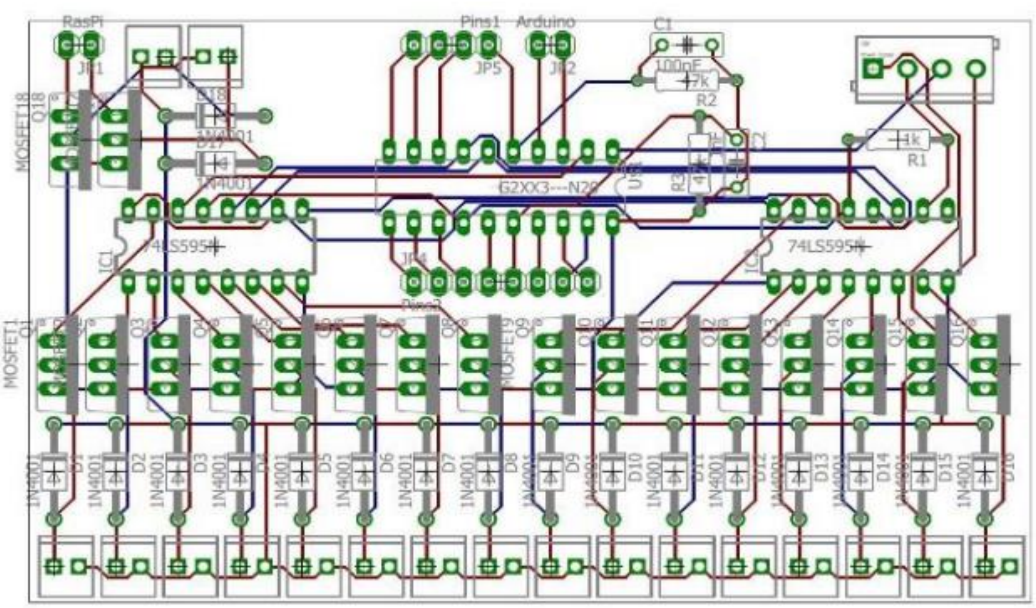

Figure 4.11.1b - Printed Circuit Board for Solenoid control.

4.12 Power Hardware

4.12.1 Inverters

For the full scale product we would like to use the string inverter,C2000™ Solar

DC/AC Single Phase Inverter, that comes paired with the C2000™ Solar DC/DC Converter with Maximum Power Point Tracking (MPPT). This combination of string inverter and string DC/DC with MPPT would offer a good balance of efficiency and expense. As long as the panels in the string are mounted with the same orientation and assuming there are no shading issues individual microinverters are not worth the added cost and also the added difficulty in troubleshooting and maintenance.

Figure 4.12.1a - Single Phase Inverter Developer Kit
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From the image below it can be seen this inverter utilizes a current controlled full H bridge with pulse width modulation along with an LCL filter, which were discussed previously. This image also shows the C200 F28M35H52C MCU monitoring the input, output and controlling the H Bridge.

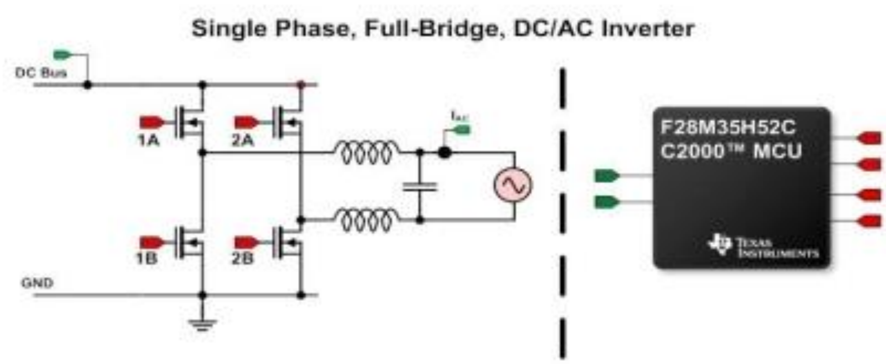

Figure 4.12.1b - Single Phase Inverter Developer Kit basic schematic.
Reprinted with permission from Texas Instruments

C200 Solar DC/AC Single Phase Inverter Features:

- Implements a single phase, full bridge, grid tied inverter.
- C200 F28M35H52C MCU serves as the controller for the DC/AC inverter, it monitors the grid and insures that the produced power is in phase and also allows for monitoring of the inverter.
- Selectable 120/220 VAC outputs up to 600W
- Has above 96% efficiency and less than 5% distortion, which allows for improved energy efficiency.
- Comes with extensive digital libraries that allow for flexible inverter solutions.

For the client's full-scale installation we recommend a commercial solution that will be easier to install and troubleshoot. This option will also meet NEC and other standards so it can be legally installed and will also ensure the safety of the public that will interact with the sculpture. The SolarEdge P300 Power optimizers can be paired with a SolarEdge inverter. They come in single phase and three phase varieties. Due to the size of the PV array a single-phase inverter will be fine, specifically the SE3000A inverter. We are recommending a central inverter rather than micro inverters because when a central inverter is paired with power optimizers the efficiency gains are marginal. Microinverters also come at a higher cost. This inverter also comes with remote monitoring and a 25-year warranty. These features should make this product especially attractive to OUC given their desire for a low maintenance product.

The SE3000A-US is ideal for full-scale application because our input voltage will be below the maximum of the unit, 500V. Also the maximum power generated from the full size array will be well below the maximum power input, STC, of 4050W. The maximum current of 9.5A will also fit within the bounds of the full size solar array. Because of all these factors a larger transformer will not be necessary

This combination of SolarEdge products allows for high efficiency, reasonable pricing, easy installation and remote monitoring and control of each individual panel along with inverter health.

For the ⅛ scale model price and safety concerns will limit us to one solar panel. However our team would still like to demonstrate a DC/DC conversion, MPPT and a grid tied inverter. So accomplish this microinverter developer kit will be utilized. Grid-tied Solar Micro Inverter with MPPT, TMDSSOLARUINVKIT, is a developer product offered from TI and will be used in this project.

Figure 4.12.1c - Micro Inverter Developer Kit.
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Features

- Implements MPPT, DC/DC conversion utilizing secondary voltage multiplier and a grid tied DC/AC inverter.
- Accepts solar power inputs from 28-45V and outputs either 280W at 220VAC or 140W for 110VAC.
- Has 93% peak efficiency and less than 4% harmonic distortion.
- The C2000 Piccolo F28035 MCU microcontroller allows for high frequency controls and monitoring necessary for tying into the grid.
- Comes with extensive digital libraries that allow for flexible inverter solutions.

4.12.2 AC to DC Converter

The power supply need for this project will be drawn from a 120Vac 60Hz wall outlet and converted to 12Vdc using a Webench Power Design from TI. This AC/DC converter outputs 12V DC at 9.5 A, these output values were determined by the maximum power consumption of 110W from all our electrical devices. The solenoid valves and water pump require the highest voltage at 12V, a voltage regulator will be used to drop the voltage to 5V and 3.3V for the additional Microcontroller units. The schematic for the AC to DC converter in represented in *Figure 4.12.2a* and given permission by TI as a reference educational design.

This converter uses a full-bridge rectifier for the conversion from AC to DC with a bypass capacitor to dampen the AC noise from the source. The Integrated Circuit controlling our converter is the LM5023, an AC-DC Quasi-Resonant Current Mode PWM Controller. The LM5023 was selected because of the ENERGY STAR low standby power rating and overcurrent protection necessary when handling high voltage inputs. This design will be implemented in one of our PCB designs, separate from the feature PCB to prevent damage to the low voltage components.

4.12.3 Voltage Regulators

The Power Supply converter will output a constant 12V, but to power the rest of the electrical components this voltage will have to be stepped down to 5V and 3.3V. The L7805 5V voltage regulator will step down the 12V to supply a constant 5V needed to power the Raspberry Pi 3 and Pixy Cam. With a maximum current output of 1.5 A, short circuit protection, thermal shutdown and safe area protection this meets the maximum current requirements of 1 A by any of the 5V components. *Figure 4.12.3a* shows the 3-terminal regulator and the thermal overload heat sink protection.

Figure 4.12.3a - L7805 5V Voltage Regulator.

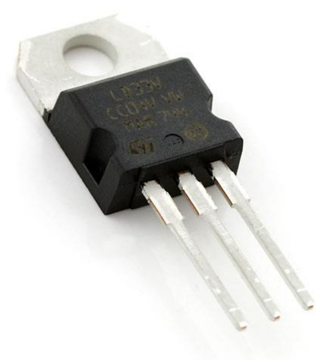

Figure 4.12.3b - LD1117V33 3.3V Voltage Regulator.

The lowest supply voltage requirement is by our MSP430 at 3.3V, this is achieved by placing the LD1117V33 voltage regulator in series with the L7805 voltage output. The MSP430 is an ultra-low power device, meaning the maximum current output of 800 mA will be plenty to supply the 330uA current input requirements of the MSP430. The benefits of this voltage regulator include a fixed regulator, which provides a reliable stability and short circuit protection needed for this project. Similar to the 5V voltage regulator this 3.3V voltage regulator has internal current and thermal limiting, with a heat sink visible in *Figure 4.12.3b*.

4.12.4 DC/DC Converter

An option to maximize the power harvested from the solar panels a DC-to-DC power optimizer with MPPT will be connected to the solar panel. The specific DC/DC converter used is the SM72445 SolarMagic MPPT Evaluation Board, with an input panel voltage between 15-40V, meeting the requirements for the 24V panel in the design. This DC/DC outputs a constant 50V at 11A giving a maximum power rating of 550W. The driving force of this converter is the integrated circuit SM72445, a programmable MPPT controller that uses PWM driving signals to buck-boost. Using a proprietary method known as Panel Mode, allowing for flexibility in the connection between the panel and the converter when the input to output voltage ratio is close to 1. The MPPT algorithm is the driving force behind the 99.5% efficiency of the panel output. Utilizing an 8-channel, 10 bit A/D converter the IC uses current and voltage sensors inputs and outputs necessary for finding the max power point of the panel output. This evaluation board includes all the components necessary to increase the efficiencies of our panels and is significantly lower in cost than the C2000 Grid tied inverter, $150 versus $850.

This product would be used if there were no budget or safety concerns regarding larger pv systems. Each one of the solar panel strings will have its own dedicated DC/DC converter with Max Power Point Tracking, MPPT. This will allow for a good balance of cost and efficiency. The string DC/DC converter that will be used is a developer TI product, C200 Solar DC/DC Converter with Maximum Power Point Tracking (MPPT).

Figure 4.12.4a - DC to DC converter with MPPT.
Reprinted with permission from Texas Instruments

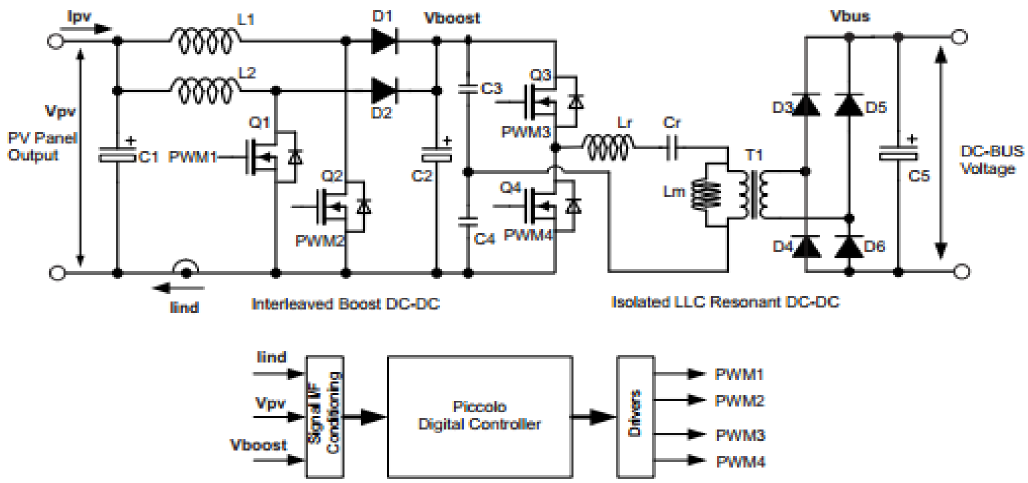

Figure 4.12.4b - DC-to-DC converter with MPPT Basic Schematic.
Reprinted with permission from Texas Instruments

This converter is made up of two basic sections the two-phase boost section and the isolated LLC Resonant section. The Piccolo Digital Controller controls all this.

Features

- The DC/DC converter has two major parts, a two-phase interleaved boost converter for maximum power point tracking and a resonant LLC converter.
- C2000™ Piccolo™ TMS320F28035 microcontroller (MCU) serves as a controller to complete the DC/DC conversion and to execute the max power point tracking.
- Supports input voltages of 200V to 300V and output of 400VDC, rated up to 500W.
- Converter has greater than 94% efficiency leading to higher performance PV arrays.
- Solar and digital power software libraries provide code chunks that are perfect for custom inverter solutions.

However for our client we recommend the use of a commercial power optimizer that will allow for MPPT tracking at each panel and will also act as a DC-DC converter. This will be much easier to install than building the necessary developer kits and those kits would not meet NEC or IEEE standards. We highly recommend that each panel has its own MPPT DC/DC conversion for its benefits in regards to efficiency. Even minor shading on a single panel in a string can drastically reduce the efficiency of the entire string. Because the location and mounting or the panels is unknown at this time individual MPPT for each panel is crucial.

