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Determining energy output in manual and automated solar arrays

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Determining Energy Output in Manual and Automated Solar Arrays

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Executive Summary

The scope for the project was to design and construct a system that could be used to both manually and automatically track the sun using solar panels to demonstrate engineering principles for classroom and laboratory experiments at both the primary and secondary education levels. For ease of demonstration, a manual and automatic tracker was designed for the experiment. Using a standard camera tripod, the solar panels were attached to fabricated mounts to allow for omnidirectional movement. For the automated, or active tracker, an Ardunio Uno microcontroller was used in conjunction with two 180° servos to adjust the active tracker solar panel into position. To do this, four light dependent resistors were used as sensors in the microcontroller code. The code consisted of four inequalities to determine whether the top or bottom and left or right are experiencing more light, send a signal to the servo and move the panel to the optimum setting.

The tests conducted for this project consisted of finding the optimal setting for the manual tracker and then comparing that over the course of the day with the active tracker. The tests successfully showed how there is an optimum range for the manual tracker and furthermore how the active is an average of 20% better than the manual over the course of the day. The final project deliverables are the apparatuses, the Arduino code, and excel workbook. The project has a number of areas to improve and has a number of experiments to study energy conversion and renewable energy. Dr. Margraves plans to use this system for future student engineering laboratory experiments, as well as demonstrations for STEM youth programs.

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Introduction

The overall goal for this thesis is to provide two apparatuses that will be utilized in a number of experiments and classes for a part of a summer program for students. The goal is to create an experiment where the students can learn engineering principles and how they can be applied. The client, Dr. Charles Margraves, wants two versions of a solar tracking array to use in his STEM youth program. One of the structures will be manually adjusted to find the optimal angle for energy production while the other will be automated through a microcontroller.

Because Dr. Margraves is planning on using these apparatuses for middle and high school students, these structures must have components that can track the movement of the sun, have a visual and mathematical representation of solar power generation, and output data in a format that can be useful and comprehensive to a high school education level. The manual mode will allow the user to physically move and adjust the position of the panel. The automatic structure will include a Maximum Power Point Tracking, (MPPT), a device that can sense the maximum sunlight around the solar panel for optimal power generation. Most importantly the apparatuses needed to highlight the benefits of using an automated tracker over the use of a manual tracker.

In order to meet these goals, a set of objectives was developed to clarify the needs of the project. The objective for this project is to create two structures that can support the solar panel(s), a wiring harness, power output meters, as well as the motors on the automated version. The primary objective will be creating and wiring the microcontroller along with the algorithm to track the position of the sun in relation to the optimal angle. The secondary objective will be to create a Graphical User Interface (GUI) that will take the information from the solar array mechanism and arrange it in a graphical view that can be used for possible lesson plans at the primary and secondary education level.

Other tracker plans can be found both commercially and in academia, however the important concept for this project is the need of simplicity in design. In order to determine whether or not these goals were achieved, a number of tests were conducted with varying time intervals and angles of the arrays. Analysis of these test results shows that the apparatus works as expected, and that the apparatus will demonstrate power output in other laboratory experiments.

Theory

The initial discovery of electricity via sunlight was through the work of William Grylls Adams and his student Richard Day in 1876 when they first discovered a small amount of electric current could be created when sunlight hit selenium, proving that a solid material could convert light into useable energy without heat or moving parts. More developments were made over the course of the next one hundred years; realizing silicon is more effective in harnessing the sun's energy. With these improvements in efficiency, materials, and construction, prices have dropped over the past twenty years, and solar has become "the least expensive power source for small-scale electrical demands located away from a utility line,"[4]. The photovoltaic industry has grown dramatically, increasing output 200 fold in this twenty year time period. Even now in remote areas, solar energy is considered the most effective solution for the main source of energy. Couple these facts with the current effects the environment is experiencing, solar energy is at the forefront of new development as coal and other fossil fuels are beginning to be phased out as a means to powering civilization[4].

Advances in energy efficiency as well as alternative forms of energy are at the forefront of developing research today. Solar energy is constantly debated on the practicality of use in comparison to regular nonrenewable forms of energy. Parida et al. describe photovoltaic conversion as "the direct conversion of sunlight into electricity without any heat engine to interfere."[3]. To accomplish this, a solar panel or array of photovoltaic (PV) cells work together to convert sunlight into electricity by allowing protons from particles of light to knock electrons free from cells in the panel. Each photovoltaic cell is constructed with semi-conducting materials, usually silicon, which is found in many forms of electronics for its conducting properties. Semiconductors serve as materials whose conductivities fell between that of highly conducting metals on one end of the spectrum and insulators on the other. Silicon and similar materials such as Germanium can be described as intrinsic semiconductors, or pure semiconductors whose conductivity is determined by their conductive properties in the elements pure form. Due to the diamond cubic structure of these elements containing highly directional covalent bonds, these materials are extremely conducive to the construction of an electric field. The bonding electrons inside the structure of the silicon are unable to move until a considerable amount of energy (a photon of sunlight) breaks an electron free. These valence electrons are then excited from their initial position, leaving a positively charged hole and thus creating the structure for a conducting environment. To create this environment, the following procedure is required to create a photovoltaic cell.[5]

These cells create an electric field similar in structure to a magnetic field, which has opposite poles; the electric field has positive and negative ends. To obtain a strong electric field, manufacturers "dope," or add small amounts of substitutional impurity atoms to silicon to produce extrinsic silicon semiconducting material[5], thus creating the environment needed for a strong electric field. This process gives each layer a positive or negative electrical charge. For example, taking a sample of silicon, it will be seeded with phosphorous into the top layer of silicon, which adds extra electrons to this layer. The same sample in then doped with boron, which will result in a smaller amount of electrons, giving that end a positive charge. This will create an electric field between the two charged layers. Once this field is created, a photon of sunlight knocks an electron free from the phosphorous end. This free electron is then forced into a certain direction and when a larger number of electrons are freed, a current is created[5]. The following figure represents how a photon affects a p-n junction.

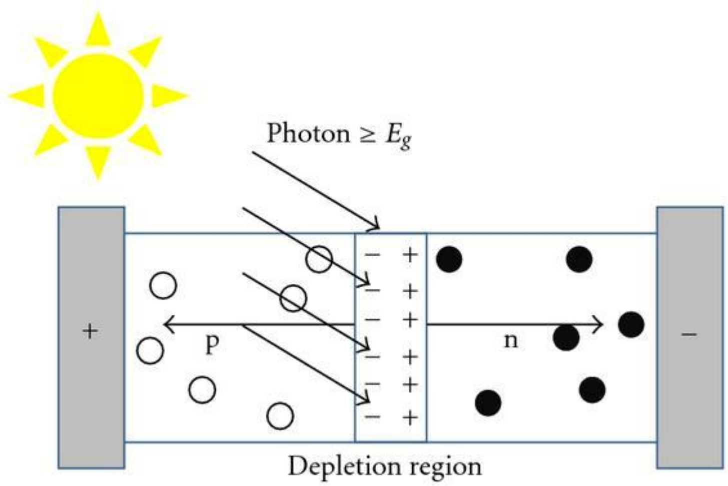

Figure 1: Representation of a solar cell

When metal contacts are placed on either end of the junction, this current is collected and is combined with the voltage from the electric field created from the cell to generate power. To help improve on the power generation of the cell, an antireflective coating is added to the silicon, which will reduce the amount of photons that will bounce off of the face of the silicon before they are able to free an electron. Finally a glass surface and a frame are added to multiple PV cells to give s protective structure from the elements and to help trap photons to create a complete solar panel with positive and negative terminals for power output[5].

Determining the best orientation and angle for the solar panel can drastically improve or decrease effectiveness of the power output, therefore it is important to understand the optimal setting for each season, which depends on location and style of tracking method. Based on the geographical location throughout the world, panels are installed differently and have varying movement depending on the position of the sun. Ideally the photons will hit the silicon junction at a 90° angle, which will maximize the amount of photons striking the panels and maximize the amount of energy being produced. The factors that control this setting are the orientation (north, south, east, west) and the angle of the array with respect to the horizontal of the surface of the Earth. In addition the correct angle of the array can depend upon the season of the year along with the latitude of the array itself. In addition to these factors the variety in whether the array will be: fixed, adjusted seasonally, or active tracking, will also determine how effective the power output along with how much maintenance is required.[1]

The three different types of tilting styles (fixed, adjusted, or tracking) can be described as follows:

- Fixed - This is the simplest set up, where the array is mounted at a single permanent orientation. The tilt needs to be the optimum angle for the entirety of the year. This angle is determined by using the latitude of the geographical location of the array. [2]

- Adjusted – Similar to the Fixed, yet as the seasons change, and the sun moves (ie higher in the winter and lower in the summer) the tilt angle needs to change as well to optimize your power output.[2]
- Tracking – Trackers direct solar panels toward the sun throughout the day. These devices change their orientation to maximize energy capture and can further be divided into a number of categories, depending on whether these trackers use sensors to orient their position or if the tracker uses a microprocessor/computer to calculate where the Sun is positioned using algorithms, geographical position, and other characteristics.[2]

Trackers serve as the best option out of the three listed above. Table 1 below, shows the effect of adjusting the angle using an array setup at 40° latitude as an example (Chattanooga, TN is located at 35° latitude, which would be minimally different than what is below). Each option of tilting styles is compared with a dual axis tracker than would always keep the panel directly perpendicular to the sun's photons.[1]

Table 1: Comparison of Varying Types of Tracking Methods

	Fixed	Adj. 2 seasons	Adj. 4 seasons	2-axis tracker
% of optimum	71.1%	75.2%	75.7%	100%

From the table above, the progression of optimum generation is increasing as the amount of changing angle is increased. As the desired power application differs, so does the tracking system. In certain cases, an active tracking system is too expensive and will decrease the maximum power that is gained from the solar panel, if the tracking system is to be powered by the panel. Due to the rotation patterns of the Earth on its axis around the Sun, if a solar array is fixed or immobile, the power generation or absorption of photons is greatly affected by the time of day and season of the year.[1] In regards to an active tracking system, which keeps the PV cell perpendicular to the sun throughout the day, regardless of the season, collected energy can be boosted in a range from 10% to 100% depending on the circumstances. However if an active tracking system is not used the PV cell array should be oriented into the optimum position, where no shadow will fall on it at any time in the day.

To get the most from a position-fixed, or even a seasonally adjusted, photovoltaic system, the panels need to be in the direction that will capture the most sun at a 90° angle. Solar panels should always face true south in the Northern Hemisphere, and north in the Southern Hemisphere.[1] In general, to get the optimum angle for a panel in the Northern Hemisphere in a fixed position all year long, the panel needs to be at an angle equal to the latitude of the geographical location with respect to the horizontal, facing south. However this method is for a panel that will be fixed all year long, therefore it is an average optimum angle for all seasons and all positions of the Sun. To gain more from the panel the seasonal method can be taken where the angle setting is specified per season.[1]

In the seasonal method, there are a number of improvements that can be made to optimize the power generation over the course of specific seasons. In the two seasonal approach, which takes into account the Sun changing position from summer and winter, the optimum angle is the latitude of the geographical location plus 15° in the winter and minus 15° in the summer. This accounts for the increase in power output as in the table above for the 2-season adjustment. Even further than that, the panel system can be improved upon by all four seasons by further specifying the position of the sun in relation to the latitude of the geographical position of the panel. The following table differentiates the seasons by the angle necessary for optimization, where x is the latitude.[1]

Table 2: Solar Optimization Equations for all seasons

Winter	$\theta = 0.9x + 30$
Spring	$\theta = x - 2.5$
Summer	$\theta = 0.9x - 22.5$
Autumn	$\theta = x - 2.5$

These equations relate to the optimum power output for four seasons as seen in Table 1. When to use these equations, can be given by the next table where the seasons are divided up in the calendar year. The efficiency of a fixed panel, compared to optimum active tracking, is lower in the spring, summer, and autumn than it is in the winter, because in these seasons the sun covers a larger area of the sky, and a fixed panel is not able to capture as much of it. These are the seasons in which tracking systems give the most benefit.[1]

Table 3: Seasonal Dates

Winter	October 13 to February 27
Spring	February 27 to April 20
Summer	April 20 to August 22
Autumn	August 22 to October 13

As stated earlier, PV cells absorb the most sunlight when the sunlight strikes the cell at a perpendicular angle. Because the PV cell generates a current, the cell can be referred to as a DC current source. The amount of current produced has a direct relationship with the voltage being produced as well from the PV cell junction and the intensity of light the panel is absorbing. Therefore the Power can be calculated in a number of different ways. Below is a representation of light striking the PV cell system. [2]

