Sharing Solar: Solar Sculpture Sponsored by OUC

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***Abstract* — The purpose of this project is to design a solar sculpture meeting our sponsor's needs that combines art and solar energy. We then implemented a 1/8th scale working model featuring solar energy system, interactive lighting, and an interactive web app to host energy production data and persuade the community to learn about solar energy. A secondary prototype was made to identify the sun's location, rotate and tilt the solar panel platform, measure and display solar energy production data, and connect the micro-controller to the internet to transmit data to the web app hosting the energy production data.**

I. Introduction

This project is a collaborative effort between the Art, Mechanical Engineering, and Electrical and Computer Engineering departments at University of Central Florida (UCF) to design a solar sculpture for our sponsor Orlando Utilities Commission (OUC). We are to create a 1/8th scale working model that implements the lighting, solar power system, the collection of energy production data, and the display of said data on a web app. In addition to this we created a dual axis solar tracker with Maximum Power Point Tracking (MPPT), stepper motors, motor drivers, and light sensors.

At the end of the semester OUC and their partner Tavistock will choose a sculpture design to be built in Laureate Park in Lake Nona. This sculpture will service the purpose of both an art piece for the community and an educational piece to teach the community about solar energy. The requirements OUC would like the solar sculpture to meet are the following: Produce 850 kWh/year in net energy, easy to maintain, last without maintenance for at least 5 years, meet safety standards, components be UL or ETL certified, be installed and designed inside $75,000 budget, and be interactive.

Our art team's top 3 designs from their original 50 were turned into paper models. Then the sponsor and their partner company chose the one design to move forward, The Dandies, shown in Figure I-1.

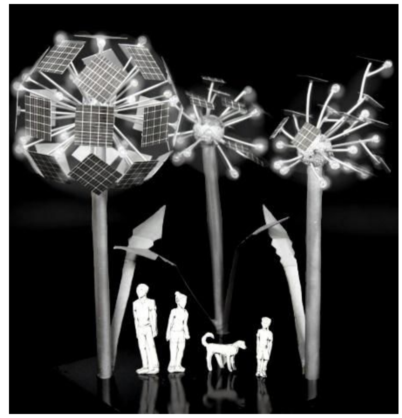


Fig. I-1. Paper model of dandelion design

This design features 3 abstract dandelions the largest featuring 25 50W monocrystalline solar panels, the two smaller ones featuring 11 20W monocrystalline solar panels each. They will also have 44 LED lights across all three dandelions that will fade out in sections to create a motion simulating the dandelions blowing away. This light display will be trigger by a touch sensitive tile located on the concrete at the base of the dandelions.

Finally, there will be an interactive web app hosting the information about the energy collected by the solar sculpture as well as resources for information on solar energy and a tool to communicate to people of all backgrounds what this level of energy can power.

II. Power System

A. Full Scale Solar Sculpture Power System

Due to the requirements from our sponsor and the design requiring a certain size, we chose Renogy 50W 12V monocrystalline solar panels for the larger dandelion because they are almost square in size and they are UL listed to reduce cost 8 panels on the larger dandelion will be non-functional since their angle will not produce much solar energy these will be non UL listed panels with the same look and size.. The smaller dandelions will use Htech Energy 20W monocrystalline solar panels which are UL listed as well.

The panels will be connected using microinverters, to decrease cost each microinverter will have two panels wired in series attached to it. We chose the

Enphase 215W microinverter because its input voltage ranges from 16-48V, therefore the inverter will work whether our panels produce a slightly larger or smaller voltage than the typical combined voltage of 24V. Also, this microinverter is the smallest (in Watts) on the market.

Using the panels listed above the larger dandelion will have 17 functional panels, each pointing in a different direction; one row of 8 will be angled at 90°, another will be at 45°, and the last panel will be at 0°. We used PV Watts, a tool for determining power output for a given system size in a given location, to determine the output of each panel shown in Figure II-A-1. The larger dandelion will produce about 797 kWh/year. The smaller dandelions will each have 10 functional panels angled at 30° facing south, they will collectively produce about 580 kWh/year. Together all three dandelions will produce about 1377 kWh/year, far exceeding the required 850 kWh/year.