The SolarEdge P300 Power Optimizer allows for extreme efficiency, 99.5%, due to its individual MPPT controls for each panel. This system can be paired with a Solar Edge inverter for monitoring. These power optimizers can be easily added to an existing system if OUC would ever have a desire to add to the solar array and they are substantially cheaper than microinverters.

4.12.5 Power System Modifications

Our Sponsor was uninterested in pursuing a novel inverter design and also wanted the sculpture to be powered from the grid without batteries. Without an inverter the solar panels served no purpose so they were also eliminated from the scaled down design. This was a cost savings and allowed for my focus to be put on the aesthetic and interactive parts of the project.

Our project started with extremely ambitious power design objectives. But due to customer concerns, budget and time constraints some aspects of the design were scaled back. Originally there were supposed to be several solar panels with an inverter built from a developer kit, this alone would cost close to $1000 dollars. Our client OUC also voiced concerns that our inverter design would not meet NEC regulations so would not be useful in their final design. OUC also wanted to use power from the grid to power the final design for the sake of simplicity and to eliminate the need for batteries. This combination of factors led us to drop the inverter and solar panels from our project and to focus more resources towards improving the aesthetic display.

Another item that proved to be too difficult to execute was a high power rectifier. There was two options for this which included a more amateur design that had high energy loss and a more professional design that was composed of about 140 components. The high complexity design couldn't be completed due to the large amount of soldering and difficulty trouble shooting such a highly complicated system. The simpler design used a large specialty transformer costing $100 and had a very long lead time. The cost of this design was fairly high, $250, because of several factors. The PCB would need very thick copper traces to handle the high current which increases the price. The high current also makes using an integrated chip for the H Bridge impossible so one would have to be made out of expensive high power diodes. Finally to boost the current high power BJTs would need to be used. The cost of this rectifier would greatly affect the overall budget for our project. Because of these factors a commercial rectifier used for medium to large scale LED displays was used.

4.12.6 Finalized Power PCB Design

The finalized Power PCB for the installation is show below in *Figure 4.12.6a*.

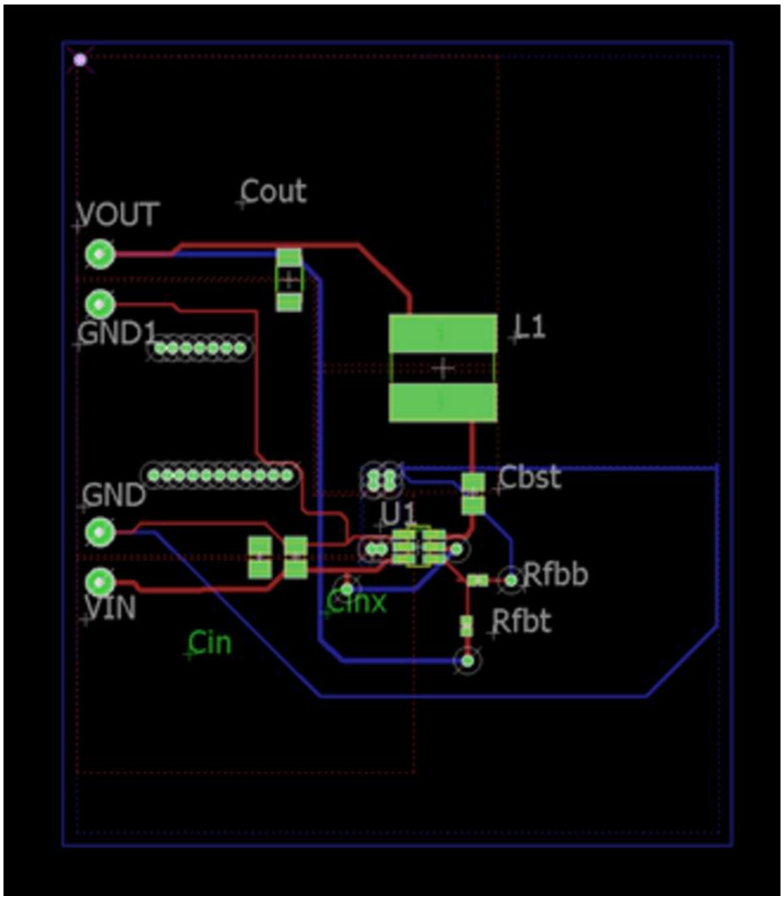

Figure 4.12.6a - Above is the PCB layout for both of our voltage switching circuits. However the values of the passive components and the ICs used in the two circuits are different.

5 Applicable Standards

Adherence to engineering standards will ensure the solar sculpture installation performs adequately, conforms to common safety protocols, and is consistent with modern engineering practices. Constructing the solar sculpture with standards in mind will also ensure that the installation will be able to smoothly interface with extraneous components. However most importantly, proper adherence to standards will mean the installation's construction process is repeatable. This is a crucial factor in the case of the solar sculpture, since it will hopefully be scaled up to full size in the near future.

5.1 Software Standards

The vast majority of the source code written for the installation will be coded in C++ (although some python scripts will be run as part of image difference calculation on the Pixy camera's onboard processor). The majority of software standards for the project will be derived from the C++11 software standard due to the team's prior experience and preferences.

5.1.1 Version Control Standards

A VCS or version control system, is a means of logging changes made to a specific source code file. A good VCS implementation ensures that all developers are making changes to the most recent version of the file being modified. It also provides a means of recovering old versions of files in the event of a large-scale problem. Ideally, a VCS greatly reduces the overhead incurred when developing software as a group.

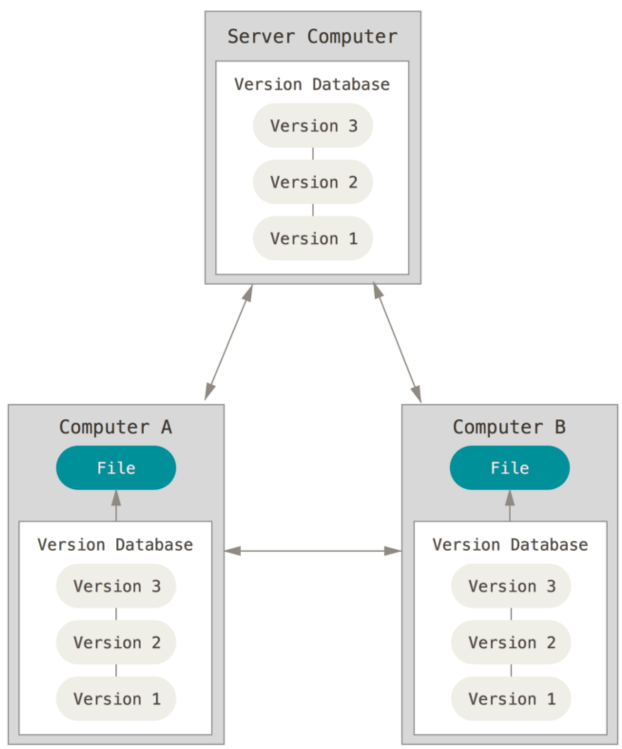

Figure 5.1.1a – model of a version control system. Reprinted with permission from Github.

There are three main types of version control systems. Localized: where developers keep track of separate versions of files via timestamps and their own personal file system management. Centralized: where a central administrator manages a server on which all source files are pushed on completion. Distributed: where all developers have a clone of the server and hence the entire project's source files. For the team's purposes a Distributed Version Control System. A Distributed VCS has a server-client relationship where clients are treated as direct copies of the server. The team favors this specific VCS implementation because the source code for the installation is not large enough to dissuade keeping multiple copies. The Distributed Version Control System provides full visibility of modifications being made to the source code for all developers. There is also easy recovery in the event of server failure.

Table 5.1.1a - Comparison of various Version Control System analysis.

Version Control System Analysis			
System	**Memory**	**Visibility**	**Error Recovery**
Local	ideal for reducing the memory space on individual machines since each developer only has the files they are working on.	This system has the least visibility, developers can only reference files they have created or manually copied.	This system is unable to recover from server failures. If a large scale problem occurs, the developers must start from scratch.
Centralized	This version control system preserves the memory space reduction of localized version control systems while allowing developers to check out additional files from the server if they need to reference other developers' modifications.	There is some additional visibility over a local system here since clients can check out files they had no part in creating so long as the administrator of the system approves.	Only the administrator can restore the server and recover older versions of source files.
Distributed	This system requires the most storage from each developer since every client to the server has a full copy of the repository's contents.	This system has full visibility since the server's entire contents are available to every developer on the project.	This system specializes in recovering from server failures. Any developer on the project can restore the server.

Major forks in the server, or major release changes to the project software will be indicated by a change in the first digit of the version release number. Major release changes are defined as changes, which add fully completed functionality to the project. Minor changes to the project software will be indicated by a change in the second digit of the version release number. Minor changes are defined as changes, which refine existing functionality. Software bug fixes will be indicated by a change in the third digit of the version release number. Bug fixes are defined as changes, which are introduced in order to resolve existing bugs in the project software. Example version number is provided in list format below.

- SoftwareRelease_1.0.0 - initial major release.
- SoftwareRelease_1.1.0 - minor release, refinement to existing functionality.
- SoftwareRelease_1.1.1 - bug fix, introduced to correct an existing software bug.

5.1.2 Whitespace

Whitespace may be used in source code to improve readability and convey meaning to a programmer reviewing the code. Indentation will be used throughout the project's code to indicate blocks of logic belonging to an object, loop, or function. All logic blocks, which proceed after an object, loop, or function curly braces will be indented once. Indentations may aggregate but should not exceed a total of six from the margin of the text editor. Single blank lines will be used to separate blocks of logic, which do not utilize the same parameters. Single blank lines will also be used to separate method definitions. Double blank spaces will be used as buffers between separate objects in the source code.

5.1.3 Commenting

Comments should be prefaced with the “//” syntax rather than the “/* */” syntax. A comment should be placed above all class definitions, function definitions, and global variable declarations briefly explaining their purpose and usage. Class variable names and function variable names should be named in a way such that their purpose is conveyed, if this is not possible an explanatory comment should be placed above the variable declaration.

Explanatory comments can be written inside functions if the developer feels a specific block of logic may be hard to follow at face value. However, all explanatory comments should be terse and to-the-point. They should be written as a ‘hint’ to developers reviewing the code rather than a full and detailed explanation of functionality. Explanation comments should be restrained to two lines. Do not duplicate explanatory comments across multiple files. Explanatory comments should appear only once at the first usage of the logic block, class, function, or variable.

5.1.4 Source File Headers

All source files should contain a commented header with the source file name, its creation date, release number in which it was last updated, and originator name. The commented header should include an explanation of the source file’s functionality, a description of any expected inputs and or outputs of the classes contained within, as well as an indication as to the source file’s purpose in the overall project source code. Developers may note suspected issues within the source file in this header, by appending a comment to the header with the suspected issue, reviewer's name, and date. Source file headers should not exceed fifteen lines in length.

5.1.5 Function Formatting

All functions definitions should be preceded by a comment explaining the function. All function declarations are to be made in header files and all function definitions are to be made in the corresponding cpp source file. The opening bracket for a function should not follow after the function's name but should instead follow on after a newline character. The contents of the function should be single indented from the perspective of the function name.

Function arguments may be wrapped to a newline if they do not fit on the line in which the function is called. However, if function arguments are wrapped, the new line should be single indented from the perspective of the function call. In the parentheses of a function call in which arguments are listed, there should be no space between the initial argument and the parentheses, nor between the last argument and the parentheses. This rule applies in function declarations and definitions as well. Within functions there should never be a newline between the first curly brace and the start of code. There should also never be a newline between the return (or last line of code) and the end curly brace of the function.

5.1.6 Naming Conventions

First and foremost, all names should strive to be descriptive in nature. A reviewer with minimal familiarity should be able to derive the purpose of any class, function, or variable based solely on name. Any abbreviations that are made within names must be explained upon first usage, and must exist globally across all files. Trailing underscores are not to be used in any names. All files should be named with all lowercase letters.

Generally underscores should be used as needed, rather than capital letters, for the purpose of distinguishing separate words in a name. In the case of a type name (class or enumeration) capital letters are used to distinguish separate words within names, though the first letter of a type name should be lowercase. Function names should follow the example of type names, using capital letters to distinguish separate words, however function names should also begin with a capital letter. Names for global constants should be denoted by all capital letters. Class member names should always be either all uppercase or all lowercase.

5.2 Communication Standards

Table 5.2a below highlights some important wireless communication standards.

These are important in order to ensure compatibility across products and also to protect the limited bandwidth available for short-range communication.

Table 5.2a - IEEE Communication Standards

Standard	Description
IEEE 802.11	Is a collection of wireless local area network (WLAN), media access control (MAC) and physical layer (PHY) specifications.
IEEE 802.15	Is a collection of standards related to WPAN and Bluetooth communication that is meant to operated at a personal space level.
IEEE 802.15.4f	Is a subsection of IEEE 802.15 that specifically describes standards for RFID technology.

Although none of these standards will specifically be used in this project it is important to understand their structure and importance. The communication protocols for UART, I^2C, SPI and USB have a structure of detailed specifications similar to the communication standards above but are not regulated in the same way by a standards organization.

UART, I^2C, SPI and USB are all serial communication protocols. Serial communication is a process of sending multiple bits over a single wire, compared to parallel communication, which requires a single wire for each bit being transmitted. Serial communication is performed using time division multiplexing, where several bits are sent sequentially, meaning the transmission speed of a serial line must be significantly higher than a parallel communication protocol to transmit data at the same rate. The main advantage of using serial communication protocols is low pin counts, as serial communications can be performed with a single I/O pin. This makes serial communication ideal for communication between microcontrollers and embedded devices with limited I/O pins. Figure 5.2a below shows a visual comparison of parallel versus serial communication.