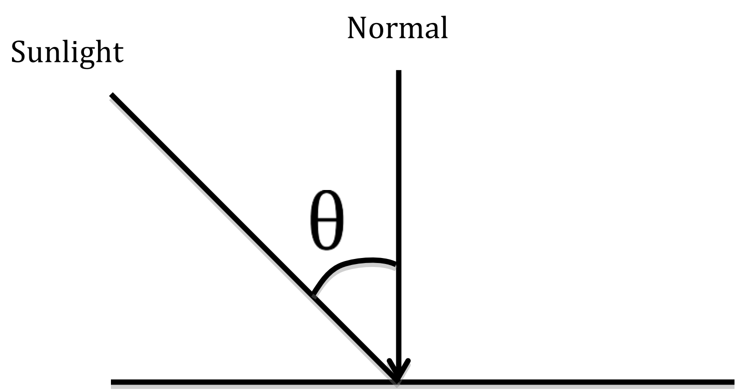

Figure 2: Solar Cell Angle of Incidence

The sunlight strikes the PV cell at the angle of incidence, θ. Assuming the sunlight is at a constant intensity, λ, the available sunlight to the cell that can be converted for power generation, W, can be given by:

$$W = X * \lambda * \cos\theta \qquad (Eqn. 1)$$

Where X represents a limiting conversion factor in the design of the panel as the current technology is unable to convert 100% of the sunlight absorbed into electrical energy. From this equation it is clear the most power will be generated when the angle of incidence is zero, or rather when the sunlight strikes the panel at a 90° angle. Furthermore, power will be generated when the sunlight is perpendicular to the normal vector. This clarifies the earlier statement of a fixed panel, which loses significant power due to the angle of incidence.[2] Another way to calculate power from the panel is to take the voltage, V, from the PV junction and the current, A, that is generated when dissipated through a load circuit and the product of the two is the power generation, W, given by the following:

$$W = V * A \qquad (Eqn. 2)$$

Experiment

Apparatus

The need for a lightweight and portable apparatus drove the design to be as simplistic as possible for use in a laboratory experiment. In that sense the decision was made for two different apparatuses for both a manually moveable solar panel and a two axis active solar tracker. The two structures needed to support the weight of not only the panel but also, the brackets that will be fabricated to house the panel and all of its components. The manual mode will allow the user to physically move and adjust the position of the panel. The active tracker structure will include a Maximum Power Point Tracking (MPPT) device that can sense the maximum sunlight around the solar panel for optimal power generation.

The manual solar tracker consists of an Aleko monocrystalline 15 watt panel with a prefabricated frame. A figure of the panel can be seen below.

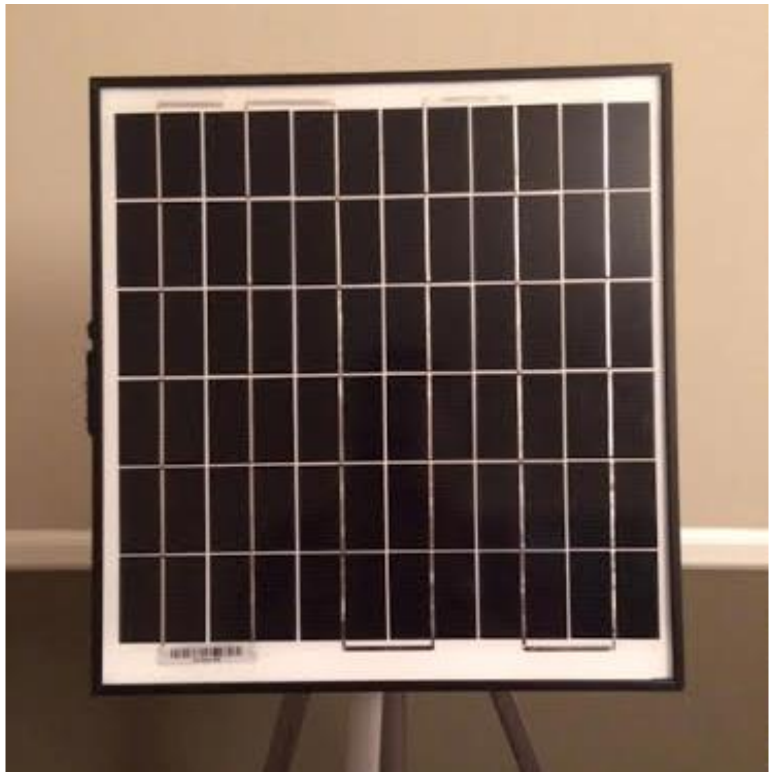

Figure 3: Aleko Monocrystalline 15 Watt Panel with a Prefabricated Frame.

The frame has been modified to house a bracket horizontally at the midpoint. The bracket was fabricated out of aluminum due to its lightweight and malleable properties, in an I-beam structure in the center of the bracket and the quick release mechanism from the tripod is fastened to enable the user to remove the solar panel with ease from its base. The base is a common camera tripod stand that supports the solar panel and its angular displacement. The tripod was chosen because of its stable structure, lightweight and inexpensive properties. The specific tripod chosen is the Amazon Basics tripod. Utilizing the tripod's panhandle and crank handle, the user is able to adjust the omnidirectional position of the panel. A figure of the quick-release mechanism along with the backside of the panel can be seen below.

Figure 4: Fabricated Bracket with Quick Release Mechanism Attached

Figure 5: Rearview of the Manual Array Attached to the Tripod

The tripod's leg braces and leg lock lever can be adjusted to change the length of the telescoping legs. This allows for adaptability towards irregular terrain. This base is also the starting component for the active tracker. A LED load circuit was attached to the output of the solar panel to provide a visual representation of power generation, as well as the ability to measure current and voltage for data collection. The LED load circuit is comprised of three LEDs that brighten as the power increases from the panel. A front view and rear view of the LED circuit can be seen below.

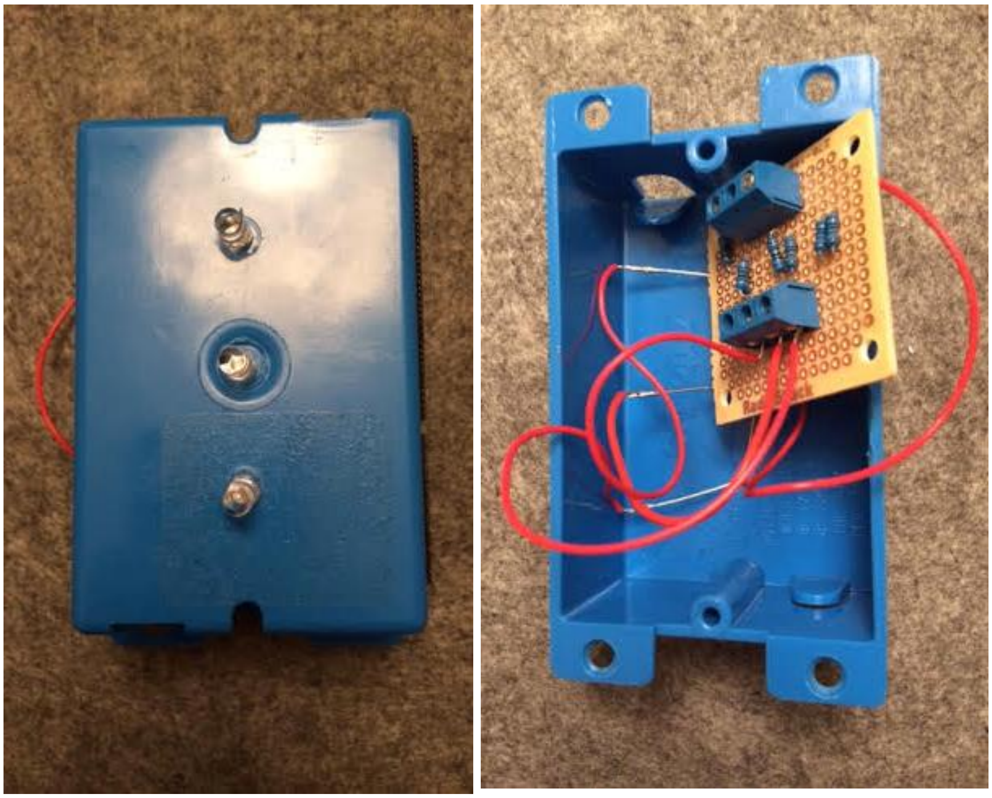

Figure 6: Front and Rear View of LED Circuit

The physical apparatus of the active tracker is more complex than the manual tracker due to the additional components that aid the automation processes. Initially the design was planned to include a stepper motor in the X-Y directional plane to assist in a 360° motion and add a 180° servomotor in the X-Z direction to allow for omnidirectional movement. The bracket designed for the active tracker originally was designed to house both of these components while holding solely the panel and housing the electrical components and the microcontroller on the base of the fabricated bracket. However in the initial circuit construction, the stepper motor and motor driver circuit were shorted in soldering and developed complications. The decision was made to use two 180° servomotors which would still allow for omnidirectional motion, however it changed the development of the control circuit script.

The electrical instrumentation and control of the system will be done using a microcontroller known as an Arduino Uno. Some of the specifications of the device include 14 digital input/output pins, where 6 of the output pins are for pulse width modulation (PWM). PWM is a technique used to allow the control of supplied power to an electrical device. From the microcontroller, a unit step signal will be sent to the motor. The average voltage sent to the motor is controlled by the switching characteristics set by the Arduino. Below is an example of an Arduino Uno microcontroller.

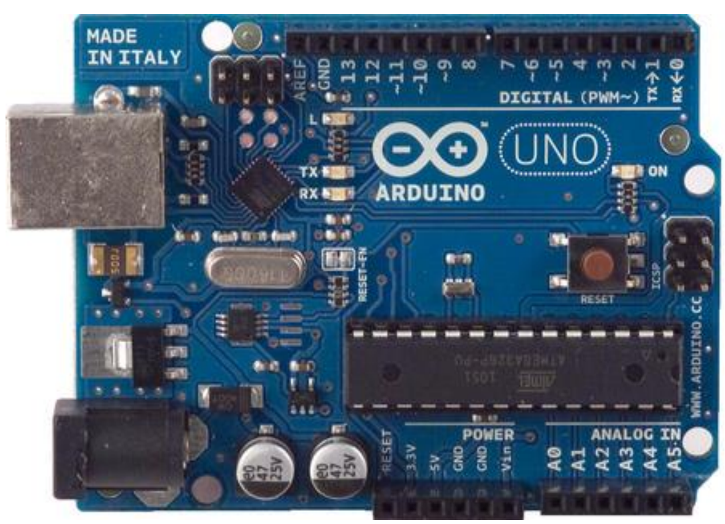

Figure 7: Arduino Uno Microcontroller

The duty cycle, which is the ratio between the turn-on time and the period of the square wave function, dictates the average voltage to the circuit and can be controlled by the Arduino programming. The larger the duty cycle, the higher amount of power supplied to the load. To regulate the time the signal is sent to the motors and light dependent resistors (LDR) will be placed along the face of the panel as sensors. LDR's are made out of a semiconductor material that change its resistance as it is exposed to light. When in the dark, the electrical resistance can be as high as a couple thousand ohms, and as small as a few hundred ohms in the light. The LDR circuit will be fed through the Arduino. The following is an example of the LDR that is implemented in the active tracker.

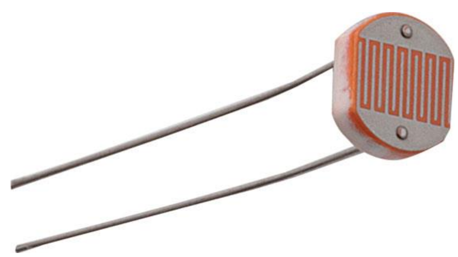

Figure 8: Light Dependent Resistor

As the LDR's are exposed to light, their electrical resistance is reduced, and therefore will increase the current within the circuit. This can be clearly seen by Ohm's Law, where

$$I = \frac{V}{R} \qquad (Eqn\ 3)$$

where I is the current, V is voltage, and R is resistance. The Arduino will read the signal and will provide a feedback loop to the PWM. The differential in the measured current from the set optimal current will be sent to the PWM pins that will translate into angle displacement for the motors. The signal will be sent continuously to each of the motors until the LDR current has met the parameters set within the Arduino. The active tracker has specified that a user friendly GUI be implemented to provide feedback of the data collected. The Arduino's programming syntax is a C++ based language and will require a way to store data accumulated by the system.