Direction	kWh/y From 50W Panels			Total
	90 Degrees	45 Degrees	0 Degrees	
S (180)	43	72		
SE (135)	44	69		
E (90)	39	60		
NE (45)	27	46		
N (0)	18	38		
NW (315)	25	44		
W (270)	37	57		
SW (225)	43	67		
Total	276	453	68	797

Fig. II-A-1. Power output for each panel direction and angle collected from PV Watts

B. Working Model Power System

i. Solar Panel and Wiring

For the working model we will be using 2"x2" solar cells to represent the 50W panels, we will only use 6 cells to provide energy production data while reducing the amount or wiring inside the structure; the other solar panels will be represented with fake solar cells that look like the actual solar cells. All 4 cells will be wired together in series and fed to the MPPT which will output the maximum power to the battery.

ii. Maximum Power Point Tracking (MPPT)

A maximum power point tracker is an electronic device that varies its load impedance in order to maximize the power output of the solar panels. Solar cells have non-linear output characteristics which are typically shown on an I-V curve graph, an example is in Figure II-B-1 shown below.

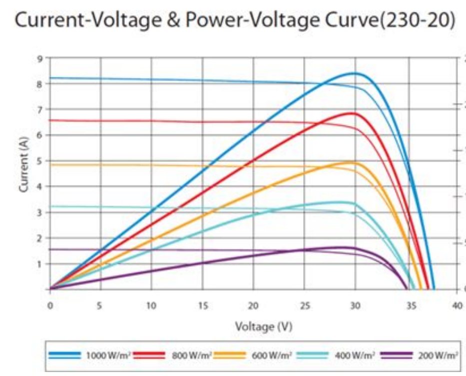


Fig. II-B-1. I-V Characteristics of a Suntech STP230 solar panel at different conditions

The maximum power point of a solar panel lies at the knee of the I-V curve. The sample panel shown above has a V_{MP} (maximum power voltage) of 29.8V and Imp of 7.72A under the standard 1000 W/m^2. The graph shows that the voltage variation is much less compared to the current variation under different irradiance. The panel has an internal resistance that changes with solar intensity so if a static load is connected directly to a panel and its resistance is higher or lower than the panel's, the power drawn will be less than the maximum available.

There are several algorithms that can be used to achieve maximum power point tracking. The simplest of them all is the constant voltage method. This method uses a single voltage to represent V_{MP} and is usually programmed by an external resistor that can be part of a network that includes a NTC thermistor so the value can be temperature compensated. Sources give this method an overall rating of about 80% which means that under differing irradiance variations, the method will collect about 80% of maximum power.

Another method is the open circuit voltage method in which V_{OC} is used to calculate V_{MP} according to the equation:

$$V_{MP} = k * V_{OC}$$

K is typically a value between 0.7 and 0.8 and accounts for the small drop in V_{MP} that can be seen in the above graph as the irradiance drops. The short circuit current method is a very similar method that uses I_{SC} to estimate I_{MP} instead. It uses a short load pulse to generate a short circuit condition where the voltage goes to zero.

A fourth method is called perturb and observe. Here the voltage or current of the panel is decreased or increased while monitoring the change in the power output. The direction of the change is reversed when the panel power decreases. Proper step size is an important consideration in this method because too large a step will result in oscillation about the maximum power point and too small a step will result in a slow response to changes in irradiance. Averaging the panel power value can help reduce the response to noise. One last method to be considered is called the incremental conductance method which locates the maximum power point when:

$$dI_{PV}/dV_{PV} + I_{PV}/V_{PV} = 0$$

Or when the instantaneous conductance is equal to the negative of the incremental conductance. The circuitry required to implement this algorithm is more complex and it is well suited for conditions of rapidly varying irradiance. When cells are arranged in a series, the iterative methods can be better method since partial or differing angles of incidence can make it so you have to search for V_{MP}. But for whatever method is chosen, it is better to be accurate than fast since fast methods tend to bounce around the maximum power point due to noise in the power system.

Solar inverters tend to have an on-board MPPT that already maximizes the power coming in from the panels. In considering inverters for the full-scale sculpture we will need to have this. For our prototype we should plan on making our own MPPT board, since we do not plan on purchasing an inverter for our working model and secondary prototype.

iii. Battery and Charge Controller

A charge controller is a device that can safely and efficiently charge a battery. Most 12V panels actually output around 17V under ideal conditions so that a 12V battery can still be charged when the sun is low in the sky or conditions are not ideal. The charge controller regulates the output down to prevent damage to the battery. Its job is similar to that of the MPPT and many companies make controllers that will integrate an MPPT algorithm already.