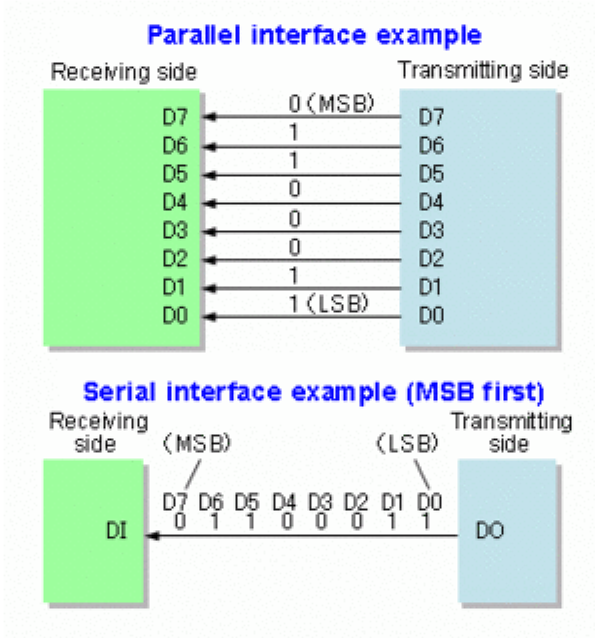

Figure 5.2a - Parallel vs Serial Communication
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5.2.1 UART

UART stands for universal asynchronous receiver/transmitter, and is a common serial data transfer protocol used by several communication standards such as RS-232, RS-422, and RS-485. The transmission of data over UART works by taking a byte of data and transmits the bits in sequential order, where a 2nd UART receiver can then recombine those individual bits back into complete bytes using a shift register.

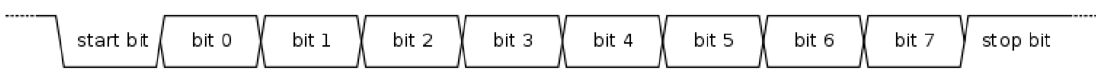

Figure 5.2.1a - UART Data Transmission
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Figure 5.2.1a above shows how the data is framed for a typical UART communication. The idle state for UART communication is a high-voltage state. This high-voltage state during no data transmission serves a secondary purpose of indicating that the transmission line and transmitter are powered on and have not been damaged.

When the data transmission begins, a low level (logic 0) bit is sent as the 'start bit'. This start bit signals the receiver that a new string of data is coming. The bits that follow are the data bits, which are typically 8 bits to transmit a byte at a time, but can be configured for 5 to 9 bits as long as both UARTs are configured with the same settings. After the data bits have been transmitted, a high level (logic 1) stop bit is transferred. The low level start bit and high level stop bit means that there is always a high level to low level transition to indicate the start of communication.

This process of using a start bit and stop bit, with a transition from high to low indicating the beginning of transmission is what describes UART, rather than a specific voltage level. Various voltage levels such as 3.3V or 5V can be used for UART communication, depending on the voltage levels used by the microcontrollers that are communicating. This also means that the voltage levels of the signal can be converted to a higher or lower level in order for microprocessors that use different logic voltage levels to communicate with each other.

UART communication at the common 3.3V or 5V logic levels used by many microprocessors is not always reliable, especially over longer distances or around high levels of electronic noise. For this reason, it is common to convert the signal to higher voltage levels, making it easier to distinguish a logic 0 from a logic 1 in the signal.

Many standards use the data transmission format of UART, and simply define the standardized connectors and voltage levels. For example, RS-232 and EIA-232 communicate using the UART protocol but defines a standard connector and defines the voltage for logic 0 to be from +3 to +15 volts, and the voltage for logic 1 to be between -15 and -3 volts. These voltages are with respect to a common ground pin for added reliability, and the range between -3 and +3 volts is considered an invalid level for the RS-232 standard. A minimal 3-wire RS-232 connection consists of a wire for transmitting data, a wire for receiving data, and a common ground.

UART is an asynchronous data transfer protocol, meaning the communicating UART devices do not share system timing or clock signals. Rather, both UARTs must be set at the same speed, or baud rate, and rely on the use of start and stop bits in order to correctly transmit data. This timing dependency is one of the biggest drawbacks of UART. A solution to this is to use a synchronous protocol, such as USART (Synchronous/Asynchronous Receiver Transmitter), which is a modification of UART protocol that contains an extra wire for clock transmission for synchronous operation. Other synchronous protocols include SPI and I^2C, which also use an extra wire for the clock signal.

For this project, a form of simplex (one way) UART communication is implemented between the MSP430 microcontroller and the MOSFETs that control the solenoid water valves. The MSP430 sends a single byte as a serial data signal through a single wire to the 8-bit shift register. The shift register then converts the byte received from the MSP430 into it's 8 individual bits in order to send each MOSFET a logic high or logic low level voltage to control the individual solenoid valves. A diagram of this process can be seen in *Figure 5.2.1b* below.

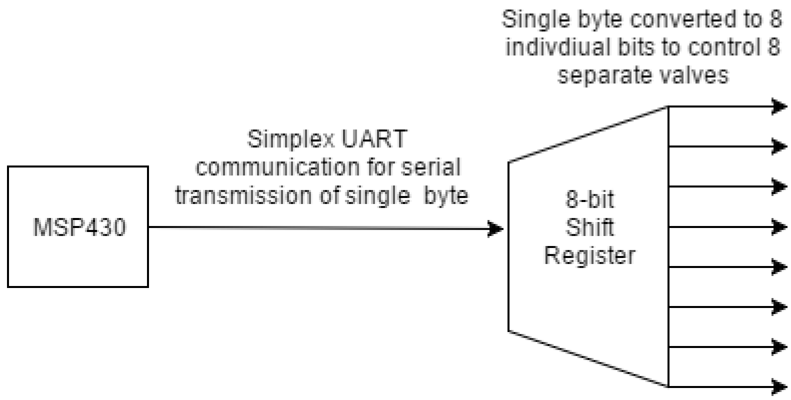

Figure 5.2.1b - UART Communication between MSP430 and Shift Register

5.2.2 I²C

The Inter-Integrated Circuit bus, or I²C (pronounced I-squared-C), is a patented interface that was developed by Philips Semiconductors. I²C is a synchronous, half-duplex protocol, which only uses 2 wires. These two wires provide the data (SDA) and clock (SCL) signals. It was designed to provide a 2-line bus for simple and low cost communication between integrated circuits, or IC to IC. The main design was intended for communication between two separate chips on a single PCB, but is also commonly used for components on separate PCBs that are connected with a cable.

The SDA and SCL lines use pull-up resistors to provide high signals, meaning the signal is held high normally, allowing the hardware to control the signal with open-drain drivers, which ground the signal. Essentially, this means rather than driving the high-level voltage from the master microcontroller output, the use of pull-up resistors means the device only needs to provide a ground to produce a low-level (logic 0) signal, and release the bus to produce the high-level (logic 1) signals through the pull-up resistor. A sample I²C connection schematic is shown below in Figure *5.2.2a*, with one master microcontroller, three slave devices, and the pull up resistors for the SDA and SCL lines.

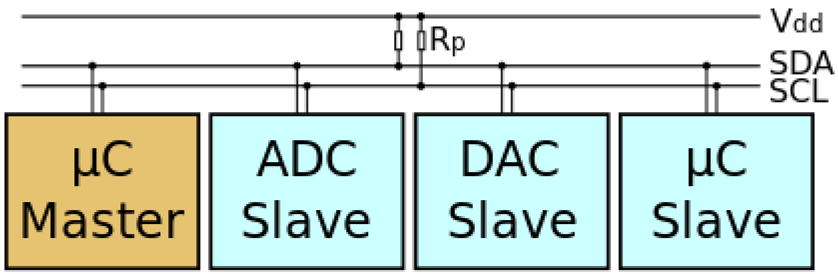

Figure 5.2.2a - UART Data Transmission
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One of the main features of I^2C is the ability to have a large number of components on a single communication bus that only uses two wires. I^2C allows for multiple devices on a single I^2C bus to play the role of the master device, as well as the ability to easily control multiple slave devices. This is achieved by using an addressable communications protocol, where each device has a unique 7-bit or 10-bit address.

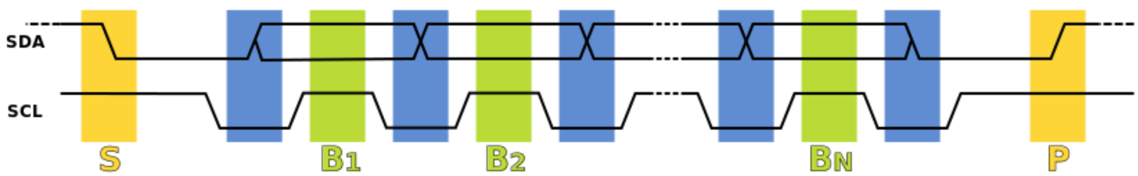

Figure 5.2.2b - I^2C Data Transfer Sequence
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Figure 5.2.2b above shows a timing diagram for the I^2C data transfer sequence. During communication with slave devices, the master generates all clock signals for both communication to and from the slave. Each communication begins with the master generating a start bit (S in the figure), which is indicated by the SDA line being pulled low while the SCL stays high. At the first blue bar in Figure 5.2.2b, the SDA sets the first data bit, while the clock SCL is low. When SCL rises high, the first data bit is read (B_1). At the next blue bar, the SCL clock drops low and the next bit is set on SDA. When the SCL clock goes high again, the bit is then read (B_2). This process repeats for all 8 bits in the 8-bit data word, with the data on SDA transitioning while SCL is low, and then the data being read when SCL is high (through B_N, where N is the number of bits being transmitted in the data word).

The end of the data word transmission is signaled by an acknowledge bit from the receiving device, by the receiver device pulling the SDA line low when the master device releases the SCL line to high (just prior to 'P' in Figure *5.2.2b*). If the master reads the acknowledge bit as high rather than low, it can assume the last data word was not received and take appropriate action, such as restarting the data transfer sequence for that piece of data. The acknowledge bit is followed by a stop condition or a repeated start if the data transfer needs to be restarted due to a failed acknowledge signal. The stop condition is a low-to-high transition of the SDA line while the SCL line is high ('P' in *Figure 5.2.2b*).

The particular strength of I^2C is the capability of a microcontroller to control a network of device chips with just two general-purpose I/O pins. However, it also has several limitations due to this use of only two pins. Limited communication speeds are available, and many devices do not support the higher transmission speeds. Since devices can set their own communication speed, slower devices can limit the operational speed of faster devices on the same I^2C bus. Due to the use of pull-up resistors that keep the communication lines at high-level voltage, I^2C draws more power than other serial communication buses.

While the 2-wire implementation for communication between multiple devices is ideal in many applications, these drawbacks my pose challenges if any of the limitations of I^2C pose an issue with devices that require serial communication between integrated circuit devices. In these cases, there are many other bus technologies used in similar applications, such as Serial Peripheral Interface Bus, although these bus technologies require more pins and signals to connect devices.

For this project, the I^2C is the communication protocol that will be utilized between the Pixy Cam, or CMUcam5, and the Arduino Microprocessor for two-way data communication. I^2C is also one of the possible communication protocols that may be used between the Arduino and msp430 microcontrollers in the final design.

5.2.3 SPI

The Serial Peripheral Interface (SPI) is a synchronous serial bus developed by Motorola and present on many of their microcontrollers. It has become widely adopted communication interface specification that is used primarily for short distance communication, mainly in embedded systems. SPI is used in various applications, such as communication between devices on integrated circuits, Secure Digital, or SD, storage cards, and liquid crystal displays.

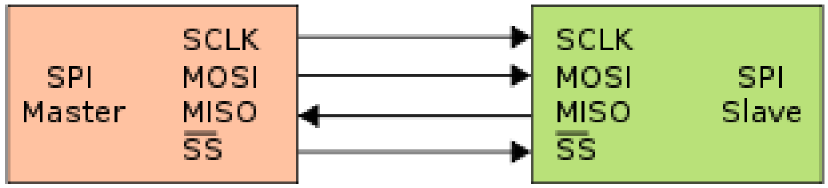

Figure 5.2.3a - Basic SPI bus Operation
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A basic SPI bus with single slave device is shown above in *Figure 5.2.3a*. The SPI bus consists of four wires: one wire for master to slave communication, known as master out slave in (MOSI); one wire for slave to master communication, known as master in slave out (MISO); one wire for timing, or serial clock (SCK); and an additional active-low wire for choosing the recipient when data is transmitted between multiple devices, known as slave select (SS).

The SPI devices are able to communicate in full duplex mode using this master-slave architecture, and the single slave select (SS) line allows the master device to communicate with multiple slave devices. A daisy-chained configuration can also be implemented for applications, which require the slave devices to be able to share data with each other as well. Communications between the master and selected slave use the unidirectional MISO and MOSI lines. to achieve data rates over 1 Mbps in full duplex mode.

In addition to the 1Mbps data rate, another advantage to SPI is if only one slave device is used, the SS line can be pulled low externally, and the SS signal does not have to be generated by the master, allowing for use of three wires rather than four. A disadvantage to SPI is the requirement to have separate SS lines for each slave. This may not be an issue for microcontrollers in which there are plenty of output pins or circuits with extra board space. But for small microcontrollers with a low pin count, a multi-slave SPI interface may not be possible and other solutions should be considered.