Similar to the manual tracker, the quick release mechanism was fitted to the aluminum base. Again, this allows for the user to remove the panel from the tripod base. However, the panel and crank handles of the tripod will not allow omnidirectional motion. To accomplish this, an aluminum base and wood section was cut to house the X-Y directional driving shaft. The wooden section and a series of fasteners is used to elevate a plastic pulley from the aluminum bracket and maintain the same height as the depth of the servo as seen in Figure 9. The wooden base allows for the center shaft to move with as little of friction as possible.

Figure 9: Active Tracker Base Attached to Tripod with View of X-Y Servo

The X-Y plane servo was offset from the shaft to minimize any unnecessary weight and friction from the panel to the servo's rotary components. A second pulley is placed directly on the servo in conjunction with two rubber bands. The rubber bands act as the belts in the pulley system. Moving above the pulleys, a rectangular segment of aluminum was cut and bolted to the wooden section to stabilize the shaft during operation. Above the aluminum plate the driving shaft is bolted to a mounting frame that is fastened to the frame of the panel. The mounting frame consists of two sections of aluminum flat bar that were bent in a "L" shape and overlapped to form a "U" shape frame. It was then fastened to the center shaft, and then to the sides of the panel's frame. The "U" frame can be seen in Figure 10.

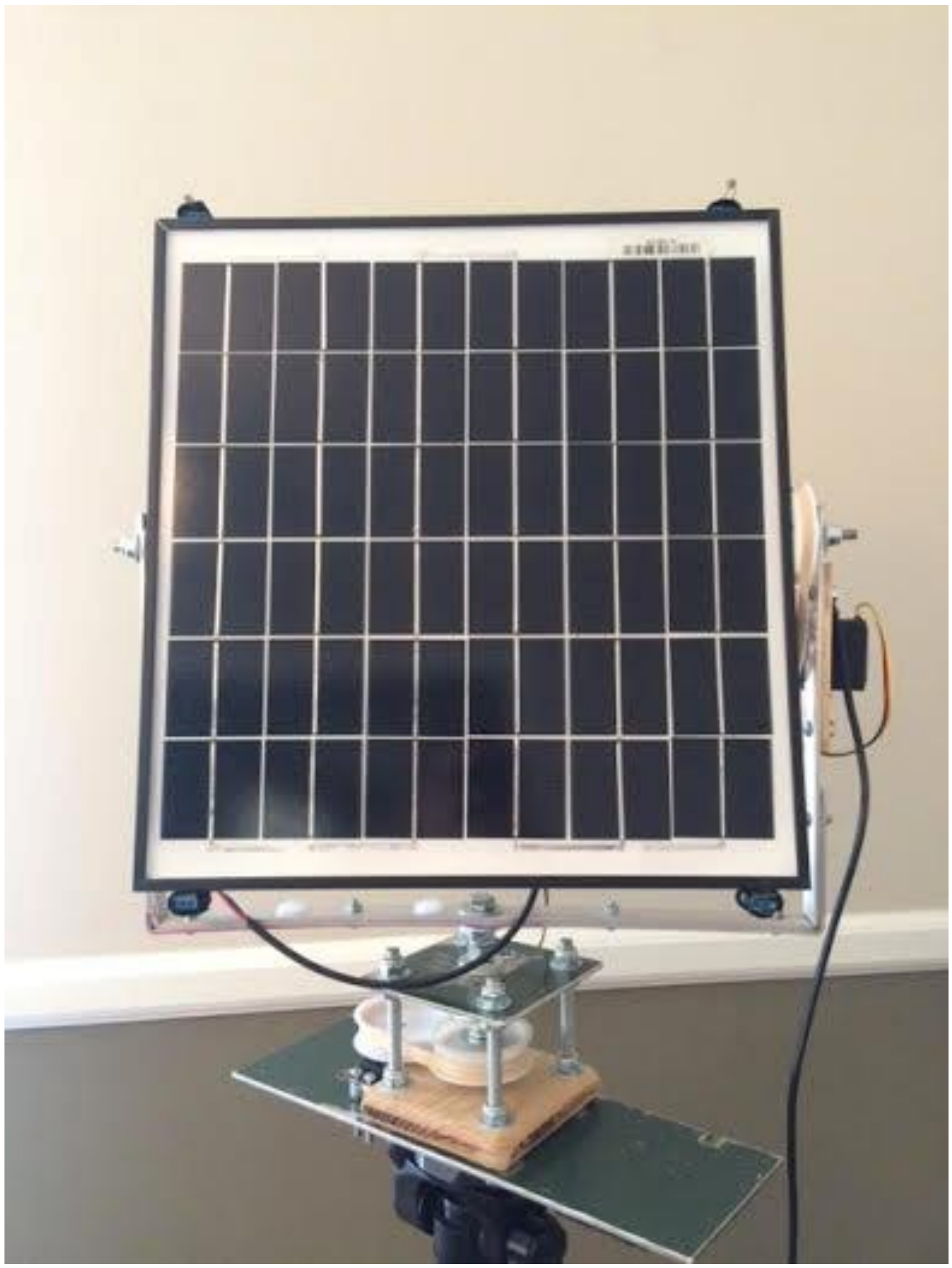

Figure 10: Front View of the Active Tracker

From the front view, on the right side of the panel, there is a rectangular section of wood bolted to the “U” frame; notice that the section of wood is not bolted at the centerline, but offset to the right. This is due to the implementation of another drive shaft driven by the X-Z servo. The X-Z servo is bolted to the centerline of the wooden section using provisions designed by the manufacturer. On the other side of the section, the drive shaft of the servo is adhesively attached to a pulley. A second pulley is placed where the “U” frame is fastened to the panel frame. Rubber bands are used as the belts for the pulley system. The fasteners that attached to the panel frame are intentionally loose to allow for X-Z directional motion.

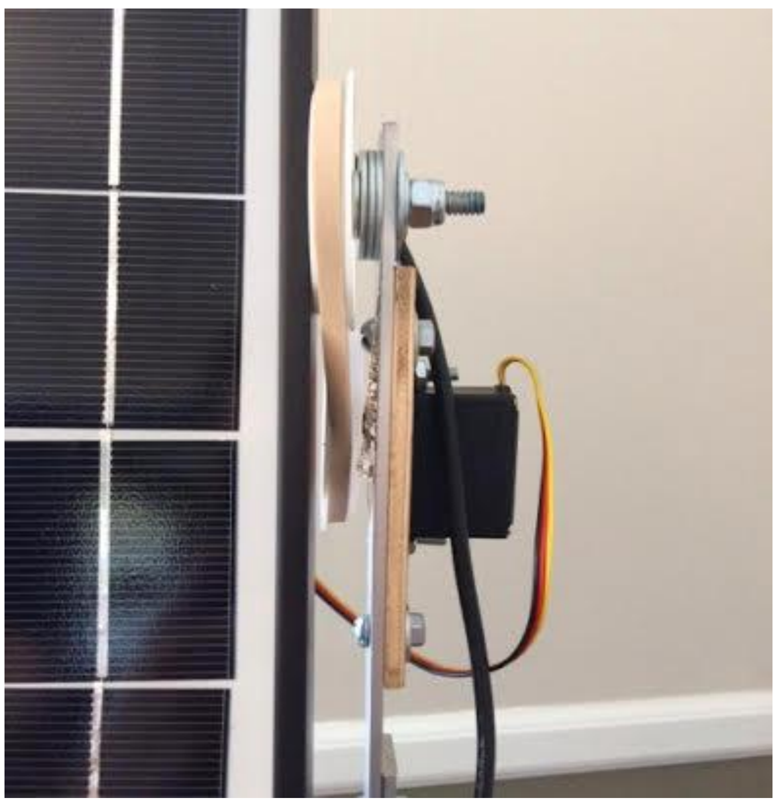

Figure 11: X-Z Plane Servo for the Active Tracker

The control circuit was built on a segment of proto-board. The Arduino Uno microcontroller was attached to the board using industrial strength Velcro. The board itself was then attached to the back of the solar panel using a similar method. Wires from the 5V power supply and digital PWM of the microcontroller were attached using ribbon cable and solder. From the analog inputs of the microcontroller, the wires are fed to the proto board and into the mounted terminal blocks. From the terminal blocks on the board, red #22 AWG stranded wire is pulled to the light dependent resistors at each of the corners of the panel.

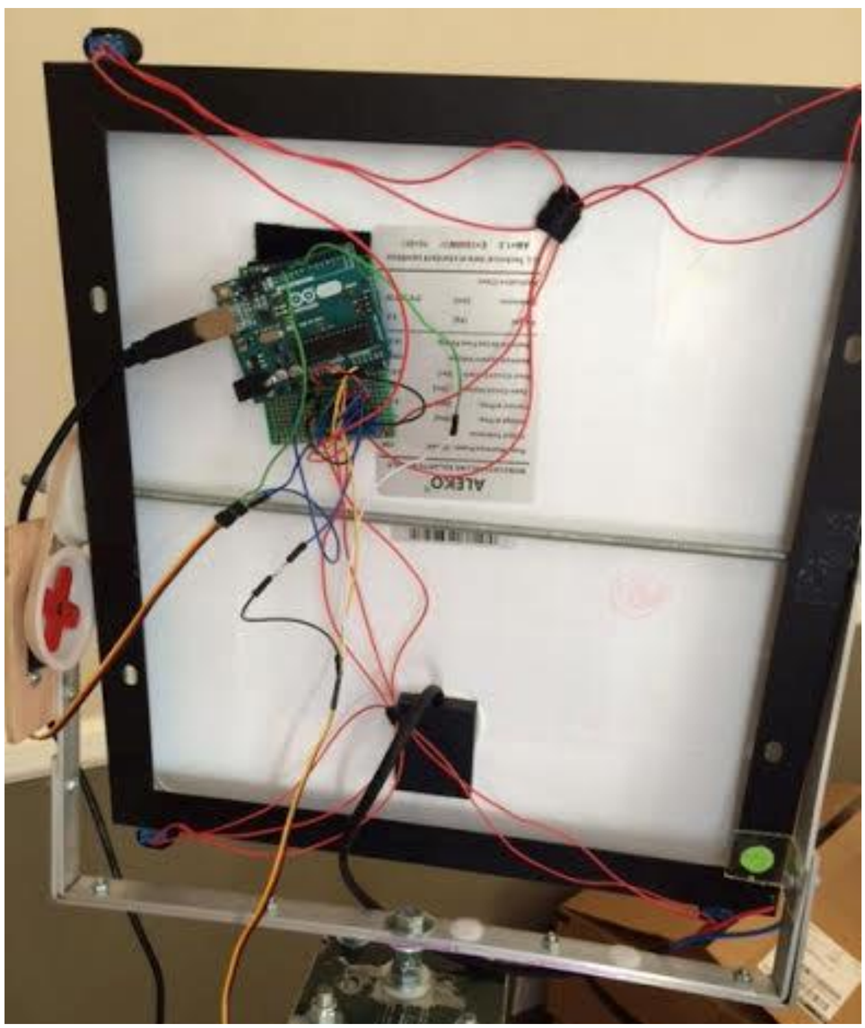

Figure 12: Rear View of the Active Tracker

The light dependent resistors are electrically connected through a terminal block that is attached using Velcro to each of the panel's corners.

Figure 13: Placement of Light Dependent Resistor

The following description and creation of the code used for the active tracker was created in conjunction with an electrical engineering peer, Douglas Jensen. The operational functionality of the active tracker can be viewed in the drawing found in Appendix D. From a hardware aspect, the Arduino Uno microcontroller is supplied power via a USB to the A/B input on the device. When energized, the microcontroller has the capability to emit either a 3.3 V or a 5 V power source. Utilizing the 5 V source and a ground pin, four 10 kΩ, 1/4 W resistors are daisy chained together. At each branch, a light dependent resistor, with a light resistance range 0.5 to 10 kΩ, is placed in series with the 10 kΩ resistor. Pins A0 through A3 are then connected between the 10 kΩ and the LDR. This is done so that the microcontroller can read the voltage drop across the LDR with respect to the ground pin. Additionally, the 5 V source and ground pins are connected to the positive and negative terminals of the X-Y and X-Z servos. Standard wire colors are used to identify the positive (red), negative (black) and pulse (yellow) terminals of the motors.

The pulse input of the servo is routed to digital outputs 9 and 10 for pulse width modulation. The order at which the pulse terminals are connected to the digital outputs does not matter. The output terminals of the solar panel are connected to the positive and negative terminal block of the load circuit. The terminal contacts are labeled positive and negative. The load circuit was implemented as a visual representation of the power generated by the panel. As the panel displaces toward a light source, the LED's in the circuit will brighten.