Because one of the goals of the project is to minimize the maintenance that will need to go into the sculpture and also to make it as safe as possible, the full-scale structure will not have a battery and therefore not need a charge controller. However, we will have a battery to power our prototype since we cannot actually feed the electricity onto the grid at UCF and we still have to power our own electronics.

There are many kinds of batteries we can consider for use in our prototype. The most common rechargeable batteries that are used today are nickel cadmium, nickel-metal hydride, lead acid, lithium polymer, and lithium ion polymer.

Nickel cadmium (NiCd) batteries are a mature technology that has long life, high discharge rate and an economical price. However, they are relatively low in energy density and they contain toxic materials that are environmentally unfriendly. They are also one of the most rugged rechargeable batteries.

Nickel-metal hydride (NiMH) batteries have 30-40% higher energy density than do NiCd ones and they contain no toxic metals. This comes at a reduced cycle life and a more complex charge algorithm since it generates more heat while charging. They also require regular full discharges and are about 20% more expensive than NiCd.

Lead acid batteries are the most economical for large power systems where weight is not a big concern. They are also low maintenance and capable of high discharge rates but have a low energy density, limited number of discharge cycles, and are environmentally unfriendly.

Lithium ion batteries are high energy and lightweight. They are also low maintenance since they do not require periodic discharges but they do, however, need a protection circuit that limits voltage and current and can be subject to capacity deterioration over time. They are also expensive to manufacture, costing about 40% more than NiCd technology.

Lithium polymer is the least developed of the technologies but these kind of batteries also have the smallest profile. They can be manufactured to resemble the thickness of a credit card and are lightweight. However, they are still expensive to manufacture and do not yet offer many improvements on a typical Li-ion battery. Their main advantage is their small form factor.

For our project we decided to use lithium-ion batteries since there are inexpensive options available and they are energy dense. Most of these kinds of batteries come with charging protection circuits built in to prevent them from exploding but they also require the user to follow an intricate charging process that includes five steps.

Pre-conditioning must happen when a battery has been depleted to the point that its cells essentially die. The battery has been allowed to discharge too much and its voltage has dropped significantly below its rated voltage. During pre-conditioning, the charge current is limited until the battery reaches a minimum voltage and it can withstand all of the current in the constant current phase. The cells must be rejuvenated before they can begin to be fully charged.

Next comes the constant current phase in which the battery can be charged at its maximum rate until it reaches its rated voltage. In this phase, it can be advantageous to charge the battery at a slower rate. This is because if it is charged at a slower rate, it will be more likely to reach 100% capacity when it hits rated voltage, otherwise, it may reach this voltage while still below max capacity.

After constant-current comes constant-voltage. Here, the current steadily decreases while the voltage is kept constant in order to prevent overcharging. While still below full capacity, the charging is terminated and moves into the last phase which is called charge top-up. Because the battery can discharge itself naturally over time, that top-up phase waits until it falls to a specified voltage, then charges it back up to rated voltage.

The MPPT and charge controller designs will be used in both the working model and secondary prototype except some values will be changed to suit the different solar panels. A battery will also be present in both designs.

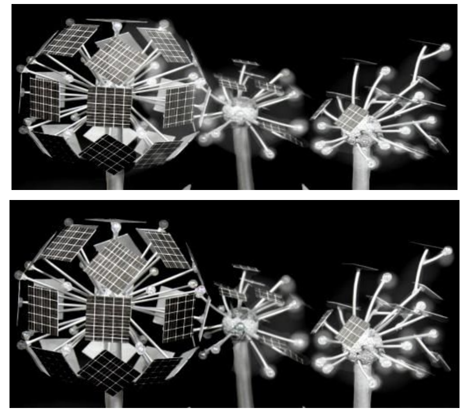


Fig. II-B-2. Example of light show sequence

B. Working Model Lighting and Programming

In the model we used 1.5” diameter round christmas lights, separated in sections so they can be connected to the microcontroller and faded in sequence. The microcontroller we chose to use in the model is the Arduino Uno. These controllers are easy to program and provide several pins for our use. Each sections will be placed on a pin; then the program will fade each section in sequence by decreasing the voltage supplied until it’s zero. This program will be triggered by a small 2” x 2” touch sensitive tile connected to one of the controller pins.