Both SPI and I^2C are commonly used for communication between microcontrollers, and many microcontrollers can use either protocol. In this project, this is the case for communication between the Arduino and MSP430, as well as the Arduino and system health unit, both of which may use either SPI or I^2C. SPI has several advantages and disadvantages when compared to I^2C:

Advantages:

- Push-pull drivers (as opposed to open drain in I^2C) provide good signal integrity and speed.
- Higher throughput than I^2C.
- Slaves do not need a unique address, unlike I^2C.
- Lower power requirements than I^2C due to less circuitry and lack of pull-up resistors.
- Unidirectional signals allows for easy isolation to prevent current flow.

Disadvantages:

- Requires more pins than I^2C, even when using the 3-wire SPI with a single slave device.
- Typically only supports one master device, where I^2C is designed to allow several.
- Additional slave devices require additional wires or a daisy chain configuration, while I^2C still uses only two wires even when more devices are added to the bus.

5.2.4 USB

USB connections adhere to a strict set of computing communications protocols in order to ensure compatibility. These standards are known as USB mass storage device class or USB MSC or USB UMS. All data transfer USB hardware such as HDDs, card reader and mobile phones adhere to these standards.
Mass Storage Class Features:

- Supports bulk-only transport (BOT) protocol. BOT protocol transfers data and command and status data through bulk transfer
- The number of bulk IN and OUT endpoints is set to 1
- Requires standard descriptors such as Device Descriptor, Configuration Descriptor, etc

For this project, USB communication protocol is used in order to interface and program the various microcontroller devices such as the Arduino, MSP430, and Raspberry Pi.

5.3 Solar and Safety Standards

The main safety concerns for this project steam from the high power output of our PV array. Due to this sculpture being accessible to the public and the added water feature element safe installation that is within the safety standards set forth by the National Electrical Code and other entities are of the utmost importance.

The National Electrical Code, NEC, contains several sections specifically pertaining to PV arrays that aim to protect people and property from electrical hazards. Specifically NEC 690 touches on instillation, sizing, protection, switches, breakers, connectors, array, ratings, polarity, identification, connection to other sources, battery storage and finally systems with over 600V. The NEC is the most extensive electrical code in the US and is followed in all 50 states. See *Table 5.3a* below for example of codes that are relevant to solar installations.

Table 5.3a - Solar and Safety Standards

Standard	Description
NEC 690	Covers all installation or photovoltaic systems including panels, inverters, charge controllers, array circuitry
UL Standard 1703	PV panel standards
IEEE 1457	Standards for interconnected distributed electrical power systems
UL Standard 1741	Standards for inverters, converters and controllers
UL 2703	Rack mounting systems and clamping devices for PV modules

Underwriters Laboratories also sets out standards related to PV systems. Many codes in the NEC, for example Section 690.4(D) which states that inverters used in PV systems must be identified as such, set out identification standards so components can be easily recognized and used safely. Having a UL listing fulfills this requirement and is generally regarded as the highest standard of listing. Other types of listings include Intertek and TUV.

IEEE, Institute for Electrical Engineers, is a professional organization of engineers that work to insure the integrity of the profession and work to create universal standards. IEEE-SA, Institute for Electrical Engineers Standards Association, is a branch within IEEE responsible for the creation and updates to global standards. This standards include but are not limited to power and energy, IT, telecommunications and biomedical electronics. The sections on power systems will be relevant to this project.

A new resource from IEC, International Electro technical Commission, is the ISEP, International Solar Energy Provisions, which is a collection of various codes that are all safety and PV related. This publication is meant to be a quick reference for solar codes across different organizations that can be easily referenced by PV installers.

Due to the sculpture being a non-habitable structure no IFC, International Fire Code, codes will be relevant or NFPA, National Fire Protection Association. This also reduces the number of relevant codes from NEC and other sources.

Power coming from the grid is also a concern and that system will have to be installed with NEC standards, IEEE standards and UL listings in mind.

On any solar PV system there will be two disconnect, on each side of the inverter used for the system. These two disconnects are the DC and AC disconnects that protect the utility grid and photovoltaic array from over current. The PV disconnect buffers the current between the solar panel array and the inverter. The AC disconnect is typically located on the exterior of system and limits the over current potential from the inverter inputting into the grid. This is typically a switch but could use a fuse in replacement.

Sizing the DC disconnects for a system is reliant on the National Electrical Code standards used for PV systems and based on the equipment, components and connectivity used in each particular system. The output rating of the inverter that is placed on the outside of the system and protects from over current protection needs to be rated based on NEC 690.10 stipulations.

Specifically to size the DC disconnect of the system NEC 690.80 is used gauge the module interconnection conductors and size the DC over current protection. Where a single overcurrent device is used to protect a set of two or more parallel-connected module circuits, the ampacity of each of the module interconnection conductors shall not be less than the sum of the rating of the single fuse plus 125 percent of the short-circuit current from the other parallel-connected modules. Shown in Table 5.3b the rating type and rating are determined by the voltage, circuit load, amps and wiring of the system.

Table 5.3b - Standard Array Sizing Specifications

Rating Type	Rating
Maximum System Voltage	600 VDC
Range of Operating DC Voltage	230 - 600 VDC
Maximum Operating Current - DC	9.5 Amps
Maximum Array Short Circuit Current - DC	10 Amps
Maximum Utility Backfeed Current - DC	0.075 Amps
Operating Voltage Range - AC	106 - 132 VAC
Operating Frequency Range	59.3 - 60.5 Hz
Nominal Output Voltage - AC	120 VAC
Nominal Output Frequency	60 Hz
Maximum Continuous Output Current	15.0 Amps
Power Factor	>0.99
Maximum Continuous Output Power - AC	1800 Watts
Maximum Output Fault Current - AC	15 Amps
Maximum Output Overcurrent Protection	15 Amps
Efficiency	96.5%

Total Harmonic Distortion	<5%

Consideration for temperature is necessary for the design of this project, as the heat increase the maximum power-point current is decreased slightly. With Florida's hot weather these considerations as well as additional National Electric Codes will be considered to assure the longevity and reliability of this system.

The reliability of this project is one of the most important aspects. OUC wants a low maintenance sculpture and maintenance will be expensive and will put the sculpture out of commission, which will limit the public's exposure to the benefits of solar energy. The table below highlights some UL standards that assure reliability of PV arrays.

Table 5.3c - Reliability Standards.

Standard	Description
UL 61215	Requires that crystalline silicon photovoltaic modules be tested to determine their electronic and thermal properties.
UL 61216	Requires that thin film photovoltaic modules be tested to determine their electronic and thermal properties.
IEC 60410	Requires that samples be taken for testing at random from a production batch

Due to the water aspect of the solar sculpture all receptacles will have to be GFCI, Ground Fault Circuit Interrupter, for safety reasons. There are multiple NEC codes regarding GFCI receptacles in certain areas such as in the bathroom 210.8(A)(1) and in other areas exposed to water like the kitchen 210.8(A)(6) and swimming pools 680.32. Article 680 is also relevant for fountains and landscape features involving water, which our sculpture is most closely related to. UL 943 outlines the requirements for GFCIs.

Figure 5.3a - GFCI Plug.

5.4 PCB Standards

5.4.1 Standard J-STD-609B

When designing our PCB some standards to be considered are the J-STD-609B Standard for Marking and Labeling of Components, PCBs, and identifying Lead and Lead-Free Attributes. Marking and labeling these components helps the assembly, rework and recycling of our PCB design. Using large metallic components it is important not to leave a larger recyclable footprint unable to be reused. Soldering the transformer and external components to the PCB a lead-free solder material will be used to make the connections. With the utility grid interconnectivity with high AC voltages, this standard accounts for maximum component temperature not to be exceeded during assembly or rework processing. Standards including base material construction, surface finish and conformal coating will be realized when manufactured by the 4PCB company. This includes the exposure of surface mount elements and wiring.

5.4.2 Standard IPC-1782

Part of the Association Connecting Electronics Industries the IPC-1782 Standard outlines the Standard for Manufacturing and Supply Chain Traceability of Electronics Products. Component traceability considers the unnecessary consumption of resources, such as time, labor and cost, when communicating with the PCB manufacturer. This communication standard considers the reliability, quality and sources necessary for end-to-end printed circuit board realization.

The minimum requirement for this standard for manufacturing and supply chain traceability based on the perceived risk as agreed between user and supplier. This standard is crucial for our design because it includes all products, processes, assemblies, parts, components, equipment used and other items defined by users and suppliers in the manufacturing of printed board assemblies.

These assemblies include the AC to DC power converter, the 12V solenoid switching circuit, and the system monitoring design.

5.4.3 Standard IPC-1601A

This standard outlines the Printed Board Handling and Storage Guidelines necessary for the PCBs used in this project. Used by the industry, this standard protects printed boards from contamination, physical damage, solder-ability and moisture uptake. When complying with these standards, considerations for packaging material types, methods, production environment, handling, transportation of product, and establishing baking profiles for moisture removal were all considered in depth. Ordering from local distributors will allow for thorough consideration and reliability because our close proximity. Being in Florida the moisture barrier bags required for distribution are the major concerns when it comes to packaging and handling requirements.

5.4.4 Standard ASTM D2633-13a

This Standard for the Test Methods for Thermoplastic Insulations and Jackets for Wire and Cable are necessary for the hydroelectric interaction of our design. Information from this standard will be important for the waterproofing methods taken towards sealing any exposed live cables. Without waterproofing the cables used have minimal water insulation so additional compensation for these wires are necessary. Testing of these wire-jackets include a water absorption test to determine how they will react in high moisture environments. Submerging the wires in a controlled temperature surrounding allows for appropriate for the final realization of the project design.

6 Testing

This section will first provide an overview of the breadboard testing and component testing that has already been done by the team in preparation for the prototype's construction. Images of the test environments are provided, as well as a description of each test case and whether or not the test was deemed satisfactory by the team. This initial testing is to provide a confidence factor in hardware components that are already possessed by the team.

Once all tests for currently operational components of the solar sculpture installation have been reviewed, there will be a discussion of the test criteria and test cases that will need to be run in order to verify the functionality of the finished ⅛ scale solar sculpture prototype that will be presented at the end of the senior design 2 semester.

6.1 Water Supply System Testing

The Aubig 12v DC submersible pump rated at 2.2 gallons per minute will be tested first, followed by a Smartpond 120v AC submersible pump rated at 5 gallons per minute. While this project will not be using AC powered pumps, one of the team members already had this pump available, and higher gallon per minute rating of the AC pump still provides useful test data.

The purpose of this test is to confirm that these small submersible pumps have enough power to create a significant flow at the top of a 1-meter rise, in additional to determining what the actual flow amount is at the top of that 1-meter rise. This information will provide useful in order to determine how many of the small Aubig 12v DC pumps will be needed to provide sufficient flow to the solenoid valves, or if a larger more powerful pump is needed.

Test Case:

- The pump is submerged at the bottom of a barrel of water, with output hose run up to a height of 1.3 meters (slightly higher than the expected height of 1 meter to allow for slight design variations).
- The output of the hose located 1.3 meters above the pump is directed into a 1-gallon jug.
- A timer is started when the pump is turned on, and stopped once the 1-gallon jug overflows. This time is recorded to provide an estimated gallon per minute flow rate at the top of the tube.
- The process is repeated for various water pressures by varying the height of the water above the pump before turning it on.

This test case is performed using the 2.2-gallon per minute pump, and then performed in the exact same manner for the 5-gallon per minute pump. The test setup can be seen below in *Figure 6.1a*.

Figure 6.1a - water pump test environment setup.

Test Results:

Table 6.1a - water pump test results

Water Pump	**Water Level Height**	**Time** **To Fill 1 Gallon**	**Calculated Flow** **(At 1.3 meter height)**
Aubig 12v DC 2.2 GPM Flow Rating	15”	32.0 s	1.88 gpm
	12”	33.1 s	1.81 gpm
	9”	33.6 s	1.79 gpm
	6”	34.2 s	1.75 gpm
Smartpond 120v AC 5.0 GPM Flow	15”	20.5 s	2.92 gpm
	12”	21.2 s	2.83 gpm

Rating	9”	23.0 s	2.61 gpm
	6”	23.1 s	2.60 gpm

Initial calculations for the flow rate required to operate all 16 solenoid valves simultaneously varied widely from 3 to 8 gallons per minute due to many variables such as friction coefficients, water velocity, and the water pressure due to gravity. For this reason, we chose the Aubig 12v pump due to the fact that it was small and inexpensive, allowing these practical tests to be run before possibly purchasing a significantly more expensive pump without being able to test it beforehand.

These test results provided a more realistic idea of how much flow is provided at the top of a 1 meter lift from a single small 2.2 GPM Aubig 12v DC pump. The slightly larger 5 GPM pump did provide more flow than the Aubig pump, by approximately 50%. However, the amount of additional flow at 1 meter was not an increase proportional to the increased cost of larger pumps.

With the flow rate values obtained through testing of slightly below 2 gpm at 1.3 meters, it appears that the small Aubig 12v DC pumps would be capable of providing enough flow if multiple pumps are used. As a broad estimate, 2 to 4 of the small Aubig pumps should be enough to provide the flow needed to run all 16 valves simultaneously.