Arduino Code Description

Within the software of the microcontroller, variables are routed to the used inputs and output pins so that the microprocessor knows which i/o assignments are needed. Within the program setup function, the servos are assigned to digital output pins 9 and 10. Additionally, a reset function was implemented so that when the microprocessor is initially energized, it displaces the 180° servos to the 90° orientation. When this occurs, the panel face will be facing toward the ceiling or sky; this is referred to as the "initialization period". Within the program loop, variables are associated with the analog readings of the sensor. The variables are named to indicate the location of the LDRs with respect to the front view of the panel. Moreover, variables for the average values of the top, bottom, right and left sensors were created to simplify the code within the computation segment. The tolerances of the servos were also calibrated using the variables "speedh" and "speedv" and the function "max(*tolerance, # of steps)"* specific for the code found in Appendix C. These variables control the speed of the motor to move a single step per loop iteration. The next segment of code utilizes the serial monitor that is provided by the Arduino interface. The serial monitor is a necessary tool used to debug the software. However, it was also used to track the position of both servos and the analog readings of the LDR's. When the serial monitor is open, it will read the string "running" during the 5 second initialization period. After the setup, a graphic will appear on the serial monitor in the shape of a rectangle. This is to represent the front view of the panel. In each corner, the analog read values of the sensors will be displayed in accordance to their physical position on the panel. This allows the user to identify which sensor is experiencing the most luminosity. This also serves as a method for confirming the servos are moving in the correct direction in response to the sensor values. A figure of the serial monitor can be seen below.

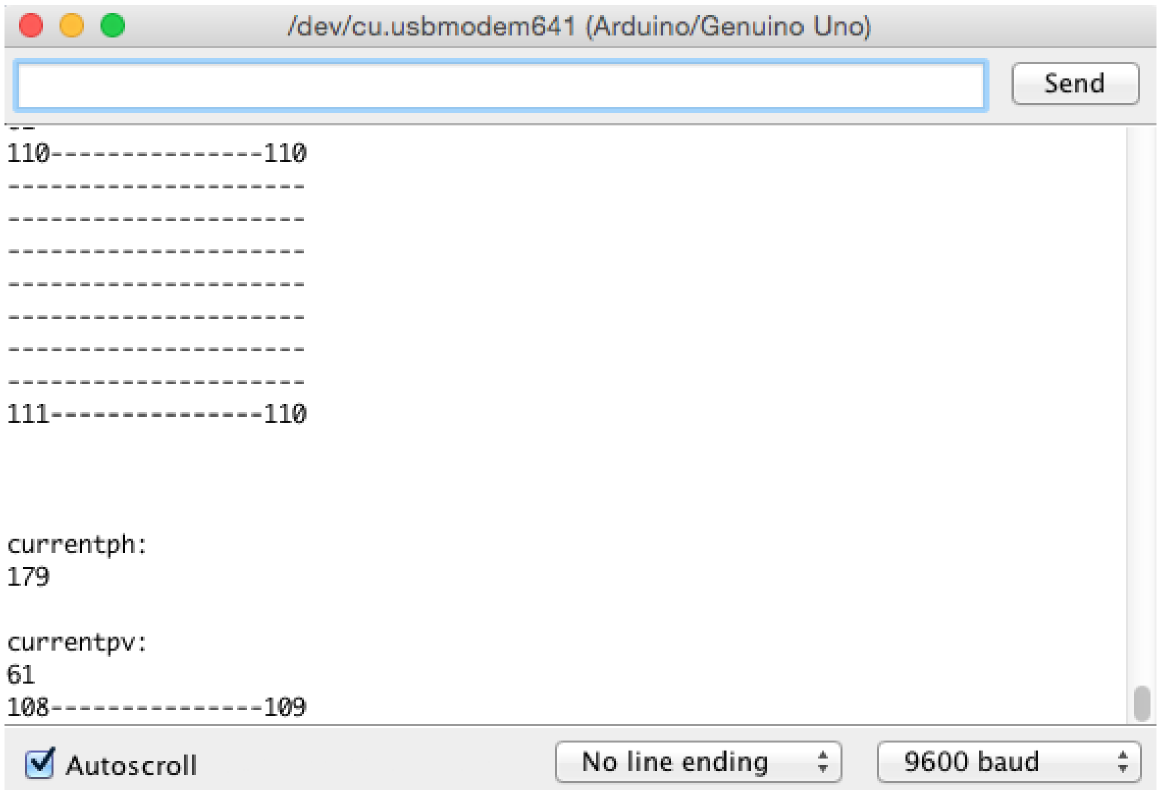

Figure 14: Example Reading from Serial Monitor

The logic implemented for the active tracker to decide direction consists of a comparative inequality and functions as follows:

- If the average value of the top sensors, ATS, is less than the average value of the bottom servos, ABS, and the difference between the average values is greater than the sensitivity margin, then the servo will decrement towards the top sensor.

- If the average value of the left sensors, ALS, is less than the average value of the right servos, ARS, and the difference between the average values is greater than the sensitivity margin, then the servo will decrement towards the left sensor.
- However, when the values are equal and less than the sensitivity threshold, the servo will stop and hold position. Each iteration of the loop is delayed 100 ms.
- Therefore as the Sun's position changes throughout the day, the active tracker will follow, keeping the rays of photons normal to the panel.

For a complete list of materials used in the construction of the apparatuses, as well as the code implemented on the Adruino Uno, see Appendix C.

Procedure

The procedure for this experiment can be broken down into two main tests. The first test will be to determine the optimum angle for power generation of the fixed array. The other test will be to determine the overall power generation over the course of a day. In this test, the fixed array, at its optimum angle, will be compared to the active tracker. The full procedure is dictated by the setup of the two apparatuses, data collection and analysis. Parameters that will affect each test are: the angle of the fixed array, the load generation circuit used for each apparatus, the weather on the particular day, and the instruments used to collect data for analysis.

To set up the fixed array for testing, first the tripod needs to be erected. Each of the telescoping legs needs to be fully extended and the brace must be locked. The panhandle head of the tripod needs to be parallel with the ground. After confirming the pan handle head is level, lock it in to place with the pan handle. After doing so, loosen the panhandle by one and a half complete turns. Perform the same steps concerning the panning lock nut. Fully tighten the side tilt locking nut as this portion of the tripod will remain stationary. The crank handle can be turned to the users preference, however at least one full turn is necessary so the tripod base will not interfere with the pan handle. A figure seen below labels the parts needed to alter before attaching the panel itself.

Figure 15: Tripod with part descriptions

Once all the steps have been taken, prepare the quick release platform by moving the arm to the open position. Next slide the quick release mechanism attached to the panel into the quick release platform and lock down the arm onto the quick release mechanism. Now the panel is set, however the load generation circuit needs to be attached to the panel array.

To attach the load generation circuit, the Velcro attachment on the side of the panel frame will be used. The blue wire from the back of the panel, or the negative power output will be connected to the terminal block opening on the left if facing the three openings on the empty terminal block. This is the negative terminal for all three LED bulbs. The positive end will be connected to a wire with two alligator clips on either end, which in turn will be connected to the multimeter. Using the multimeter to complete the circuit, by placing the other lead of the multimeter into the opening of the terminal block on the right side. This will allow the user to measure DC voltage and current for the panel. Using an inclinometer, the user can measure the angle of the panel, using the panhandle to adjust the sensitivity; the angle of the panel can be changed by tilting the panel itself. The multimeter and the inclinometer used for the fixed array testing and the active tracker testing can be seen below in the following figures.

Figure 16: RadioShack Multimeter Used in Testing

Figure 17: Swanson Inclinometer Used for Testing

In a more detailed description different angles will be measured approximately one to two minutes apart. The angles will be from 25 degrees to 70 degrees with 2.5-degree increments. The fixed array will always be facing true south as all tests will be made in the Northern Hemisphere. The angles are predetermined based on the latitude of the testing location and the data given by the National Renewable Energy Laboratory, NREL, to optimize power generation depending on the season and style of the fixed array. The data was all recorded on an Excel spreadsheet to include: time of day, voltage, amperage, wattage, and sky conditions.

The test began by setting up the fixed array to ensure its stability, then positioning it 180 degrees South. The array was required to remain in direct sunlight for the purpose of maximizing photon collection. Using the inclinometer and the multimeter described above, the angle, DC current, and DC voltage were all recorded beginning at 25 degrees. The trials would then vary by a 2.5-degree increase in angle and another measurement of DC current and DC voltage. There was a one-minute resting period between tests to ensure, the angle measurement and to realign the array to a 180 degrees South position if it had been altered. The same procedure will be run on 10 days to get reliable data of what angle will provide the optimal generation for the season.

In addition to the power optimization test, the fixed array will then be tested on a smaller range of angles with the time of day varying. This will allow finding an average optimum angle setting for the season, which may vary from the previous test. This data will then be compared to the data of the active tracker. The active tracker will also be tested throughout the day to see the average power generation. The two will then be compared to determine if the active tracker is more effective in power generation and maintaining the 90° angle of the panel to photons.

Concerning the active tracker, the setup of the tripod is similar to the fixed array. Each of the telescoping legs needs to be fully extended and the brace must be locked. The panhandle head of the tripod needs to parallel with the ground. After confirming the pan handle head is level, lock it in to place with the pan handle. Once this is done, the active tracker can be placed onto the quick release platform. Again, prepare the quick release platform by moving the arm to the open position. Next slide the quick release mechanism attached to the base of the active tracker into the quick release platform and lock down the arm onto the quick release mechanism. It is important to remember to place the active tracker base where the extending edges are perpendicular to the panhandle on the tripod. Then the components of the active tracker must be set into position. Each LDR will need to be placed in its respective corner, and are labeled “TL” for top left orientation, “TR” for top right orientation, “BL” and “BR” for the bottom left and the bottom right orientation. Next, on the computer that will be used to run the active tracker, pull up the file entitled ST_hybrid. Plug in the USB cord into the Arduino Microcontroller and then plug the opposite end of the cord into the computer. Wait until the servos initialize, (this can be confirmed by hearing the one to two second whirring sound of each servo). Unplug the cord from the computer after hearing this sound and place the bands onto the horizontal servo, similar to the figure below.

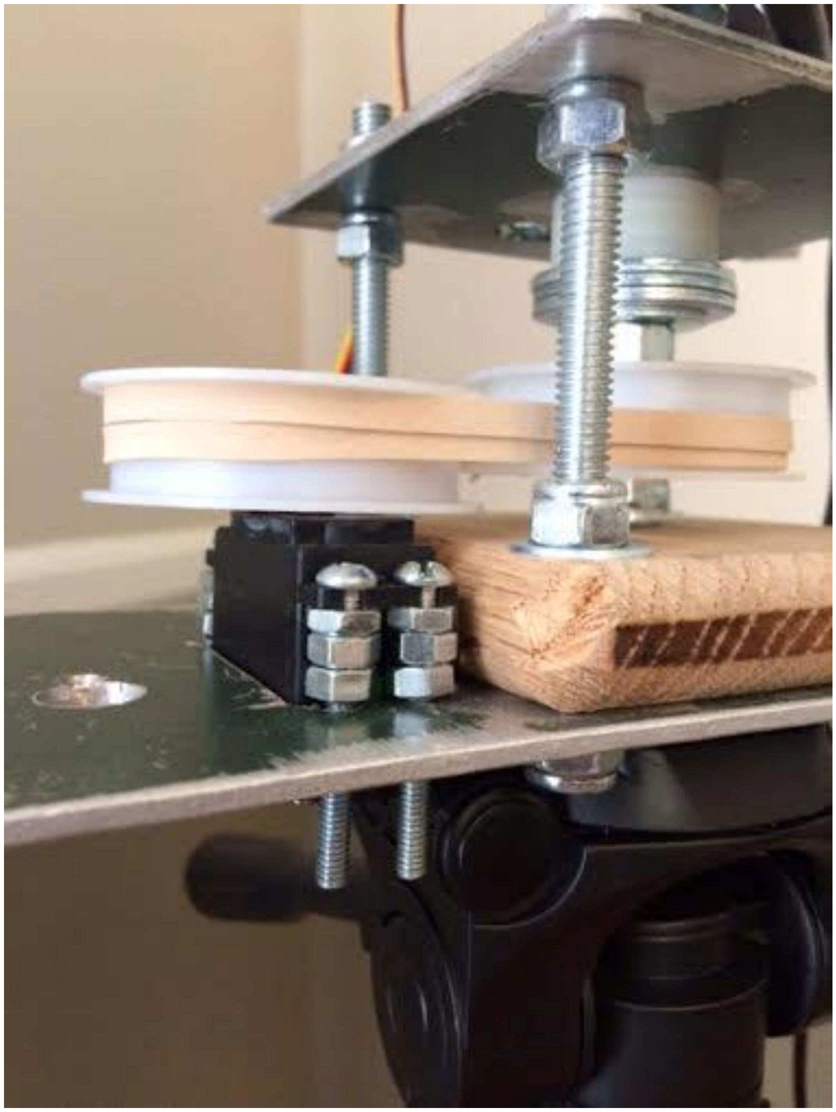

Figure 18: Complete Setup of X-Y Servo

For the X-Z servo, the first step is to rotate the panel until it is parallel with the ground and then attach the two rubber bands on the two pulleys. Overlap the rubber bands as the pulleys have half the thickness of the X-Z servo pulleys. A figure can be seen below as to how to attach these bands.