III. Interactive Lighting and Programming

A. Full Scale Sculpture Lighting and Programming

The lights on the solar sculpture will be globe lights with LED bulbs inside. We chose LED bulbs in order to increase the longevity of the bulbs and prevent any frequent maintenance. We chose a S14 1W LED bulb with 25,000 life-hours; if we operate these lights for 12 hours per night they would last just over 5 years. The globe light fixture will be 8” in diameter and made out of durable acrylic that will not yellow.

When a user activates the touch sensitive tile the lights will dim in a sequence to represent the dandelions being blown away as shown in Figure III-B-2; the tile can’t trigger the light show while it’s in progress or for a couple seconds after to allow time in between shows. The lights will be wired together in sections and each terminated on a different I/O allowing each section to fade independent of the others.

IV. Interactive Web App

A. Web Server

The web server runs on an EC2 Linux virtual machine on Amazon AWS. It hosts a custom database based in MySQL as well as a PHP application. The database is used to store the values for power generated by the solar panels using the current and voltage sensor readings. This database consists of only one table with 3 columns. The first column is for the ID of the data row. The second column is for the timestamp, while the third one is for the power generated up to the time displayed in the timestamp column.

The PHP application includes three files that perform the basic CRUD functionalities needed for this project: insert, read, and delete. The file insert is loaded every time the MCU needs to access the database. This file returns a new connection which is needed when the PHP application sends a query to the database. It is used every time the MCU sends POST requests to the server. The PHP application executes an insertion query with the values received from the microcontroller. Finally, the read file is the one that links to the web app and displays the values contained in the database.

B. Web app

The web app is an important part of our project because it allows the public to access the information on how much energy the solar sculpture harvests from the sun. It does this by displaying the data collected in an understandable way; which is a requirement given to us by our sponsor. The web app uses AngularJS and JQuery to make it interactive and more appealing to the user.

The web app will be part of a website that contains relevant information about this project. The website's interface was written in HTML and CSS. Additionally, Bootstrap, a front-end responsive framework, was used to make the process of development smooth and efficient. The website is fully accessible across all devices, which allows it to reach a bigger audience. The home page displays a welcome message and a menu bar or dropdown depending on what devices is being used by the user. The menu includes links to the statistics page, the learn more page, the gallery page and the OUC website. The font stack uses Google Fonts, with the primary font being Open Sans.

V. Solar Energy Data Collection And Transmission

A. Current Sensor

For our design we need to measure power generated by the solar tracker; to achieve this we need to include a current sensor. There are two main types of current sensors, closed-loop sensors and open-loop sensors.

Closed-loop Sensor can measure both AC and DC current and provides electrical isolation. Some benefits of this type sensor include fast response, high linearity, low temperature drift, and low sensitivity to electrical noise. The sensor output is easily converted to voltage. The closed-loop sensor is often chosen for applications requiring high accuracy and they are most commonly used in commercial and industrial applications.

Open-loop Sensor is a hall sensor mounted in the air gap of a magnetic core, with a conductor running through the core. The conductor will produce a magnetic field comparable to the current running through the conductor. The signal from the hall sensor is very low so it must be amplified, which is generally included in the sensor. This type of sensor normally includes temperature compensation and calibrated high-level voltage circuitry. The open-loop sensor is susceptible to saturation and temperature drift. This type of sensor has a price advantage in the high current range of 100A and above; they are also smallest in size and weight. The sensor also maintains constant power consumption regardless of the current sensed but they are best for applications with restricted temperature variation.

Considering the details above about the two different types of current sensor, we find that the best sensor type for our application is the open-loop because of its cost advantage and its small size. We chose the Allegro ACS711KLCTR-12AB-T because the maximum temperature and sensitivity is the best of the three product we compared. Also, this product has a high maximum temperature and its maximum current sensing (12A) is large enough to accommodate the MPPT current (8A).