This test also revealed that the height of the water that the pump is submerged under has a noticeable effect on the flow rate of the pump. As the water level above the pump drops, the flow rate drops as well. This is caused by the extra pressure provided at the pump’s intake due to the height of the water above it. The extra pressure at the intake means the pump requires slightly less effort output to make the water rise 1 meter, and the additional power results in a slightly faster flow rate at the top of the output tube. While this extra flow rate may not seem significant, it is still good to keep in mind for determining the water level that will be used in the reservoir.

6.2 Computer Vision System Testing

The Pixy Camera’s motion segmentation using color tagging will be tested first. While color tagging will not be used in the finalized installation’s vision system, testing it will verify the Pixy Camera’s capability to evaluate pixel intensity in well-lit and low-light environments. Once robust pixel evaluation capabilities have been verified, communications between the Pixy Cam and the Arduino Uno

Microcontroller will be tested. Finally, an implementation of the custom image difference algorithm will be tested.

It is important to note prior to testing that the Pixy Cam is running at 50hz for the purpose of these tests. This is the rate at which the team wants the camera to run on the full-scale installation, so that it can provide robust motion detection and thus waterfall response. However running at such a high rate of frame capture means there is a degradation in the image resolution. All images presented alongside the testing section are captured directly from the Pixy Camera and are thus 640x480 pixel resolution. The resolution can be enhanced in the future if need be, by reducing the speed at which the Pixy Cam captures and analyzes image frames.

Test Case 1: This test is to be performed in ideal light conditions. Verify the Pixy Camera can successfully recognize an object and segment it from the environment using the object's color signature. Verify the Pixy Camera can track an object via color tagging as it moves across the scene.

Test Case 2: This test is to be performed in low-light conditions, comparable to evening light. Reducing the illumination will flex out the Pixy Camera's ability to measure pixel intensity in a poorly lit environment. Verify the Pixy Camera can successfully recognize an object and segment it from the environment using the object's color signature. Verify the Pixy Camera can track an object via color tagging as it moves across the scene.

Test Case 3: Verify the Pixy Camera can successfully connect to the Arduino R3 via USB connection, transmitting object motion data to the Arduino in the form of two-dimensional horizontal and vertical coordinates.

Test Case 4: Verify the Pixy Camera can properly calculate image difference between two frames, producing an intermediate gradient output image that shows the change in pixel intensity from frame to frame. Motion in the scene should show up as white cell signatures, any pixels, which do not change from frame to frame, should remain black.

Table 6.2a - Test description and results for Test Case 1.

Test Case 1

Well-lit environment. Object Recognition and tracking via color tagging.

Test Setup

- Pixy Camera is connected to desktop computer via USB.
- PixyMon software is used on the desktop computer to send commands to the Pixy Camera and observe the scene from the Pixy Camera’s perspective.
- Once the object to be tracked has been presented to the Pixy Camera. The command is given to capture color signature and track the object.

Test Results

- The Pixy Camera successfully tracked the object using color tagging.

Figure 6.2a - Test Case 1 images. Captured in PixyMon. On the left, object to be tracked is presented to Pixy Camera. On the right, the Pixy Camera registers the object’s color signature and begins tracking the object after being prompted by a command from PixyMon.

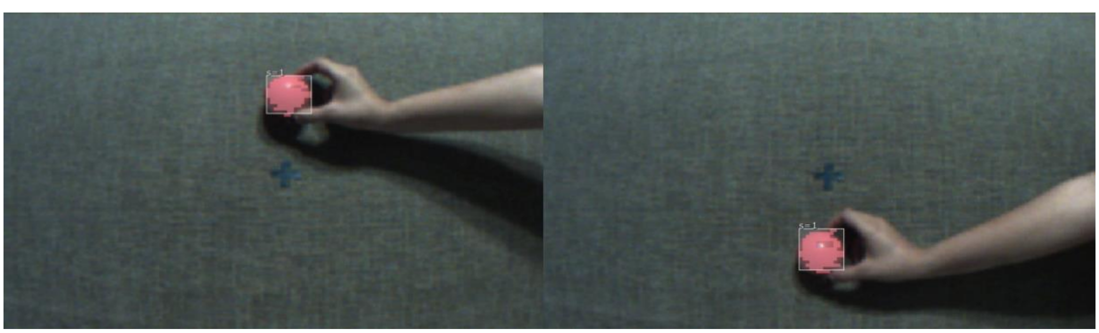

Figure 6.2b - Test Case 1 images. Captured in PixyMon. On the left, object moves up, Pixy Camera successfully tracks the motion of the object. On the right, object moves down, Pixy Camera successfully tracks the motion of the object.

Table 6.2b - Test description and results for Test Case 2.

Test Case 2

Poorly lit environment. Object Recognition and tracking via color tagging.

Test Setup

- Pixy Camera is connected to desktop computer via USB.
- PixyMon software is used to send commands to the Pixy Camera.
- Once the object to be tracked has been presented to the Pixy Camera. The command is given to capture color signature and track the object.

Test Results

- Noticeable degradation in image cell recognition.
- The Pixy Camera managed to track the object despite low pixel intensity.

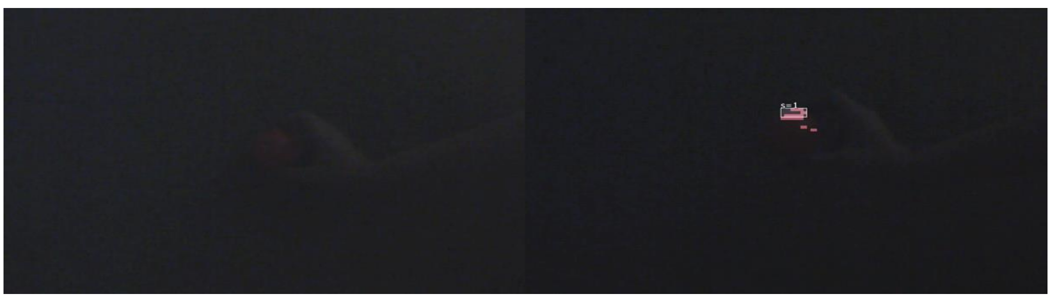

Figure 6.2c - Test Case 2 images. Captured in PixyMon. Image contrast and exposure modified for increased visibility. On the left, object to be tracked is presented to Pixy Camera. On the right, the Pixy Camera registers the object's color signature and begins tracking the object after being prompted by a command from PixyMon.

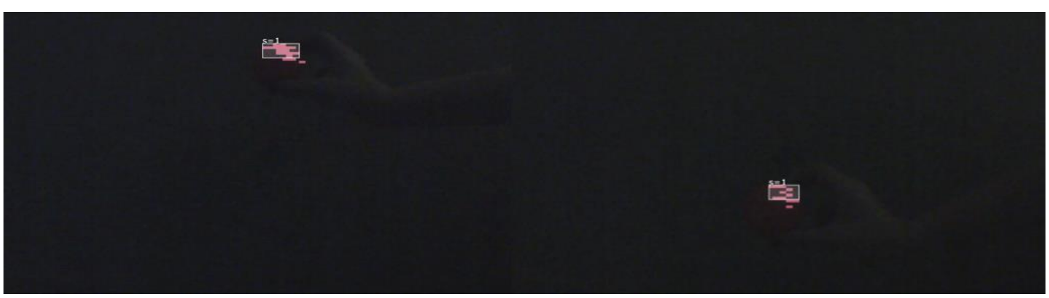

Figure 6.2d - Test Case 2 images. Captured in PixyMon. Image contrast and exposure modified for increased visibility. On the left, object moves up, Pixy Camera successfully tracks the motion of the object. On the right, object moves down, Pixy Camera successfully tracks the motion of the object.

Table 6.2c - Test description and results for Test Case 3.

Test Case 3

Real-time communication and interpretation between Pixy Camera and Arduino.

Test Setup

- Pixy Camera is connected to Arduino Uno R3 via ICSP.
- Pixy Camera libraries imported to Arduino Uno.
- Simple loop is run in Arduino microcontroller to interpret Pixy Camera object motion data for a given color signature into separate “blocks” which move across a two dimensional plane.

Test Results

- The Pixy Camera successfully tracked the object using color tagging.

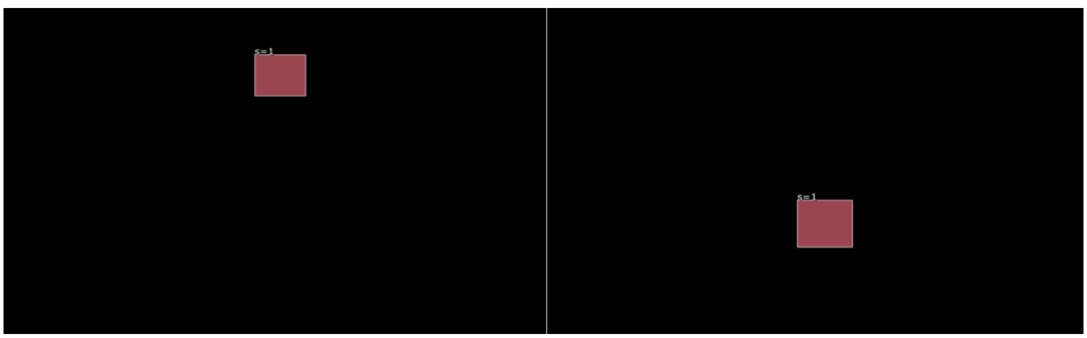

Figure 6.2e - Test Case 3 images. Captured in PixyMon. Representation of what the Arduino microcontroller “sees”. Pixy Camera tracks the moving object, transmitting its coordinates.

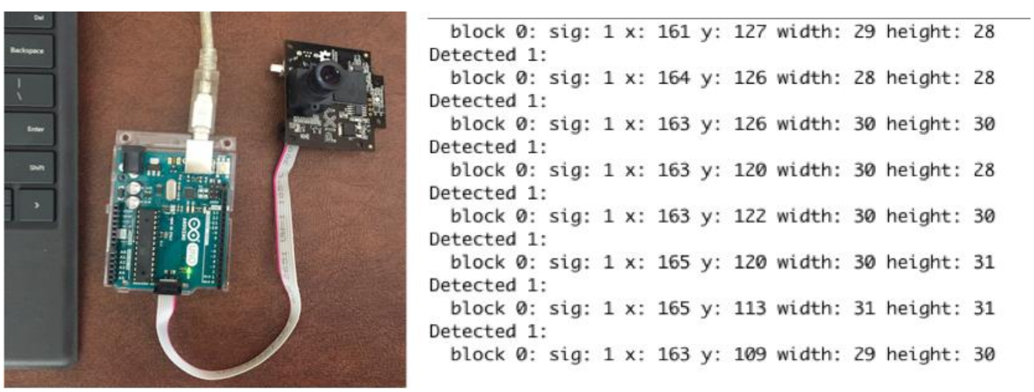

Figure 6.2f - Test Case 3 images. On the left, I2C connection between Pixy Cam and Arduino, Arduino connected to desktop via USB. On the right, image captured in Arduino serial monitor. Positional data being printed by the Arduino represents pixel coordinates of tracked object.

Table 6.2d - Test description and results for Test Case 4.

Test Case 4 Pixy Camera performance running image difference software implementation.
Test Setup ● Pixy Camera is connected to desktop computer via USB. ● Pixy Camera source code modified to track change in pixels over time (motion) rather than color signature or saturation of an object in motion. ● Currently the proposed double thresholding process is not used ● Pixy Camera tracks regions of motion in a given fixed scene.
Test Results ● The pixy camera correctly output accurate image difference frames. ● The Pixy camera correctly aggregated the moving hand into a single region of motion and was able to track its position in the frame.

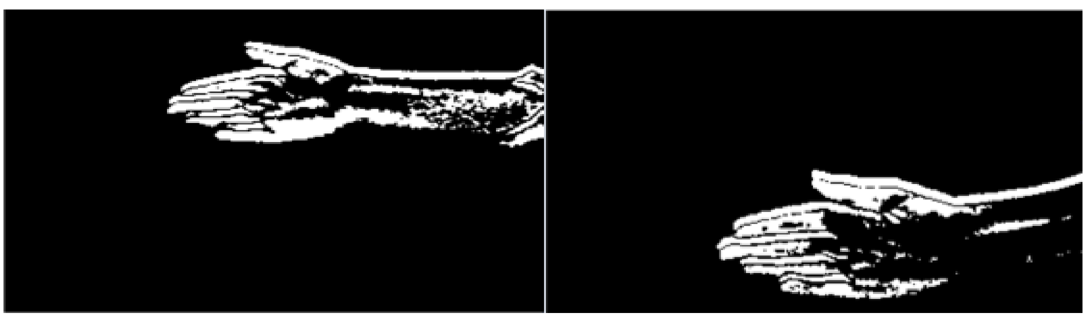

Figure 6.2g - Test Case 4 images. Captured in PixyMon. Image difference frames output by the Pixy Camera, motion is shown in white and static background is shown in black.

Figure 6.2g - Test Case 4 images. Captured in PixyMon. Red boxes show the region of motion being tracked by the Pixy Camera in relation to the center point of the frame.

6.3 Solenoid System Testing

Test environment setup as described in Section - Solenoid Control Unit and Section - Solenoid Switching Circuit. See aforementioned sections for circuit diagrams.

Test Case 1: Verify that the Solenoid Switching Circuit can appropriately boost the shift registers' 2.8-volt output voltage so that water solenoid valve will be switched on.
Test Case 2: Verify that the Solenoid Control Unit can correctly transmit serial data to the shift register inputs, setting individual output pins to active high in sequence.
Test Case 3: Verify that the Solenoid Control Unit can correctly transmit serial data to shift register inputs, resulting in a series of solenoid valves connected to the shift register outputs being correctly turned on or off in response.
Test Case 4: Verify that the Solenoid Control Unit can transmit serial data to a "daisy-chained" sequence of shift registers, resulting in a series of solenoid valves connected to the shift register outputs being correctly turned on or off in response.