Figure 19: Complete Setup of X-Z servo

Once the rubber bands are in place, next ensure all of the wiring is connected and no stray wires are left unconnected. Similar to the manual tracker, the load circuit must me attached to the lead wires coming off the back of the panel. After this is completed the active tracker is ready for testing. Using the multimeter in similar fashion as the manual fixed array, attach it to the active tracker and plug the active tracker into your power source.

Over the course of the day, the following parameters were taken every half hour: the voltage, amperage, angle, and the cardinal direction of the apparatus. This data was compared to the manual array to determine whether the active tracker was performing better than the manual array. Performing these calculations over the course of 5 days will give reliable data as to which is performing optimally.

For the active tracker the step-by-step instructions are as follows:

- After setting up the active tracker, plug in the USB cable and click on the tools button in the upper ribbon. Select Serial Monitor, this will allow for the user to know the position of both servos as the active tracker orients itself.
- Once the active tracker is in position and the position of the two servos has stabilized, or the readings for “currentph”- position of the horizontal servo” and “currentpv” – position of the vertical servo have recorded the same value for 5 seconds, the user can begin to record the data.
- Record the angle, voltage, amperage, and cardinal direction of the active tracker.

Results

From the data gathered concerning the manual tracker, the following graphs detail the ten-day average of angle versus various categories: voltage, amperage, and wattage. The load generation circuit consisting of 3 LED bulbs only draws an average of 1.25 watts instantaneously, with a maximum power of 1.5 watts. This is due to the resistors used in the load circuit. The quarter watt resistors lower the amount of power so that the LED bulbs do not become overloaded. This will also ensure that the load circuit can be used with the experiment for years to come. Therefore the data will focus on the readings directly from the circuit rather than the load generation over the course of an allotted amount of time. The data was taken over the month of February and March and is described as the turning point from winter setting to spring setting in regards to a fixed one-axis tracker. The organization of the data consists of the average manual tracker data and finding the optimal angle for power generation. Then the 2 axis active tracker will be compared to the manual tracker over the course of a day. This data will then be averaged to determine if the active tracker is working properly. The first graph compares the angle of the array with respect to the horizontal versus the DC voltage running through the circuit in Figure 19 below.

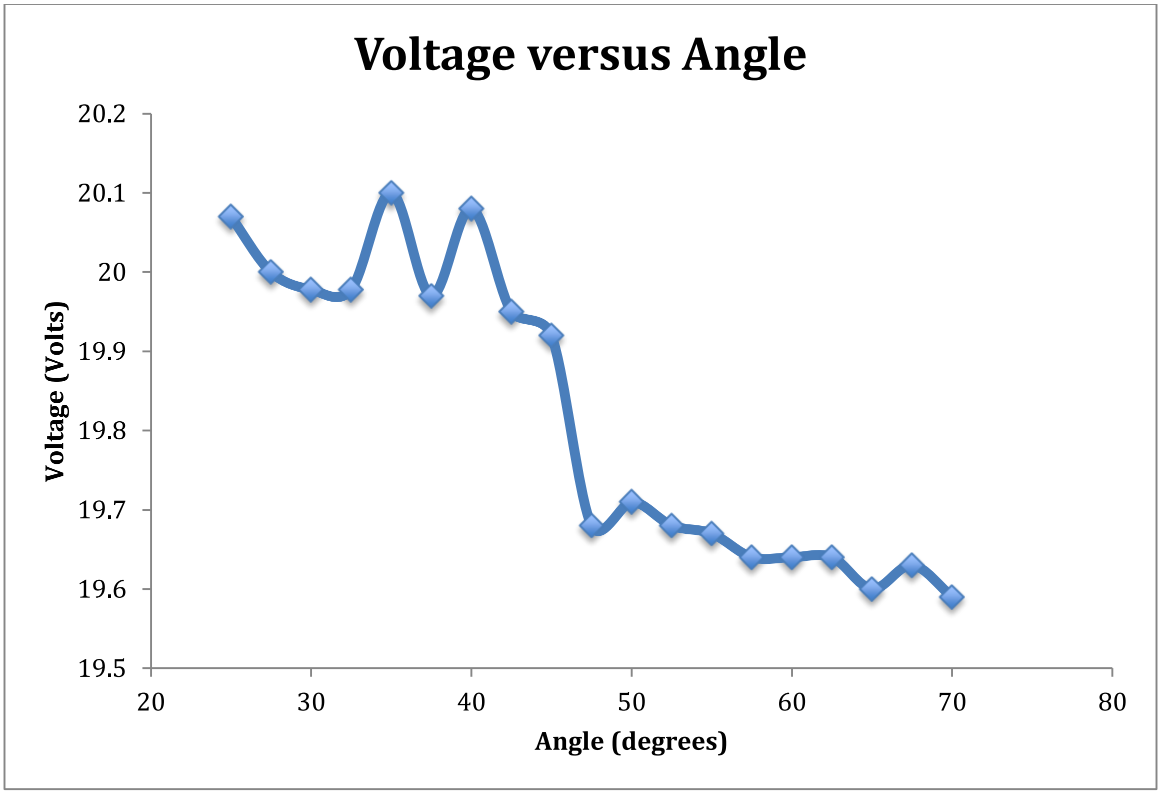

Figure 20: Manual Tracker Voltage versus Angle

The data above, taken from ten days in the winter season show peaks of voltage. The data was all taken on a sunny day with mostly clear skies to eliminate any inconsistencies in regards to optimal sunlight hitting the solar cells. The range of angles is in increments of 2.5˚ and can be explained by the equations in the theory regarding optimal positioning for the specific geographical location in the specific season of the year. The difference will be explained later in the conclusions. From the data above the highest average is at 35˚ with respect to the horizontal of 20.1 volts. The next points are 25˚ and 40˚ both with averages of 20.07 and 20.08 volts respectively. This range from 25˚ to 40˚ will be confirmed in the later figures to be used in the daily average in comparison to the active tracker. The next graph seen below in figure 20 compares the average amperage with the angle of the manual tracker.

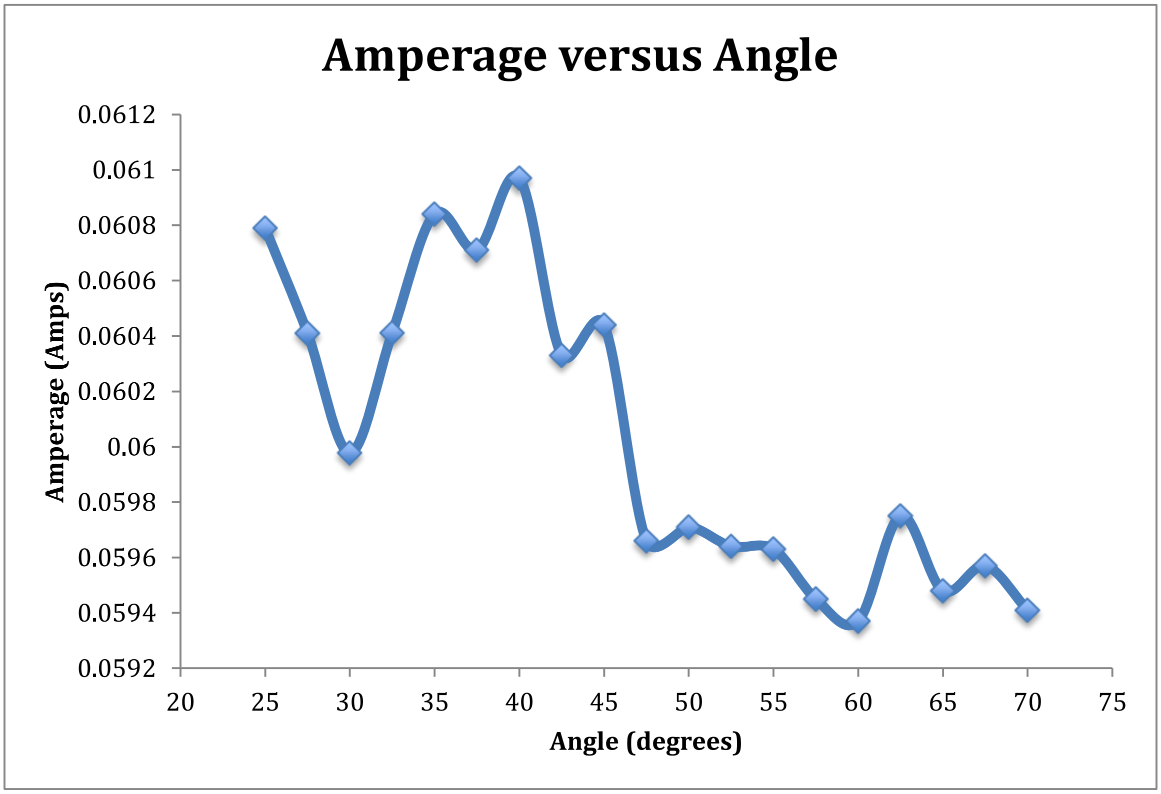

Figure 21: Manual Tracker Amperage versus Angle

The amperage versus angle is similar to the voltage comparison, however the peaks vary. The highest point on the amperage is at 40˚ with a value of 0.06097 amps. The next values are 35˚ and 25˚ with 0.06084 and 0.06079 amps respectively. The range again is maxed from 25˚ to 45˚ with a significant drop from 50˚ degrees on. The two parameters, voltage and amperage will be compared in terms of wattage to determine the overall range that will be used in the hourly test.

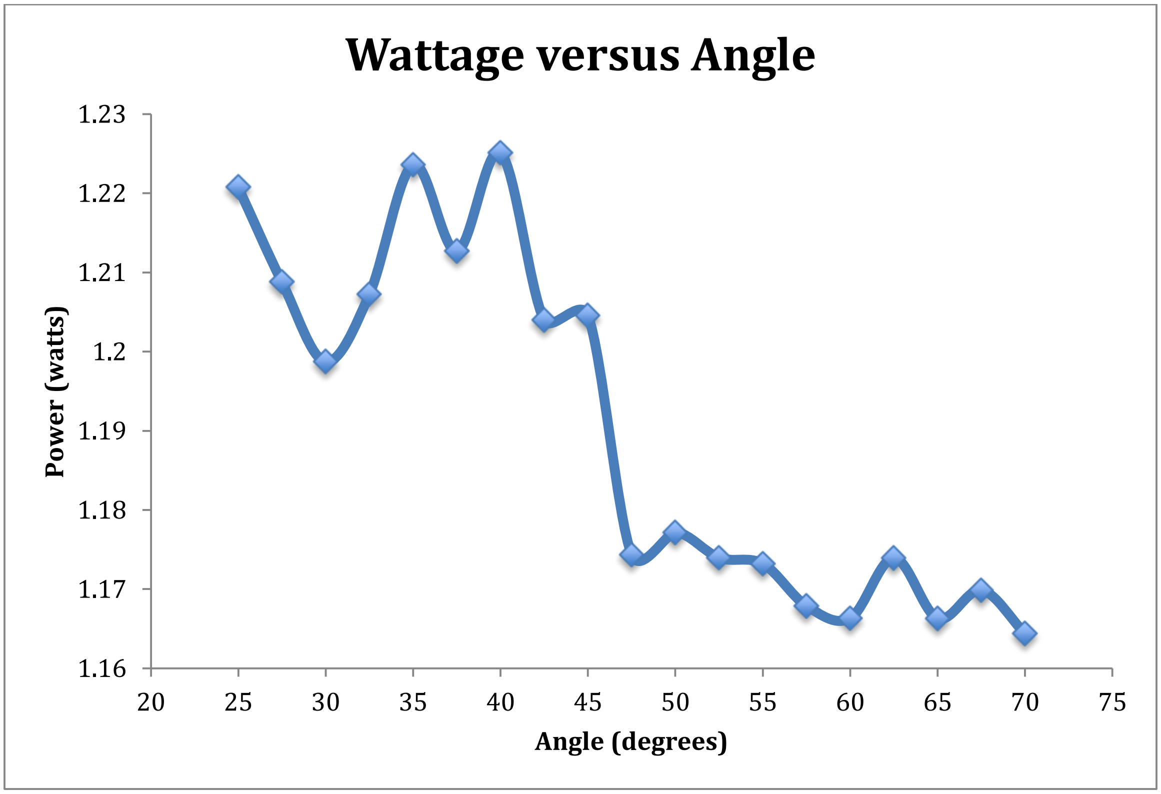

Figure 22: Manual Tracker Wattage versus Angle

As expected the wattage graph is similar in range to the voltage and amperage, with a maximum power output at 40˚ with a reading of 1.225 watts. This position is the experimental optimum position for power generation with latitude of 35˚. This will be further discussed in the conclusion section to ascertain why this was the peak degree.