B. Voltage Sensor

To measure the voltage produced by the solar panel we will use a buffer op-amp combined with a voltage divider circuit at the +In terminal as shown below in Figure V-B-1.

We used a 90kΩ and a 10kΩ for the voltage divider, grounding the 10kΩ resistor so that only 10% of the voltage produced is passed making the maximum input voltage 2V. Our positive rail will be attached to the 3.3V source and our negative rail will be grounded to allow for all voltages in the range.

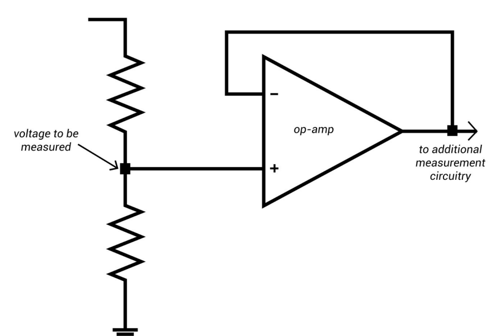


Fig. V-B-1. Buffer Op-amp with Voltage Divider Circuit

We chose to use the TI OPA344 Buffer Op-amp due to its input range -0.3V to V+ + 1.8V, which in this case is 5.1V; this range will suit our purposes nicely. Also, this op-amp uses less power with a quiescent current of 150μA. This op-amp also has a high specified temperature of 85°C allowing it to perform in the summer heat while inside an enclosure rate for outdoors.

The voltage passed through the op-amp is passed to the microcontroller. The microcontroller program then converts the voltage input into the actual voltage from the solar panel using the voltage divider equation.

C. Wifi Module

We selected the ATWINC1500 breakout board to help the microcontroller send data to the web server. This breakout board communicates using Serial Peripheral Interface (SPI) which enables the exchange between two devices (master and slave). The exchange is done one bit at a time (serial exchange). SPI operates in full duplex mode, which implements the bidirectional transfer of data at the same time. The most significant advantage of having a wireless module that supports serial communication over the ones that support parallel interfaces is that the system required simpler wiring.

Also, the ATWINC1500 supports SSL, Secure Sockets Layer, which establishes an encrypted link between a server and a client. SSL is frequently used between a web server and a browser and it allows the safe transmission of sensitive information. WEP, WPA and WPA2 are supported by the ATWINC1500 as well. This protocols adds a good level of encryption to the wireless transmission subsystem of our project.

This breakout board incorporates level shifting on all the input pins so it can be used with 3V or 5V logic. There's also 3 LEDs that can be programmed over the SPI interface or with the Arduino library to light up when the Wi-Fi module is connected to an SSID or transmitting data.

VI. Secondary Prototype: Solar Tracker

The solar tracker prototype will use light sensors to follow the sun's path producing the greatest amount of energy possible. To turn the panel we used two stepper motors; one for rotation and the other for tilt. We also included motor drivers to control the stepper motors We measured the voltage and current produced by the solar panel using the previously mentioned voltage and current sensors.

A. Microcontroller

The microcontroller is the central device that will process all of the data we gather from our sensors and use that data to obtain the optimal placement for our solar panel while providing power information that OUC requested. The microcontroller that we chose for our project is the ATSAMD21G18 series controller from Atmel. We went with this controller due to the higher performance that is provided in comparison to the ATMega328, which was our other microcontroller in consideration.

The microcontroller has an operating voltage of up to 3.3 V, which was a major consideration since we need to use up as less power as possible to meet our requirement of producing 850 kWh/year net. This microcontroller also has 24 digital pins and 14 analog pins, which provides enough pins to interface with all of our peripherals while having some left over for extra features. We also have 256 kB of flash memory, so we have enough space to perform simple to complex operations within the software so that we can control all of our external devices.

In prototyping this chip, we used the SAM D21 Breakout development board by Sparkfun, to test all of our functionality. This is a commercial off-the-shelf package that provides many of the pins broken out that we can use with a USB interface that allows us to use the Arduino IDE, with its libraries, to gather data and control our devices through an intuitive and easy-to-use interface.

B. Stepper Motors and Motor Drivers

In the selection of the motor and motor drivers, we had to take several things into consideration. First, our motors had to be able to move the load that would be producing a torque on it. Second, we needed to find a way to limit the current that would run through motors. Stepper motors can operate at voltage for much higher than it is rated for but the current needs to be limited in order to prevent damage to the coils. We chose stepper motors mainly because our system is an open-loop system and stepper motors are ideal for working with open-loop systems.