Table 6.3a – description of test case 1.

Test Case 1 Verify correct functionality of Solenoid Switching Circuit.
Test Setup ● MOSFET source tied to ground ● MOSFET drain tied to solenoid valve input ● MOSFET gate tied to 2.8volt input voltage ● Protective diode placed in parallel with "load" (solenoid valve) ● 2.8 volts applied across MOSFET gate ● Water solenoid was correctly set to 1 "active high" when a voltage of 2.8 (representing the output voltage of a shift register pin) was applied.
Test Results ● Water solenoid was correctly set to 1 "active high" when a voltage of 2.8 (representing the output voltage of a shift register pin) was applied.

Table 6.3b - description of test case 2.

Test Case 2 Verify Solenoid Control Unit functionality.
Test Setup ● 3 buzzers are setup in parallel with 3 Solenoid Switching Circuit configurations. ● MSP430 launchpad is connected to the shift register unit as specified in Section 4.9 Solenoid Control Unit. ● Shift register output pins QA-QC are tied to the three MOSFET gates. ● An 8-bit serial data signal of 00000111 is sent to the shift register from the Solenoid Control Unit for a length of 1000ms. ● Three alternating 8-bit serial signals (00000100, 00000010, 00000001) are synchronously sent to the shift register at 1000ms pulses.
Test Results ● All buzzers correctly set to active high with a signal of 00000111 ● Each buzzer was set to active high when signaled by the shift register.

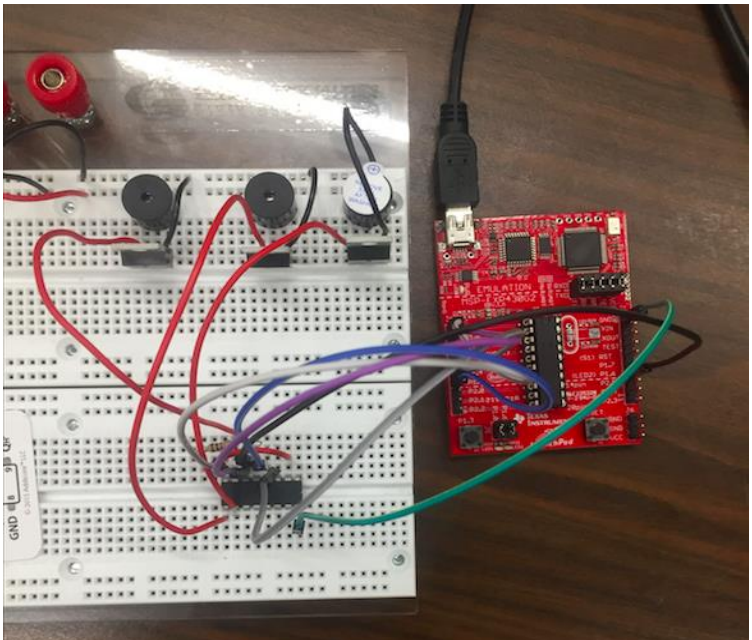

Figure 6.3a - Breadboard setup for Solenoid Control Unit/shift register combination. Buzzers used to test shifter output pins. Buzzers emit noise when set to active high.

Table 6.3c - description of test case 3.

Test Case 3 Verify that the valves can be correctly set on and off by the shift register.
Test Setup ● The buzzers are replaced with solenoid valves. The Solenoid switching Circuit will be necessary to boost the output voltage of the shift register. ● Shift register output pins QA-QC are tied to the three MOSFET gates. ● An 8-bit serial data signal of 00000111 is sent to the shift register from the Solenoid Control Unit for a length of 1000ms. ● Three alternating 8-bit serial signals (00000001, 00000010, 00000100) are synchronously sent to the shift register at 1000ms pulses.
Test Results ● All valves were correctly set to active high with a signal of 00000011. ● Each solenoid valve was set to active high when signaled by shifters.

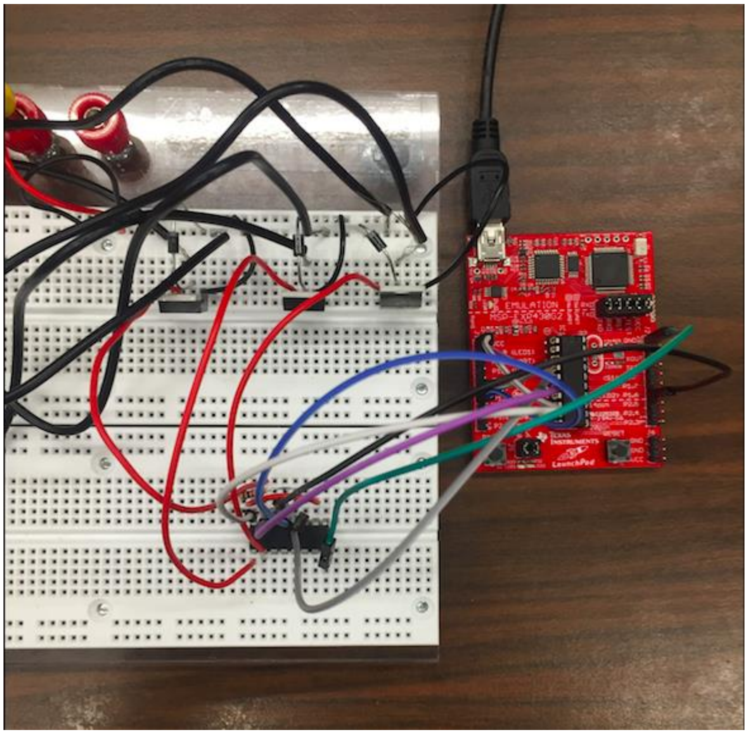

Figure 6.3b - Breadboard setup for Solenoid Control Unit/shift register and Solenoid Switching Circuit combination. Valves open when set to active high.

Table 6.3d – description of test case 4.

Test Case 4

Verify that the Solenoid valves can be correctly set by the daisy-chained series of shift registers.

Test Setup

- 3 solenoid valves are set up in parallel with 3 Solenoid Switching Circuits.
- Shift register 1 output pins QA-QB are tied to the first two MOSFETs.
- Shift register 2 output pin QA is tied to the third MOSFET gate.
- A 16-bit serial data signal of 00000001 00000011 is sent to the shift registers from the Solenoid Control Unit for a length of 1000ms.
- Three alternating 16-bit serial signals (00000001, 00000010, 00000001 00000000) are synchronously sent to the shift register at 1000ms pulses.

Test Results

- All valves were correctly set to active high by 00000001 00000011 signal.
- Each solenoid valve was set to active high when signaled.

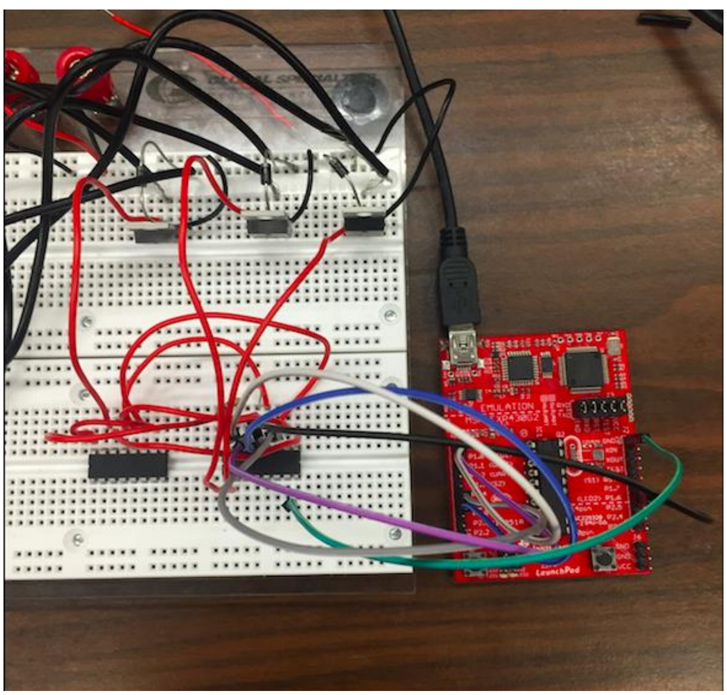

Figure 6.3c - Breadboard setup for Solenoid Control Unit and daisy chained shift registers. Valves open when they detect an active high signal.

6.4 Final Prototype Testing Criteria

Next the final testing criteria for the finished solar sculpture installation prototype will be discussed. These are the test cases that the team will go through in order to verify that the constructed solar sculpture installation prototype is performing as anticipated. It is important to remember that this is testing criteria for the ⅛ scale installation prototype not the proposed full sized installation.

6.4.1 Prototype Software Test Environment

For testing the software of the finalized prototype, it is important to isolate the functionality of the software as much as possible. Hence specific software testing environments are described for the prototype.

Software Test Environment A - computer vision system control software testing.

- Disconnect the Arduino Uno R3 serial feed from the MSP430G2553.
- Connect the Arduino Uno R3 to a desktop computer or laptop via USB type A/B connection. The computer must have Arduino 1.0.6 IDE installed on it.
- Configure the Arduino serial monitor so that it displays the microcontroller's outgoing serial data.
- Verify the Pixy Camera is running at 50hz.
- Connect the Pixy Camera to the desktop computer via USB connection (the Pixy Camera may be connected to the Arduino and the desktop computer simultaneously.

Software Test Environment B - solenoid valve array control software testing.

- Disconnect the MSP430G2553's serial feed from the daisy chain shift register configuration.
- Place the MSPG2553 Microchip on an MSP430 Launchpad.
- Connect the Launchpad to a desktop computer using a USB connection. Computer must have code composer IDE installed.
- Configure the code composer output window so that the MSP430G2553's output serial data is displayed.

Software Test Environment C - system health monitor control software testing.

- Connect Raspberry Pi 3 unit to a monitor using an ancillary HDMI cable.
- Connect a USB mouse and USB keyboard to the Raspberry Pi 3.
- Verify the connection between the Raspberry Pi 3 and the ultrasonic sensor.
- Using the Raspbian GUI display, bring up the output monitor for the unit.

6.4.2 Prototype Software Test Cases

The software specific test cases for the final prototype are discussed next.

Table 6.4.2a – description of test case 1 for prototype software specific test cases.

Test Case 1 Verify Pixy Camera communications.
Test Setup ● Software Test Environment A is used. ● Visually verify USB connection between desktop and Pixy Camera.
Expectation ● Pixymon reports the Pixy Camera successfully connected.

Table 6.4.2b – description of test case 2 for prototype software specific test cases.

Test Case 2 Verify Pixy Camera pixel saturation and hue recognition capability.
Test Setup ● Software Test Environment A is used ● Place Brightly colored object in front of Pixy Camera.
Expectation ● Object color signature detected by Pixy Camera.

Table 6.4.2c – description of test case 3 for prototype software specific test cases.

Test Case 3 Verify Pixy Camera Image difference algorithm functionality.

Test Setup ● Software Test Environment A is used ● In PixyMon desktop application, go to Settings->SPLASH->ImgDiff ● Move hand slowly in front of Pixy Camera ● Pixy Camera focus may need to be adjusted
Expectation ● Pixy Camera outputs image difference frames. ● Little or no distortion due to background movement.

Table 6.4.2d – description of test case 4 for prototype software specific test cases.

Test Case 4 Verify Pixy Camera Generalized Motion Segmentation capability.
Test Setup ● Software Test Environment A is used ● In PixyMon desktop application, go to Settings->SPLASH->MotionTrack ● Move hand slowly in front of Pixy Camera ● Camera focus may need to be adjusted
Expectation ● Red box traced around region of motion (hand) in PixyMon display ● Pixy Camera tracks region of motion in Real-time

Table 6.4.2e – description of test case 5 for prototype software specific test cases.

Test Case 5 Verify Arduino-Pixy Cam communications
Test Setup ● Software Test Environment A is used

• Connect Arduino to desktop machine • Open Arduino serial feed monitor • In PixyMon desktop application, go to Settings->SPLASH->MotionTrack • Move hand slowly in front of Pixy Camera (Camera focus may need to be adjusted)
Expectation • Observe that motion region coordinates are displayed on the Arduino serial feed monitor in real-time.

Table 6.4.2f – description of test case 6 for prototype software specific test cases.

Test Case 6 Verify MSP430G2553 positional array function
Test Setup • Software Test Environment B is used • Open "flex_graphical_display.c" application • Open MSP430 serial feed monitor • Run program
Expectation • Observe that each solenoid position in the graphical array is set to active high for a length of 1 second.

Table 6.4.2g – description of test case 7 for prototype software specific test cases.

Test Case 7 Verify MSP430G2553 variable brightness LED array functionality
Test Setup • Software Test Environment B is used • Open "flex_LED_display.c" application

• Open MSP430 serial feed monitor • Run program
Expectation • Observe that each LED position in the graphical array is set to active high for a length of 1 second.

Table 6.4.2h – description of test case 8 for prototype software specific test cases.

Test Case 8 Verify Raspberry Pi 3 ultrasonic raspiSump program functionality
Test Setup • Software Test Environment C is used • Verify ultrasonic sensor is suspended above water collection basin • Open Raspbian output monitor window
Expectation • Verify water level height in centimeters is printed to the output window.