The next figure is a three dimensional power graph to show the relationship between all the parameters. In figure 22 below, the maximum power output is summarized.

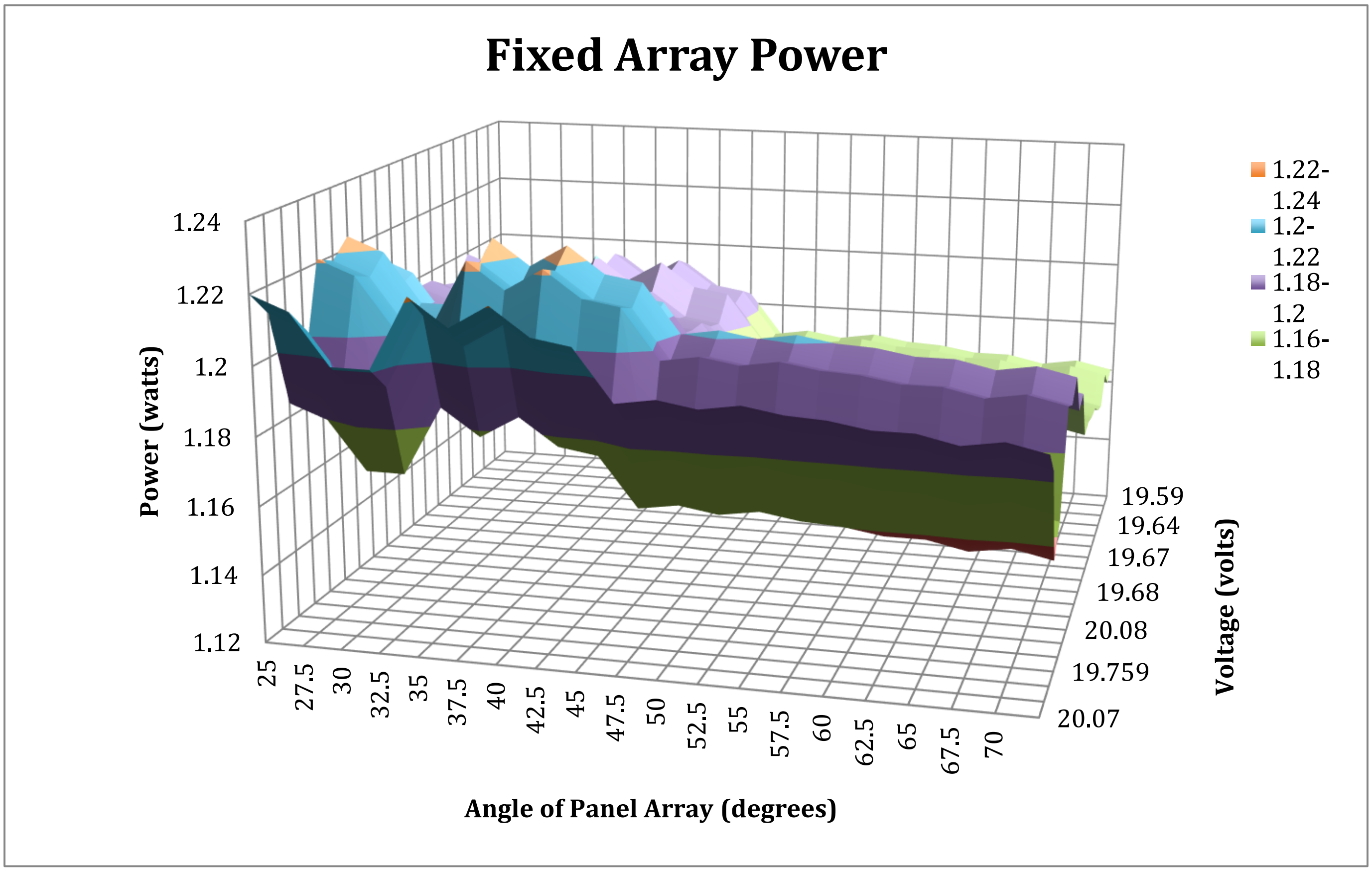

Figure 23: Manual Tracker Power Graph

Comparing the parameters of voltage, wattage, and the angle of the panel, allow for a visual representation of a heat map of the optimum range for power output. The main area of maximum power output is from 25 degrees to 40 degrees. However upon closer inspection, the highest cluster of power is from 35 degrees to 45 degrees. The following figure is a close up of the highest power output values in the range of 30 degrees to 40 degrees. Below that is a table containing the highest power value from the fixed tracker testing.

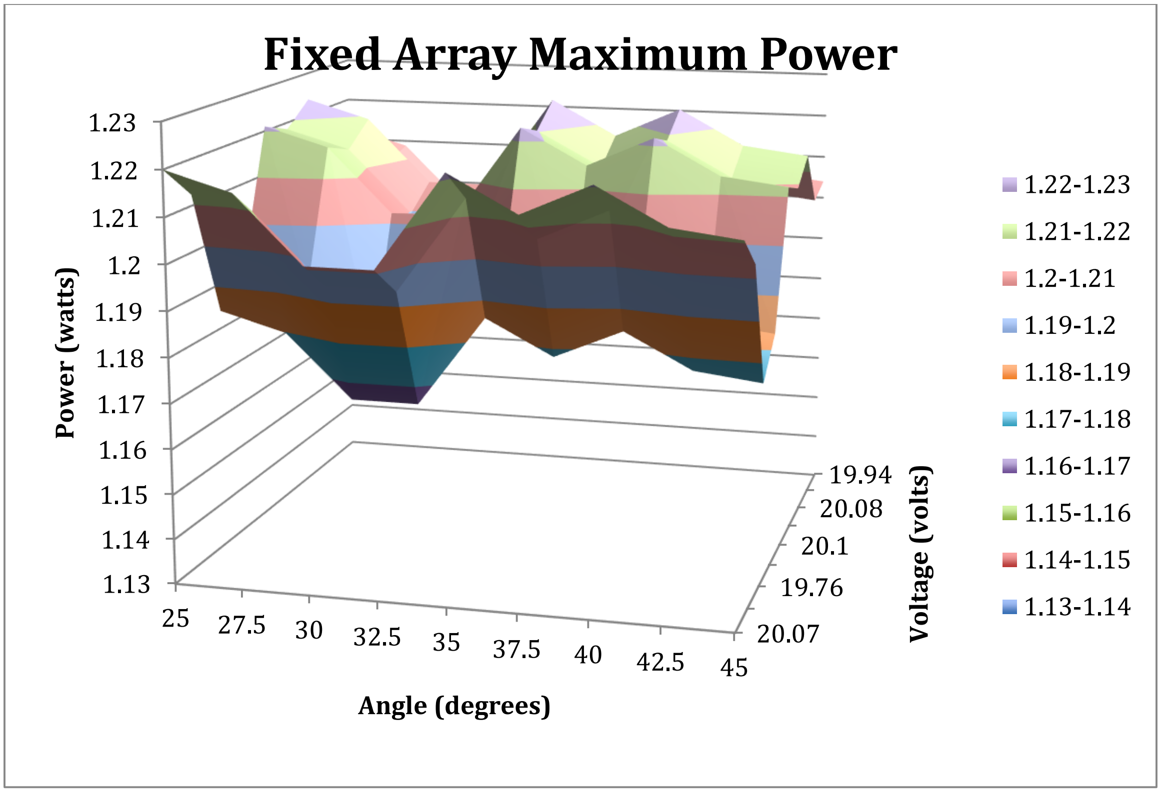

Figure 24: Manual Tracker Power Graph (30-45 degrees)

The power graph values were then summarized in value by the following table. Note the decline in value from 27.5 degrees to 37.5 degrees. The larger value for the 25 degree mark can be attributed to initial start of the instruments as well as the array initial connection to the instruments. The panel contained a small power charge, which could have led to a spike in the voltage and amperage readings. Accounting for the initial jump and disregarding the 25 degree value, there is a clear range of optimal power from angles 35 to 45 degrees with 40 degrees as the peak with an average of 1.225 watts. All of the readings can be seen below in Table 4.

Table 4: Summarized Angle Range for Fixed Array

Angle (°)	Voltage (V)	Amperage (A)	Power (W)
25	20.07	0.06079	1.22077
27.5	20	0.06041	1.208814
30	19.76	0.05899	1.168051
32.5	19.759	0.05936	1.1752981
35	20.1	0.06084	1.223618
37.5	19.97	0.06071	1.212686
40	20.08	0.06097	1.225115
42.5	19.95	0.06033	1.203996
45	19.92	0.06044	1.204558

The overall difference in power is small across the range of angles, however, the load generation circuit is used as a scale for larger panel array combinations and larger From the table, it was decided that the range of 35 to 45 is the optimal power range for the manual tracker when the tracker is fixed facing true south for power generation. Therefore the angle used for all tests, when comparing the manual tracker to the active tracker output, is 40 degrees facing true south. This will allow for an accurate representation of a fixed manual tracker used in both residential and commercial settings. This is what will be used to compare the active tracker over the course of a day. The next section will discuss the success of the active tracker over the manual tracker.

The day test consists of both apparatuses being used. The fixed manual tracker from the data above is set at 40 degrees facing true south for the entirety of the test. Each half hour beginning at 10:00 AM EST, the active tracker will be plugged in and will locate the sun. The manual tracker was placed at 40 with respect to the horizontal and the cardinal direction was true south. The following figures are Intensity Maps of both the Manual and Active Trackers.

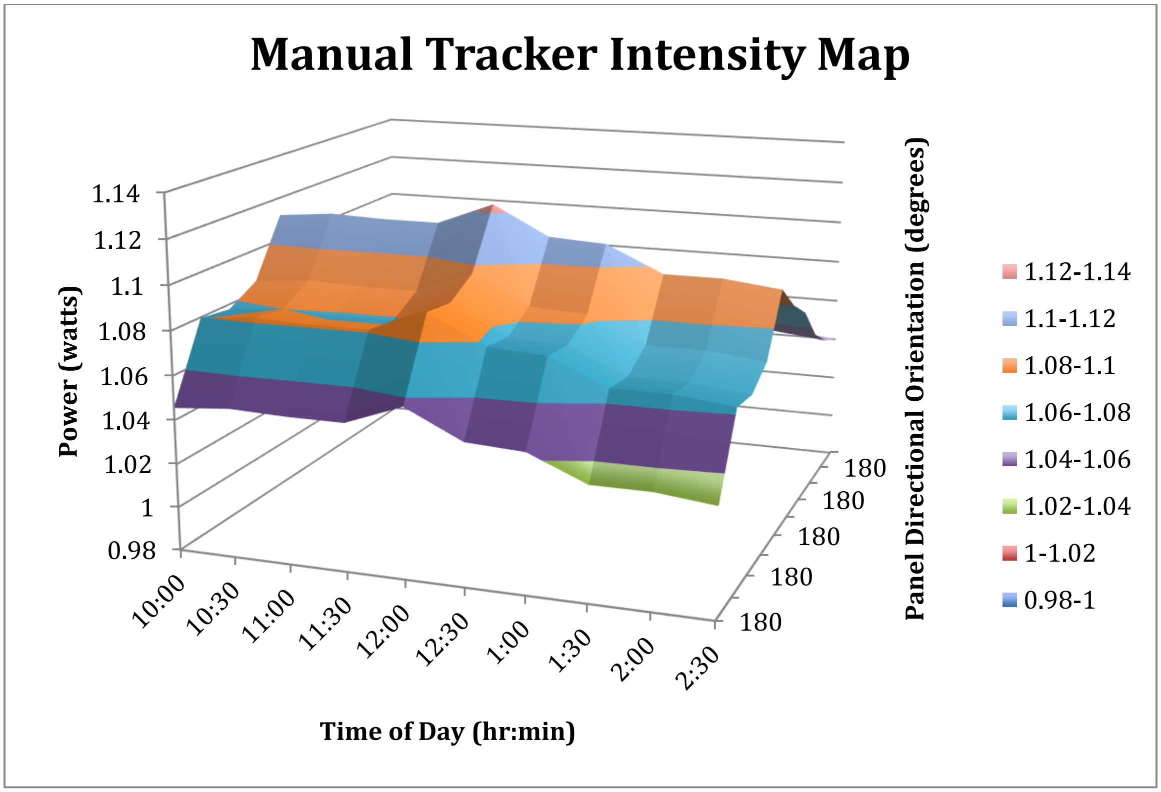

Figure 25: Manual Tracker Intensity Map

The x-axis of the intensity map represents the time of day as the tests were performed. The z-axis or the depth is the tracker's cardinal direction. For the manual tracker, all of the readings were performed at 180° south, explaining why this axis never changes. The key on the right color coordinates the ranges of power experienced by the panel. The manual tracker experienced an average maximum power of 1.12 watts, which is 9% lower than the original optimal angle tests. This can be attributed to cloud cover, the temperature of the day tests were taken, however is an accurate representation of the power rating over the course of the day. Noting also these tests were taken in mid March, after Daylight's Savings Time was observed, the azimuth of the Sun altered slightly form the original February tests. This change in the azimuth can account for the power loss, because as the sun rises higher in the sky, the angle needs to lessen to account for more rays to strike the photovoltaic cells at 90˚. The next figure is the intensity map of the active tracker over the same time span.