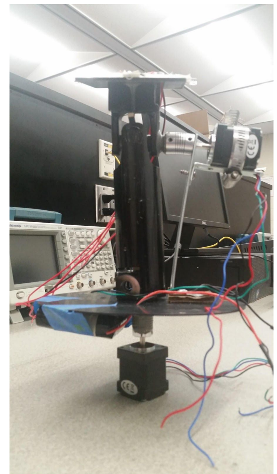
For our selection we went with the Nema 14 14HS17-0504S, which provides a holding torque of about 32.6 oz-in, a weight of 0.22 kg, and a rated voltage of 7.5 V. Also, the rated current for the motor is 0.5 A/phase.

The solar tracking functionality of the project was eventually omitted by OUC due to the low maintenance requirement of the project and motors require consistent maintenance during their time of use. For completeness, the process that we went through for implementing the solar tracking functionality is included in the next paragraph and details the implementation of the solar tracker on our secondary prototype.

In order to control the motors, we need to energize the coils of the motor in the correct sequence. For this, we used the Easy Driver stepper motor driver, sold by Sparkfun. This motor driver can supply a maximum continuous current of 750 mA/phase to the motors and loaded with a maximum input voltage of 30 V, which supports a wide operating voltage for our motors [3]. In addition, we can control the current of the driver using an onboard potentiometer so that we can protect our motors. the implementation of our motors turned out to be difficult. The holding torque for our motors is a limiting factor in the design of our motors. In our design we needed to be able to provide rotation in two directions: panning and tilting. To start let's discuss panning. Implementing the panning functionality for our design turned out to be much easier than implementing the tilting functionality, the main reason being due to the way that our structure is loaded. The loading of the structure has a tendency to want to tip over as opposed to creating a panning motion. From this, most of the forces due to gravity on the structure do not produce a torque on the panning motor. So we can pan the structure quite easily with minimum current running through the motor, thus reducing power consumption. This is the motor that can be seen at the bottom of the structure.

Implementing the tilting functionality, on the other hand turned out to be quite difficult. In order to move a solar panel in the desired direction, we connected the motor to the two axis structure using a coupler and restricted the motion of the structure to move in only one direction as opposed to two direction. Next, in order to keep the motor stable we hooked it to a support beam and clamped it down to prevent motor skips or jerks when in motion. The use of the coupler proved useful in providing flexibility for the motor to rotate given that the motor was not perfectly flush with the structure. To continue, we needed to calculate the maximum weight that the motor could move

given several factors. Both motors can be seen in the picture below. We calculated the distance between the motor and the solar panel to be about 5



inches. At this

Fig. VI-B-1. Picture of the dual-axis solar tracker structure

distance, the maximum weight of the solar panel can be about 0.2716 lb. With this weight limitation, we chose the Sunnytech 3W 12V mini solar panel with a weight of 0.15 lbs which can be moved by the top motor.

C. Solar Panel

Our secondary prototype will use Sunnytech 3W 12V mini solar panel because its weight allows the motors to move the panel smoothly. This panel will feed into the MPPT which will feed the maximum power to the battery.

D. Light Sensors

In order to track the sun, we will be using light sensors to track the general location of the sun's light on the solar panel. For the light sensors, we took two different devices in consideration: the CdS photocell and the phototransistor.

The CdS photocell is a light-dependent resistor whose resistance changes with respect to the amount of light hitting the resistor. When there is no light hitting the photocell, the resistance is very high; on the other hand, when there is a lot of light hitting the photocell, the resistance becomes very low. By connecting this photocell in series with another resistor, we can create a voltage divider circuit, where we can measure the voltage across the resistor to determine the amount of light hitting the photocell. We can also create the same type of circuit using the phototransistor. When we did some research on the photocell and the phototransistor, we found that the photocell was not RoHS compliant due to the presence of Cadmium in the device. As a result, we decided to go with the phototransistor since it was RoHS compliant and was functionally equivalent to the photocell.