6.5 Power Testing

6.5.1 Hardware Test Environment

Testing of solar equipment will take place outside of the Harris Engineering Corporation (HEC) building at the University of Central Florida. All tests will be conducted with no precipitation and during days of varying sunlight but mostly sunny skies. Multiple tests on different days will be needed to judge variable weather conditions. This testing is important for the understanding of how environmental changes from day to day will affect the overall power output generated and used for this project. Testing the solar panel will assure the data sheet specification are within a reasonable percentage difference. The tests conducted on the solar panel will include open circuit voltage test (Voc), a short circuit current test (Isc), and an operating current test (I). Repeating measurements will be necessary to ensure consistency and compared to manufacturer specifications.

6.5.2 Solar Panel Testing

The first test conducted is the open circuit voltage test with the solar panel completely disconnect from the DC converter. Connecting the voltage probes to the output terminals of the solar panels an open circuit voltage is measured. The panel will be tested in maximum sunlight, lying flat with the sun 90 degrees above the solar panel, at noon for maximum power output. This will be the maximum open circuit voltage capable by the solar panel. Additional open circuit voltages will be measure in low-light, cloudy, and sunset situations to find the minimum open circuit voltage that will still output sufficient power.

Next the short circuit current will be tested using a digital multimeter connect to the positive and negative output probes of the solar panel. Connect the probes while the solar panel is not in direct sunlight as to assure no damage to the operators or equipment. Then lay the solar panel flat with the sun perpendicular to surface, this will be accomplished at noon. Recording the initial measurement and the maximum measurement to find the short circuit current similar to the manufacturer's specifications.

The last test to be conducted is the operating current output when the solar panel is connected to the DC converter. Attaching the DC probes to the output terminals of the converter device similar to the solar panel will allow for an operating current measurement. This will be the current used by the DC to AC inverter feeding energy back into the grid. This parameter will be maximized when the panel if perpendicular to the sun and has been operating for a few minutes. The maximum power point tracking algorithm needs initiation time to oscillate around the correct voltage and current operating points, and to adjust for obstructions in the environment.

Table 6.5.2a - Solar Panel Test cases

Value	Datasheet	Test Procedure	Measurement
V_{oc}(Open Circuit Voltage)	45.1 V	Connect multimeter in parallel with solar panel	TBD
I_{sc} (Short Circuit Current)	5.88 A	Connect multimeter in series with solar panel	TBD
I (Operating Current)	3.1 A	Connect multimeter in series with DC Inverter	TBD

6.6 Project Operation

This project will have three components that will operate with input from the public and also maintenance or an operator. This parts are the LED/solenoid array, the power system and the health monitoring system.

The LED and solenoid arrays will take input from the public by way of an optical sensor. This will then trigger the LEDs or solenoid valves to open and close accordingly. This will create an interactive visual effect for the sculpture in order to draw more attention to solar power.

The power system will have few inputs but will have several disconnects for safety and maintenance needs. The grid will also have to be monitored because the grid tied inverter cannot function during outages.

The system health monitoring will take inputs for the water level in the reservoir, voltages and currents at critical parts of the power system. If any errors or malfunctions are observed an output in the form of a maintenance LED.

7 Administrative

7.1 Project Budget

Primary budget concerns for this project are the solenoid valves. To create an image with decent resolution many valves with high density are needed. Hopefully the team can find a way around this in order to lower the cost of the project significantly. The team is still unsure of the amount of water that the installation will have to pump but is fairly certain a $50 pump will be an overestimate. It has been calculated that four 100W panels would provide enough power to meet the minimum requirements set by OUC.

More panels might be needed based on power consumption. Two were put into the budget for our scale model in order to error on the side of caution. Some components on our parts list are hopefully over budgeted in order to account for errors such as the PCB board.

OUC, the project sponsor, is providing $1000 of funding. The team will be covering the difference if the project exceeds that budget. Also the parts list does not include non-electrical hardware. Pictured below in Figure 5 is a table of components needed for the installation along with our best estimations for their cost.

Table 7.1a - Project Budget Estimations

Material	**Cost**
Solenoid Valves (16)	$188.32
Computer Vision Camera	$69.00
Arduino Uno R3	$16.06
Raspberry Pi 3	$35.69
MSP430G2553	DONATED
Solar Panel	$225.00
DC/AC Inverter	$850.00

AC/DC Converter	$33.36
Hardware Components	$16.48
Total	**$1,433.91**

7.2 Project Timeline and Milestones

Pictured below in Figure 7.2a are the project milestones, which will be used to measure the team's progress toward completion of the solar sculpture prototype. All meeting minutes are being recorded for the final project documentation.

Table 7.2a – Project milestones along with estimated date of completion.

Milestone	Date	Status
Initial Meeting	May 23, 2016	Completed
Group Formation	August 25, 2016	Completed
Initial Project Design Submission	August 26, 2016	Completed
Design and Specifications Documentation	September 9, 2016	Completed
Meeting with Sponsors	September 16, 2016	Completed
Research and Resource Identification	September 23, 2016	Completed
Updated Design and Specifications	September 30, 2016	Completed
Table of Contents Submission	November 4, 2016	Completed
Component Testing: solenoid valves	November 10, 2016	Completed
Updated Design Documentation	November 11, 2016	Completed
Component Testing: computer vision	November 18, 2016	Completed
Component Testing: water system	November 25, 2016	Completed
Component Testing: system health unit	November 25, 2016	Completed
Finalized Design Documentation	December 6, 2016	Completed
Begin Senior Design 2	January 9, 2017	Completed

Design Hardware and Software Elements	January 23, 2017	Completed
Order Equipment and Materials	January 30, 2017	Completed
Final Test of Equipment and Materials	February 13, 2017	Completed
Construct Final Project	February 27, 2017	Completed
Test Final Project	March 27, 2017	Completed
Present Final Project	April 24, 2017	Completed
Implement Full Size Solar Sculpture	February 27, 2018	Completed

7.3 Finalized Budget and Overall Work Distribution

Table 7.3a – Final Budget

Material	**Cost**
Pixy Camera	$69.00
MSP430G2553	DONATED
Raspberry Pi 3	$39.96
Arduino Uno R3	$27.99
Aubig 12V DC Water pump	$51.52
Screw Terminals 3.5mm	$30.00
Screw Terminals 2.54mm	$7.60
Breakaway Headers	$1.50
Female Headers	$1.50
20 pin DIP Socket	$0.87
MOSFET 30V	$51.52
1N4001 Diodes	$7.26
Ultrasonic Sensor	$8.99
74HC595 Shift Registers	$5.95
Quick Connects	$47.90
PVC Caps	$15.88

PVC Tubes	$20.97
Pump Tubing	$16.89
LED Light Strips	$35.96
Solenoid Valves 12V	$188.32
16 pin DIP socket	$1.50
12V Power Supply	$21.88
12ft Power cord	$6.85
PCB	$103.50
Power PCB components	$30.00
Total	**$1,433.91**

Table 7.3b – Work Distribution

Name	Computer Vision	Power Supply	PCB Layout	Water Feature Design
Connor Heckman	**1st**			**2nd**
Tahte Perkins		**1st**	**2nd**	
Ben King	**2nd**			**1st**
Jack Gray		**2nd**	**1st**	

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Appendix B: Permissions

From: **Ben King** <ben0king@knights.ucf.edu>
Date: Sat, Dec 3, 2016 at 5:33 PM
Subject: Permission to use circuit diagram from http://www.electronics-tutorials.ws/
To: info@eeweb.com

Hello AspenCore Network / EEWeb ,

I am a senior electrical engineering major at the University of Central Florida. I am working on a final senior design project and currently in the research and design phase of my project.

I was hoping you would grant me permission to to use the following images off the AspenCore Network website www.electronics-tutorials.ws for the documentation portion of my design project.

The images I would like to use are the transistor switching circuits found on your electronics-tutorials website at: http://www.electronics-tutorials.ws/transistor/tran_4.html

Please let me know if I can use this image as part of my documentation. The documentation will be strictly for academic and informational purposes only, and appropriate credit will be given to to AspenCore Network with sources cited.

Thank you,
Ben King

From: **Ben King** <ben0king@knights.ucf.edu>
Date: Sat, Dec 3, 2016 at 5:46 PM
Subject: Permission to use figures from datasheet
To: media.relations@infineon.com

Hello Infineon Technologies,

I am a senior electrical engineering major at the University of Central Florida. I am working on a final senior design project and currently in the research and design phase of my project.

I was hoping you would grant me permission to to use some of the figures and graphs from the datasheet for the International Rectifier mosfet IRLB8721 for the documentation portion of my design project.

The images I would like to use are found on your datasheet at: http://www.infineon.com/dgdl/irlb8721pbf.pdf?fileId=5546d462533600a40153566056732591

Please let me know if I can use this image as part of my documentation. The documentation will be strictly for academic and informational purposes only, and appropriate credit will be given to Infineon Technologies.

Thank you,
Ben King

From: **Ben King** <ben0king@knights.ucf.edu>
Date: Sat, Dec 3, 2016 at 5:55 PM
Subject: Permission to use figures from datasheet
To: techsupport@mccsemi.com

Hello Micro Commercial Components,

I am a senior electrical engineering major at the University of Central Florida. I am working on a final senior design project and currently in the research and design phase of my project.

I was hoping you would grant me permission to to use some of the figures from your MCC 1n4001-1n4007 series diode datasheet for the documentation portion of my design project.

The figure I would like to use is found on your datasheet at:
http://www.mouser.com/ds/2/258/1N4001-1N4007(DO-41)-349533.pdf

Please let me know if I can use these figures as part of my documentation. The documentation will be strictly for academic and informational purposes only, and appropriate credit will be given to Micro Commercial Components.

Thank you,
Ben King

Ben King <ben0king@gmail.com> 6:06 PM (0 minutes ago)
to info

This message is for Tarun Agarwal, who provided me with this email when I asked how to reach him. If this is not his direct email, please kindly forward it to him.

Hello Tarun,

I am a senior electrical engineering major at the University of Central Florida. I am working on a final senior design project and currently in the research and design phase of my project.

I was hoping you would grant me permission to to use the some circuit drawings that you used to explain the purpose of flyback diodes for the documentation portion of my design project.

The images I would like to use are the circuit drawings showing the operation of flyback diodes found in your post on elprocus.com:
https://www.elprocus.com/freewheeling-or-flyback-diode-circuit-working-functions/

Please let me know if I can use this image as part of my documentation. The documentation will be strictly for academic and informational purposes only, and appropriate credit will be given with you cited as the source.

Thank you,
Ben King

Permission to reference circuit diagrams http://bryanwbuckley.com/projects/mppt.html

Jack Gray <jackrgray94@gmail.com> 12:26 PM (0 minutes ago)
to bryan.w.buckley

Hello Bryan Buckley,

I am a senior electrical engineering major at the University of Central Florida. I am working on a final senior design project and currently in the research and design phase of my project.

I was hoping you would grant me permission to to use the following Voltage and Current Sensing Circuits off your Max Power Point Tracking Project for the documentation portion of my design project.
The image I would like to use is Voltage and Current Sensing Circuits with MPPT found on your Project at: http://bryanwbuckley.com/projects/mppt.html

Please let me know if I can use this image as part of my documentation. The documentation will be strictly for academic and informational purposes only, and appropriate credit will be given to Bryan W Buckley with sources cited.

Thank you,
Jack Gray

Permission to reference Grid-tie solar system

Jack Gray <jackrgray94@gmail.com>
to info

12:44 PM (0 minutes ago)

Hello TheSolarPlanner.com,

I am a senior electrical engineering major at the University of Central Florida. I am working on a final senior design project and currently in the research and design phase of my project.

I was hoping you would grant me permission to to use the following Grid-Tie Solar System off your tutorial for the documentation portion of my design project.
The image I would like to use is the Grid-Tie Solar System found on your website at:
http://www.thesolarplanner.com/

Please let me know if I can use this image as part of my documentation. The documentation will be strictly for academic and informational purposes only, and appropriate credit will be given to website with sources cited.

Thank you,
Jack Gray

Permission to reference Grid Tie Inverter Schematic

Jack Gray <jackrgray94@gmail.com>
to contact

1:09 PM (0 minutes ago)

Hello Lazar Rozenblat,

I am a senior electrical engineering major at the University of Central Florida. I am working on a final senior design project and currently in the research and design phase of my project.

I was hoping you would grant me permission to to use the following Grid Tie Inverter off your website for the documentation portion of my design project.
The image I would like to use is DC to AC Inverter Schematic found on your website at:
http://solar.smps.us/grid-tie-inverter-schematic.html

Please let me know if I can use this image as part of my documentation. The documentation will be strictly for academic and informational purposes only, and appropriate credit will be given to website with sources cited.

Thank you,
Jack Gray

Robert Perkins <tahteperkins@gı 6:19 PM (0 minutes ago)
to TMicroelectron.

Hello STMicroelectronics

I am a senior electrical engineering major at the University of Central Florida. I am working on a final senior design project and currently in the research and design phase of my project.

I was hoping you would grant me permission to to use the following images off your website for the documentation portion of my design project.
The image I would like to use is an image found on your website at:
http://www.st.com/content/ccc/resource/technical/document/application_note/be/93/fe/64/3e/08/46/52/DM00038253.pdf/files/DM00038253.pdf/jcr:content/translations/en.DM00038253.pdf

Please let me know if I can use this image as part of my documentation. The documentation will be strictly for academic and informational purposes only, and appropriate credit will be given to ST with sources cited.