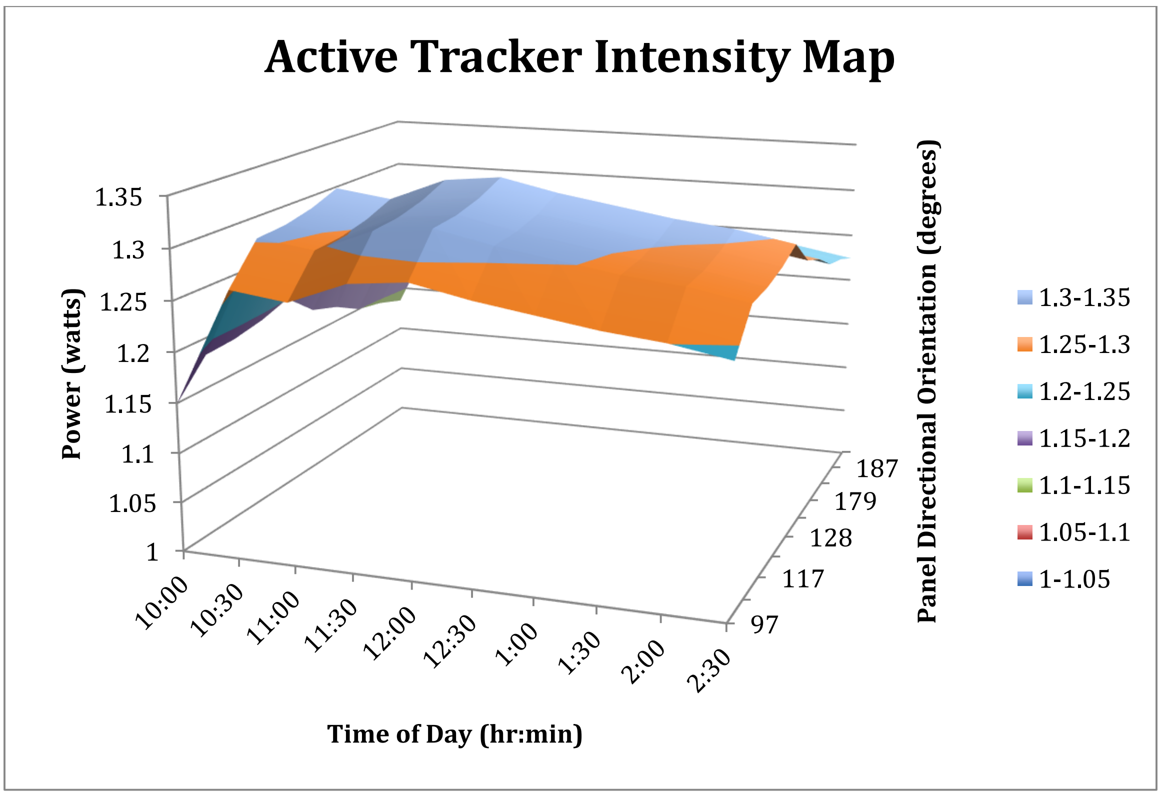

Figure 26: Active Tracker Intensity Map

Similar to the manual tracker, the active tracker map has the same axes. The cardinal direction increases throughout the day, as the azimuth of the Sun changes. For the active tracker, the gradient of power at the different times is less. This is to be expected, as the goal of the active tracker is to maximize the amount of photons hitting the photovoltaic cell at 90˚. The average maximum power reading is 1.34 watts. This value is 10% greater than fixed array during the optimal angle test and almost 20% greater over the hourly test. Overall the active tracker's lowest average value from 10:00 AM EST to 2:30 PM EST was 1.14 watts, which is around 2% greater than the maximum the manual tracker, was able to accomplish. The following table summarizes the average values recorded for both the active tracker and the manual tracker.

Table 5: Averaged Values from Hourly Tests

Type of Tracker	Active									
Time of Day	10:00	10:30	11:00	11:30	12:00	12:30	1:00	1:30	2:00	2:30
Direction (˚)	97	112	117	117	128	178	179	184	187	189
Angle (˚)	50	50	53	44	42	39	38	43	42	43
Voltage (V)	19.525	21.500	21.375	21.750	21.850	21.650	21.500	21.350	21.250	21.075
Amperage (A)	0.0589	0.0606	0.0607	0.0610	0.0615	0.0602	0.0597	0.0589	0.0586	0.0581
Power (W)	1.14904625	1.3029	1.2974625	1.32729375	1.343775	1.3022475	1.28355	1.2564475	1.24471875	1.2244575
Type of Tracker	Fixed									
Time of Day	10:00	10:30	11:00	11:30	12:00	12:30	1:00	1:30	2:00	2:30
Direction (˚)	180	180	180	180	180	180	180	180	180	180
Angle (˚)	40	40	40	40	40	40	40	40	40	40
Voltage (V)	18.88	18.92	18.90	18.90	19.08	18.85	18.83	18.63	18.63	18.58
Amperage (A)	0.0554	0.0572	0.0571	0.0575	0.0589	0.0582	0.0577	0.0568	0.0564	0.0560
Power (W)	1.045675	1.08099225	1.07919	1.0872225	1.1235175	1.09707	1.08667313	1.05743438	1.04951875	1.03927125

In the active tracker section of the table above, angles have a range from 53 to 38 on average throughout the day. As the time of day carries on, the active tracker had a tendency to move from east to west, true east being at 90 degrees and true south being at 180. On average, the active tracker was 18% better at generating power than the manual tracker when it was locked into place at 40 degrees facing true south.

Conclusions and Recommendations

The goals of this project were met and the apparatuses prove to be an effective means of demonstrating engineering principles through the use of solar panels. The scope of the project asked for a mechanism that can automatically optimize the position of a solar array for maximum electrical power output. The system should be able to adjust its position over time to follow the sun, and must be able to be mounted on uneven terrain. The results proved that the active tracker performs optimally against the manual tracker, and can be used both indoors and outdoors to demonstrate tracking capabilities. This apparatus will prove to be a valuable experiment and demonstration of principles for Dr. Margraves when discussing not only energy transfer concepts but also the difficulties when designing and prototyping an experiment.

The final apparatus for the manual tracker includes the tripod with the solar panel that can be rotated in any fashion to demonstrate solar power generation throughout the day. Furthermore the load generation circuit shows both visually with the LED bulbs as well as with the multimeter to calculate voltage, amperage, and wattage to give an intensity map or a number of comparisons in solar energy.

The final apparatus of the active tracker gave a higher power output than the manual tracker. The active tracker created the optimal scenario in the hourly tests, however some adjustments were made due to some complications with the tracking code. The LDR method of tracking was not precise enough to optimally set itself due to the inequality in the code. The average values of the LDR that are used to determine how many steps the servos should move were not large enough to constitute a step. The first step to counteract this issue was to place a tinted screen over the LDRs in hopes to lower the readings on the LDRs. However the issue was the difference in the average values rather than the values themselves. The next step involved altering the tolerance values in the code itself. Indoor with artificial light, when the apparatus was initially tested, the active tracker required a vertical tolerance of 20 and a horizontal tolerance of 10. This means that if the average of the top LDRs is 45 and the average of the bottom LDRs is 32 the servos do not move. One main issue arises inside with multiple light sources, the active tracker could sit in between two light sources with all of the LDRs and inequalities satisfied, however the panel would be sitting out of optimal positioning.

Once the apparatus was taken outside, another problem arose with the active tracker. When the active tracker was placed outside of optimal range, it would stabilize before it reached the best power output. Altering the tolerances of the active tracker helped, however there were still moments over the course of daily tests where the active tracker would stabilize and not follow the sun. A continuous check is required to ensure when the tolerances need to be altered. However as seen in the results, the active tracker was still able to average a 20% better power output than the manual counterpart. Furthermore the average power output for the active tracker was greater than the manual was ever able to accomplish. Therefore the final apparatus provided to Dr. Margraves will prove to be useful for both demonstrations and laboratory experiments for primary and secondary level education students.

The following is a list of recommendations to be made on both of the apparatuses to improve this project and similar tracking systems.

- Redesign a larger load generation circuit that will allow for a larger change in visual representation of power. Ideally the load circuit would output how much power it was experiencing rather than using a multimeter and inclinometer.
- Redesign the physical control circuit to include a stronger belt system and allow for omnidirectional movement. Furthermore more powerful servos that allow for more movement than 180˚ would benefit the omnidirectional movement. Additionally, it would be ideal if the power generated from the panel powered the control circuit so that the entire experiment would be self-contained.
- Add a potentiometer, or an adjustable resistor, which consists of a wiper that slides across a resistive strip to deliver an increase or decrease in resistance. This would allow for a change in the LDR inequality code to ensure that the issue of stabilizing due to the difference in value of what each LDR is experiencing.
- A complete redesign of the code, where the active tracker had a set path to rotate through taking readings at every point and then back tracking to the optimal position would ensure the active tracker to be in the ideal position at all points in time.

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2. Mousazadeh, Hossein, et al. "A review of principle and sun-tracking methods for maximizing solar systems output." *Renewable and sustainable energy reviews* 13.8 (2009): 1800-1818.

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Appendices

Appendix A: Bill of Materials

Bill of Materials			
Quantity	Product Description	Unit Price	Amount
1	Arduino Uno	27.79	27.79
1	Resistors	8.09	8.09
1	LED Assorted Colors	5.90	5.90
2	Aleko 15W Solar Panel	59.00	118.00
2	AmazonBasics 60-in Tripod	23.49	46.98
2	Turnigy™ TGY-R5180MG 180Degree MG Analog Servo 2.0kg/ 0.12sec / 12g	4.99	9.98
1	19 Gauge Wire	7.39	7.39
2	Proto Board	4.20	8.40
1	10pc Light Dependent Resistor	2.10	2.10
1	Misc Hardware	100.00	100.00
		Total	334.63

Appendix B: Testing Procedure

Manual Tracker

1. Remove the tripod from its carrying bag.
2. Open the telescoping legs such that the tripod can steadily stand.
3. Adjust the height of the tripod accordingly.
4. Remove the solar panel from its box.
5. Notice the quick-release mechanism on the back of the panel located at the center of the aluminum bracket. Slide the mechanism on to the quick-release holster on the top of the tripod. To ensure continuity, you should hear a "click" sounds from the mechanism.
6. With the panel connected, move the pan and crank handle of the tripod to confirm the panel is connected correctly.
7. Remove the load circuit box from packaging. Notice the Velcro on the top of the box and on the top of the tripod. Attach the load circuit to the top of the tripod in the associated Velcro patch.
8. Open the back of the load circuit box to expose the circuitry.
9. Notice the red and blue wires enclosed by the black cable shielding. Using the provided flat-head screw driver, proceed to attach the red wire to the terminal block labeled, (+), in the load circuit box.
10. First loosen the screw. Then place the wire into the terminal hole. Once wire is in the hole, proceed to tighten the screw.
11. Repeat steps 9 and 10 for the blue wire. However, be sure to attach the blue wire to the terminal block labeled (-).
12. Close the back of the load circuit box.