The phototransistor is a device that uses light to create a path for current to travel through. This device in turn acts as resistor whose resistance decreases as the light hitting the base of the device increases. Using the same configuration as the photocell above we can construct a similar circuit that will allow us to use a voltage measurement to measure the light hitting the phototransistor. The figure below shows this circuit:

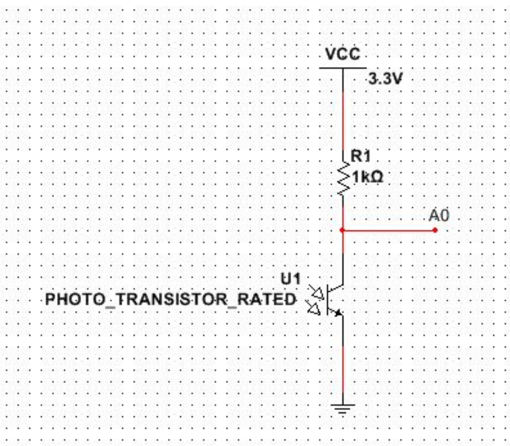


Fig. VI-D-1. Light Sensor Circuit

The circuit is powered by the microcontroller, supplying 3.3 V, and the voltage measured at A0 will be used to determine how much light is hitting the phototransistor. The choice of a 1 kOhm resistor is desired because of the fact that sunlight will be hitting the phototransistor directly and having too large of a resistance will lead to voltage saturation at higher levels. For better responsiveness indoors, higher resistance values can be switched in, somewhere in the range of 2.2kOhm to 10 kOhm, without altering the functionality of the circuit. Since the idea of this prototype is to track the sun outdoors, lower resistance values are desired so that we can work in a wider range of lighting conditions. For this circuit setup, a lower voltage measured at A0 corresponds to brighter lighting conditions and a higher voltage measured at A0 corresponds to lower lighting conditions.

In our design we used four of these circuits to be able to determine the general location of maximum lighting relative to the location of the phototransistors.

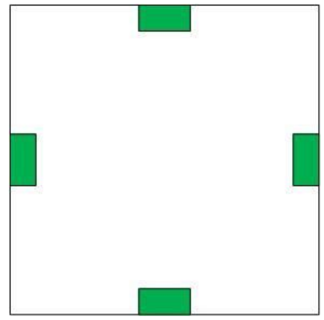


Fig. VI-D-2. Phototransistor Array Layout

In this layout, we have the phototransistors placed in the North, South, East, and West positions of the solar panel.

For panning motion, the East and West phototransistors will be used to determine the optimal direction to move the solar panel. While there is light hitting the East or West phototransistors, the structure will rotate in order to align the movement of the sun with the North-South axis of our structure.

For tilting motion, the North and South phototransistors will be used to determine which direction the solar panel should move towards. If more light is hitting the north phototransistor, the structure should tilt northwards and if more light is hitting the south phototransistor, the structure should tilt southwards.

Acknowledgement

We would like to thank our sponsor Orlando Utilities Commission and their partner company Tavistock for their time and their feedback during the course of this project. Also we would like to thank Justin Kramer and Sam Choi for their assistance when needed and their efforts in helping the teams and project along.

Dr. Robert Hoekstra and Prof. Robert Reedy played an instrumental part in tutoring and assisting our teams. Thank you for your time spent helping us with our presentations, models, and engineering information. You were the greatest help in this project helping us learn and grow with real world experience.

Finally we would like to thank Dr. Wei and the ECE faculty for their part over the past few years in teaching us the basics of electrical and computer engineering.

Biography

Jose Jerez is a senior electrical engineering student. He has concentrated his coursework at the University of Central Florida on power engineering and will go on to work in this field as a protection and controls engineer when he graduates in May 2017.

Ruben Vazquez is a senior computer engineering student. He has interests in embedded systems and machine learning and will be attending the University of Florida as a Ph.D student in computer engineering, focusing on machine learning and reconfigurable computing starting in August 2017.

Carla Majluf is a senior computer engineering student. During her career at UCF she has focused on software engineering and database development. After graduating she plans on working as an applications developer and getting her computer science masters in human technology interaction.

Carolyn Cressman is a senior electrical engineering student. She has an interest in design and enjoys collaborating with other majors. She has experience working as an engineering intern with Walt Disney World and as a temporary power technician at PSAV. After graduating she plans to pursue a career working as an engineer in design.

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