Thank you,
Tahte Perkins

Robert Perkins <tahteperkins@gı 6:04 PM (0 minutes ago)
to press

Hello World Nuclear Association

I am a senior electrical engineering major at the University of Central Florida. I am working on a final senior design project and currently in the research and design phase of my project.

I was hoping you would grant me permission to to use the following images off your website for the documentation portion of my design project.
The image I would like to use images found on your website at:
http://www.world-nuclear.org/nuclear-basics/greenhouse-gas-emissions-avoided.aspx

Please let me know if I can use this image as part of my documentation. The documentation will be strictly for academic and informational purposes only, and appropriate credit will be given to World Nuclear Association with sources cited.

Thank you,
Tahte Perkins

Robert Perkins <tahteperkins@gr 5:42 PM (0 minutes ago)

to infoNA

Hello

I am a senior electrical engineering major at the University of Central Florida. I am working on a final senior design project and currently in the research and design phase of my project.

I was hoping you would grant me permission to to use the following images off your website for the documentation portion of my design project.
The image I would like to use is an image found on your wepage at:
http://www.solaredge.com/us/products/power-optimizer#/
http://www.solaredge.com/us/products/pv-inverter/single-phase#/

Please let me know if I can use this image as part of my documentation. The documentation will be strictly for academic and informational purposes only, and appropriate credit will be given toSolarEdge with sources cited.

Thank you,
Tahte Perkins

Robert Perkins <tahteperkins@gr 5:55 PM (0 minutes ago)

to txn

Hello Texas Instruments

I am a senior electrical engineering major at the University of Central Florida. I am working on a final senior design project and currently in the research and design phase of my project.

I was hoping you would grant me permission to to use the following images off your website for the documentation portion of my design project.
The image I would like to use images found on your website at:
http://www.ti.com/tool/TIDM-SOLAR-DCDC
http://www.ti.com/tool/TIDM-SOLAR-ONEPHINV
http://www.ti.com/tool/TIDM-SOLARUINV#buy

Please let me know if I can use this image as part of my documentation. The documentation will be strictly for academic and informational purposes only, and appropriate credit will be given to Texas Instruments with sources cited.

Thank you,
Tahte Perkins

Contact Alternative Energy Tutorials

We always encourage you to share your ideas and improvements with us, so if you have any questions about our Alternative Energy Tutorials website, Then please feel free to contact us using the form below. Many thanks for your show of support.

Contact Us Using The Form Below

Your Name (required)

Tahte Perkins

Your Email (required)

tahteperkins

Subject

Permission for Picture Use

Your Message

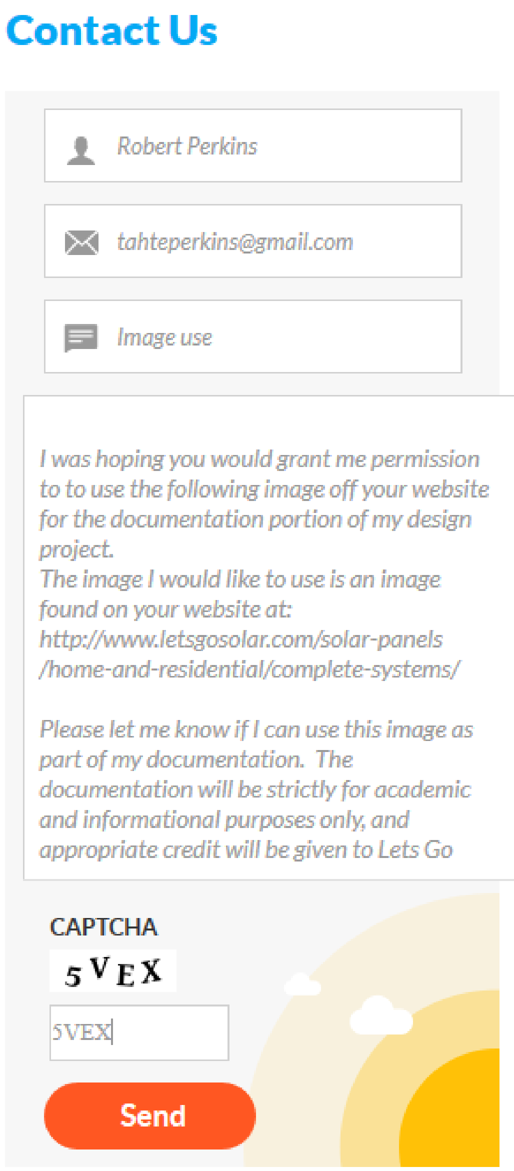
I am a senior electrical engineering major at the University of Central Florida. I am working on a final senior design project and currently in the research and design phase of my project.

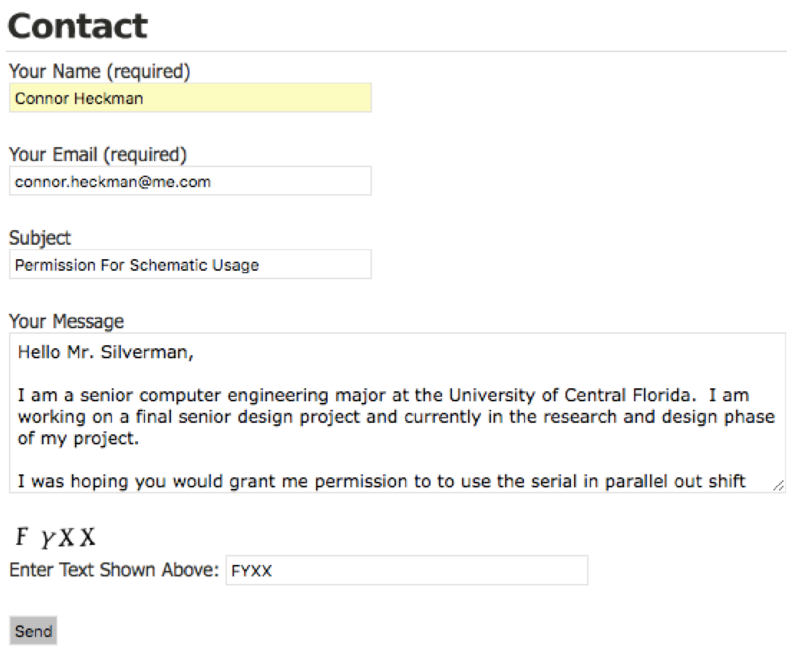
I was hoping you would grant me permission to to use the following images off your website for the documentation portion of my design project.
The image I would like to use is image found on your webpage at:
http://www.alternative-energy-tutorials.com/energy-articles/connecting-solar-panels-together.html

Please let me know if I can use this image as part of my documentation. The documentation will be strictly for academic and informational purposes only, and appropriate credit will be given to [website/company] with sources cited.

Thank you

Send


Contact Us
Robert Perkins
tahteperkins@gmail.com
Image use
I was hoping you would grant me permission to to use the following image off your website for the documentation portion of my design project.
The image I would like to use is an image found on your website at: http://www.letsgosolar.com/solar-panels /home-and-residential/complete-systems/
Please let me know if I can use this image as part of my documentation. The documentation will be strictly for academic and informational purposes only, and appropriate credit will be given to Lets Go
CAPTCHA
5VEX
5VEX
Send



Contact

Your Name (required)
Connor Heckman

Your Email (required)
connor.heckman@me.com

Subject
Permission For Schematic Usage

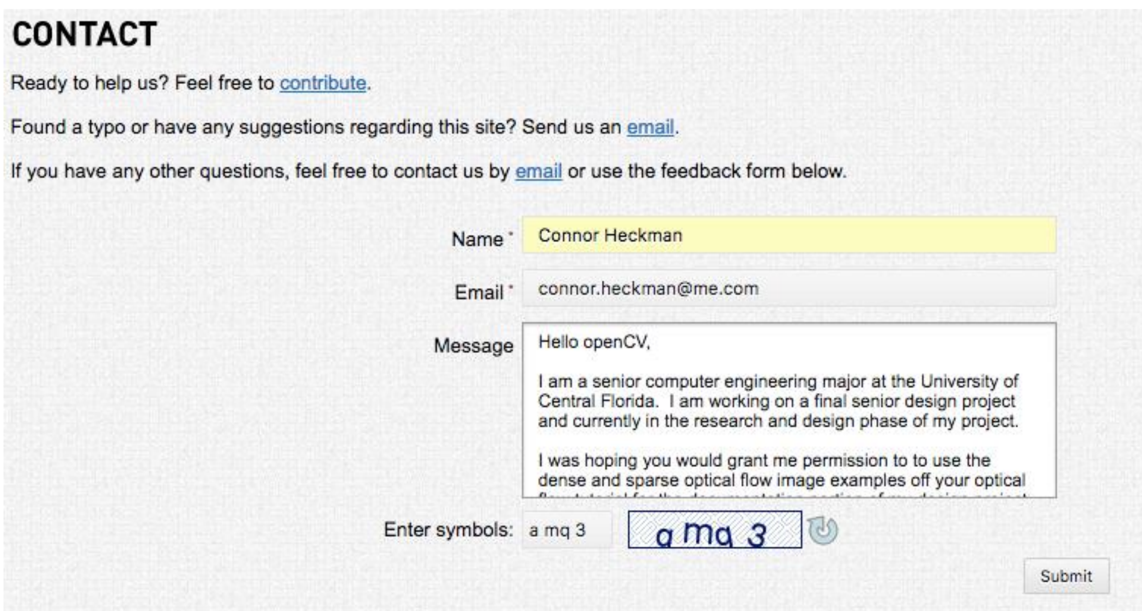
Your Message
Hello Mr. Silverman,

I am a senior computer engineering major at the University of Central Florida. I am working on a final senior design project and currently in the research and design phase of my project.

I was hoping you would grant me permission to to use the serial in parallel out shift

F YXX
Enter Text Shown Above: FYXX

Send



CONTACT

Ready to help us? Feel free to contribute.

Found a typo or have any suggestions regarding this site? Send us an email.

If you have any other questions, feel free to contact us by email or use the feedback form below.

Name * Connor Heckman

Email * connor.heckman@me.com

Message
Hello openCV,

I am a senior computer engineering major at the University of Central Florida. I am working on a final senior design project and currently in the research and design phase of my project.

I was hoping you would grant me permission to to use the dense and sparse optical flow image examples off your optical

Enter symbols: a mq 3 a mq 3

Submit

Appendix C: Hardware Components

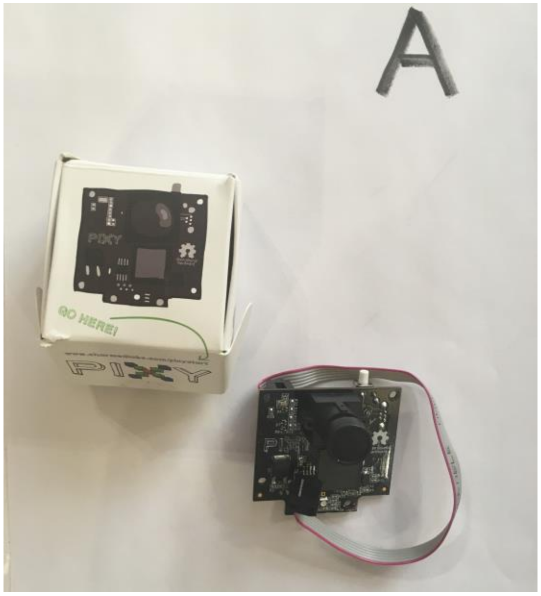


Figure A Pixy Cam

Figure C US Solid ¼" Solenoid Valves

Figure B Arduino Uno R3

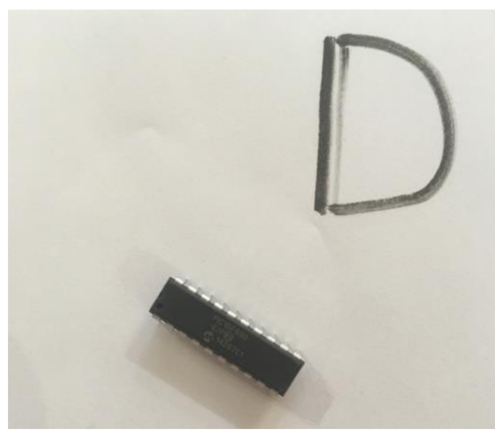


Figure D Microchip PIC16F690

Figure E 12V DC 2.2GPM Submersible Water Pump

Figure F Alternate Solenoid Valve

Figure G Raspberry Pi 3

Figure H Ultrasonic Sensor

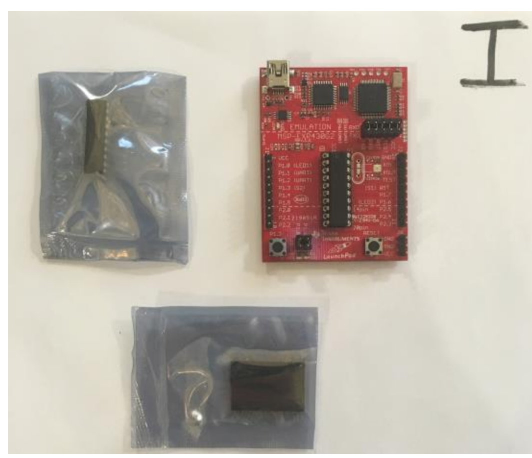


Figure I MSP430

Figure J 8-Bit Shift Register

Figure K MOSFETs

Figure L Water Flow Testing Supplies

Figure L 120V AC 5GPM Submersible Water Pump