Active Tracker

1. Remove the tripod from its carrying bag.
2. Open the telescoping legs such that the tripod can steadily stand.
3. Adjust the height of the tripod accordingly.
4. This step requires two people. Remove the solar panel from its box.
5. Notice the quick-release mechanism on the bottom of the aluminum bracket. Slide the mechanism on to the quick-release holster on the top of the tripod. To ensure continuity, you should hear a "click" sound from the mechanism.
6. With the panel connected, notice that the sensor terminal blocks are hanging off the back the panel. Place each sensor into the correct Velcro area at each corner of the panel. The terminal blocks are labeled in accordance to their position.
7. The control circuit will be already connected via Velcro to the back of the panel offset from the nameplate. Utilizing the elementary drawing, verify that the connections are correct.
8. Verify connection continuity to the servo motors in accordance to the elementary drawing.
9. Remove the load circuit box from packaging. Notice the Velcro on the top of the box and on the top of the tripod. Attach the load circuit to the top of the tripod in the associated Velcro patch.
10. Open the back of the load circuit box to expose the circuitry.
11. Notice the red and blue wires enclosed by the black cable shielding. Using the provided flat-head screw driver, proceed to attach the red wire to the terminal block labeled, (+), in the load circuit box.
12. First loosen the screw. Then place the wire into the terminal hole. Once wire is in the hole, proceed to tighten the screw.
13. Repeat steps 9 and 10 for the blue wire. However, be sure to attach the blue wire to the terminal block labeled (-).
14. Close the back of the load circuit box.

15. Notice the two rubber bands at each servo is not connected to its associated pulley. Attach the rubber bands to their associated pulley warily such that the bands do not break.
16. Remove the USB to A/B cable from the packaging box, and connected the A/B male side to the microcontroller.
17. Connect the USB to the computer utilized to execute the experiment.
18. To verify continuity, the LEDs located on the microcontroller will turn on.
19. On your computer interface, open the windows explorer and venture to your C:.
20. Click Program Files (x86)
21. Click the Arduino Folder
22. Open the Arduino application.
23. From the top taskbar of the Arduino Interface click File>Open and navigate to the directory of the Solar Tracker code file, ST.ino.
24. Once the code is open, click Tools>Serial Monitor to display the serial monitor for the servo position tracking and the GUI.
25. Click Verify, to compile and upload the code to the microcontroller.

Appendix C: Ardunio Code

```
#include <Servo.h>

Servo Hservo;
Servo Vservo;

int currentpv = 90;   // initial position
int currentph = 90;
int LDRTL = A0; // LDR Top Left (frontview)
int LDRTR = A1; // LDR Top Right (frontview)
int LDRBL = A2; // LDR Bottom Left (frontview)
int LDRBR = A3; // LDR Bottom Right (frontview)
int toleranceh = 1;
int tolerancev = 3;

void setup()
{
 Serial.begin(9600);
 Serial.println("running");
 Hservo.attach(9);  // Attach XY direction servo to Digital output 9
 Vservo.attach(10); // Attach XZ direction servo to Digital output 10
 pinMode(LDRTL, INPUT);
 pinMode(LDRTR, INPUT);
 pinMode(LDRBL, INPUT);
 pinMode(LDRBR, INPUT);
 Hservo.write(currentph);
 Vservo.write(currentpv);
 delay(5000); // Delay 5 seconds for servos to intialize
}

void loop()
{
 //Analog Input Values
 int LDRTLS = analogRead(LDRTL); // reads analog inputs of LDRTL
 int LDRTRS = analogRead(LDRTR); // reads analog inputs of LDRTR
 int LDRBLS = analogRead(LDRBL); // reads analog inputs of LDRBL
 int LDRBRS = analogRead(LDRBR); // reads analog inputs of LDRBR

 //Average Values
 int AVGLDRL = (LDRTLS + LDRBLS) / 2; //Average values of the left sensors
 int AVGLDRR = (LDRTRS + LDRBRS) / 2; //Average values of the right sensors
 int AVGLDRB = (LDRBLS + LDRBRS) / 2; //Average values of the bottom sensors
 int AVGLDRT = (LDRTLS + LDRTRS) / 2; //Average values of the top sensors

 //For Horizontal Servo
```

```
 if((abs(AVGLDRL - AVGLDRR) <= toleranceh) || (abs(AVGLDRR - AVGLDRL) <=
toleranceh)) {
   //do nothing if the difference between values is within the tolerance limit
 } else {
   if(AVGLDRL < AVGLDRR)
   {
     currentph = --currentph;
   }
   if(AVGLDRL > AVGLDRR)
   {
     currentph = ++currentph;
   }
 }

 //For Vertical Servo

 if((abs(AVGLDRT - AVGLDRB) <= tolerancev) || (abs(AVGLDRB - AVGLDRT) <=
tolerancev)) {
   //do nothing if the difference between values is within the tolerance limit
 } else {
   if(AVGLDRB < AVGLDRT)
   {
     currentpv = ++currentpv;
   }
   if(AVGLDRB > AVGLDRT)
   {
     currentpv = --currentpv;
   }
 }

 if(currentph > 180) { currentph = 180; } // reset to 180 if it goes higher
 if(currentph < 0) { currentph = 0; } // reset to 0 if it goes lower

 if(currentpv > 180) { currentpv = 180; } // reset to 180 if it goes higher
 if(currentpv < 0) { currentpv = 0; } // reset to 0 if it goes lower

 Hservo.write(currentph); // write the position to servo
 Vservo.write(currentpv);
 delay(10);

 Serial.print(LDRTLS);
 Serial.print("---------------");
 Serial.println(LDRTRS);
 Serial.println("---------------------");
 Serial.println("---------------------");
 Serial.println("---------------------");
```

```
  Serial.println("---------------------");
  Serial.println("---------------------");
  Serial.println("---------------------");
  Serial.println("---------------------");
  Serial.print(LDRBLS);
  Serial.print("---------------");
  Serial.println(LDRBRS);
  Serial.println("");
  Serial.println("");
  Serial.println("");
  Serial.println("currentph:");
  Serial.println(currentph);
  Serial.println("");
  Serial.println("currentpv:");
  Serial.println(currentpv);
  delay(1000);
}
```

Appendix D: Active Tracker Control Circuit Drawings

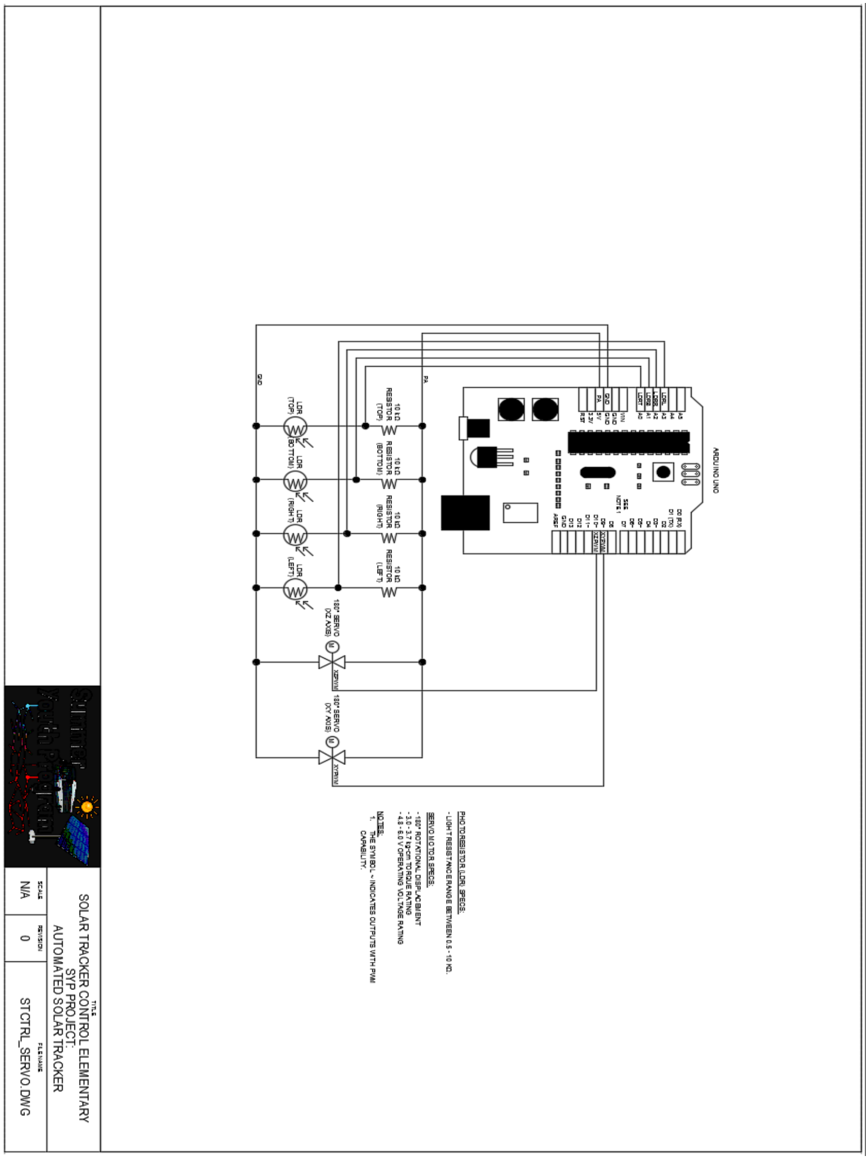

Figure A: Active Tracker Control Circuit Drawing

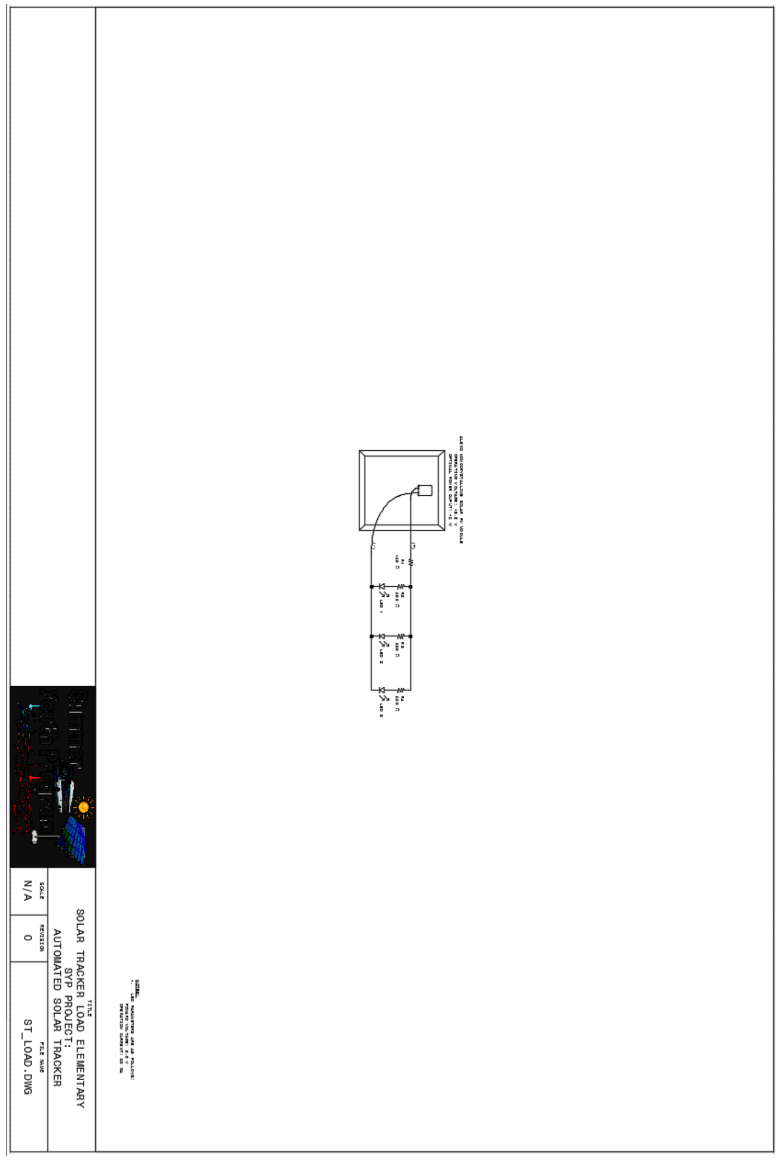

Figure B: Load Generation Circuit