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Concentrated Solar, Dual Axis-Tracking, Multi-junction GaAs Cell Photovoltaic System Design for Efficient Solar Energy Conversion

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Philip W. Swanson has received his B.S. in Electrical Engineering from the University of Southern Maine in December of 2014. His interest lies in the distributed application of clean energy technologies. He was founder and president of the USM Engineers Without Borders, a student group that focused on delivering clean energy to communities in developing countries. He lead a group that worked with an orphanage in Guatemala to bring solar power to the children of Hogar Rafael Ayau. Professionally, Philip has worked as an intern at Pika Energy, a company which designs and manufactures residential wind turbines and solar hybrid systems, which operate on a high voltage DC micro grid. Philip continues to work at Pika Energy and is aspiring to enter a graduate program in power electronics.

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Got accepted to the University of Southern Maine Electrical Engineering program in the fall of 2010. In the summer of 2013 received a technical internship at Clough Harbor and Associates and continued the internship throughout the year and into the following summer of 2014. Grew up in the town of York, Maine.

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Abstract

Inexpensive photovoltaic (PV) arrays make use of inherently inefficient mono-junction solar cells. Higher efficiency multi-junction PV cells are available but in small sizes and at much higher cost. One method of reducing the overall cost yet yielding a high efficiency is through an inexpensive concentrating device which focuses large amounts of sunlight onto a small sized but efficiently working multi-junction PV cell and running it at high concentrations. Using this method greatly reduces the surface area of the multi-junction PV cell needed to collect the solar radiation; this in turn allows for the higher efficiency panels to be utilized economically.
The primary goal of this work has been to design and build an inexpensive and experimental, dual-axis tracking concentrated solar photovoltaic system to show its economic feasibility. The secondary goal is to use the resulting sun-tracking mechanism as a platform on which other concentrated solar energy conversion devices (solar-thermo-electric, solar-thermo-mechanical, solar-thermo-chemical) can be tested for research and educational use in the future.

Relatively inexpensive common materials and simple manufacturing processes demonstrated that using a parabolic dish to concentrate solar radiation onto a tiny 1/2 cm^2 multi-junction solar cell chip would produce an electrical output greater than 8 watts. Excess heat generated is dissipated via a heat sink assembly the solar cell chip is bonded to. The system is made up from a scalable parabolic mirror, a microprocessor controlled dual-axis tracking mechanism which is guided by a four-quadrant home-made light sensor, and the multi-junction solar cell assembly including its heat sink. The parabolic mirror is designed by combining strips of off-the-shelf aluminum coated polycarbonate mirror material, all bent, positioned and held in a frame to reflect the light at the focal point where the multi-junction cell is fixed. The system follows the celestial path of the sun within 1.6 degree.

This project was completed as a senior capstone design project utilizing all of the education gained thus far in the engineering curriculum along with a large amount of self-directed learning. Every stage in the design and development of the project was an educational test that had to be overcome. Discussion on the short comings, challenges, and the use of the education received to resolve these issues are presented.

1. Introduction

Access to power namely, heat, and electricity is ubiquitous in developed nations. Much of the developing world however, still lacks access to these vital resources. Electrical power is increasingly essential for prosperity and thus must be provided to underserved regions to improve socioeconomic conditions. Although there has been much work both privately and publicly to provide these services to developing regions, there is increasing concern with the

effects of supplying demand using fossil fuels. These developing regions present an excellent opportunity to utilize clean power generation methods as energy costs are high and limited infrastructure exists. In many cases, their proximity to the equator makes solar power an excellent option.

The photovoltaic effect is the direct conversion of solar radiation into electricity by certain materials with exposure to light. Most PV cells are silicon based; however other materials including Gallium Arsenide can be used to achieve higher efficiencies as shown in Figure 1. These materials are inherently more expensive than silicon based PV. One method of increasing the electrical output per unit area and increasing efficiency is using a solar concentrating device which increases the intensity of the light seen by the solar cell. If executed properly concentrating can make this type of solar conversion more economical.
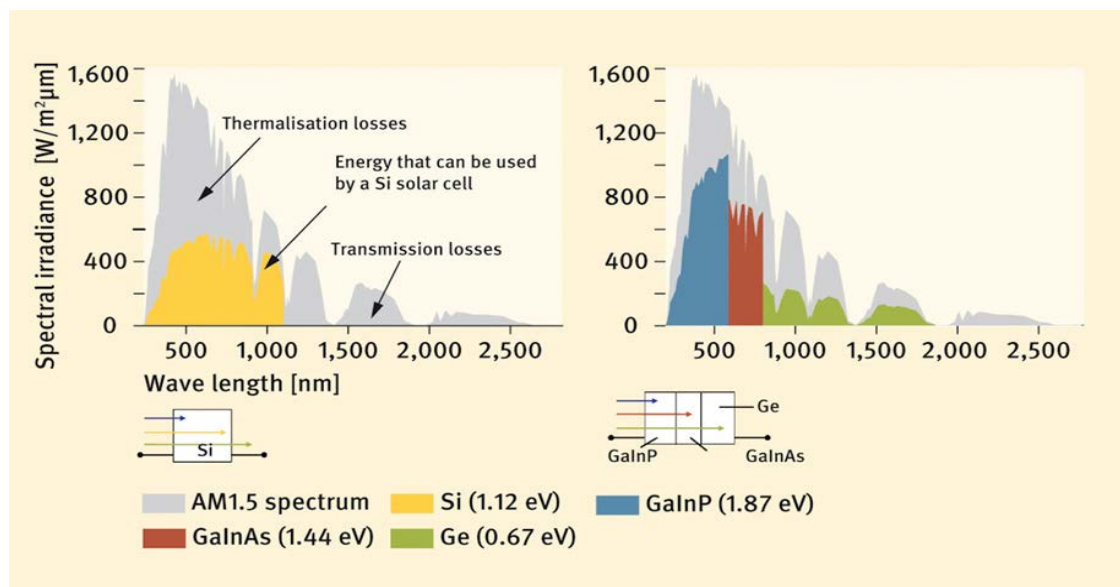

Figure 1. Comparison of wavelength absorption for Si, GaInP, GaInAs, and Ge solar cells

A combination of multiple layers of these more exotic materials assembled in tandem (series) can convert more solar energy into electricity with proven efficiencies of greater than 40% under concentration. This is accomplished by selecting different materials that react to separate wavelengths of the solar spectrum to capture more of the sun's total energy which is spread over a wide range of wavelengths as shown in Figure 1. However, highly concentrated solar radiation generates excess heat that needs to be removed from the panel to maintain efficiency. This can be accomplished by incorporating a heat sink. The heat can be transferred to a fluid using active or passive cooling. This provides the opportunity for future students to use excess heat generated for space heating, water heating, water purification or other useful purposes.

The students completing the project are members of "Engineers Without Borders" and had gotten a project approved for the installation of solar energy collectors at an orphanage in Guatemala. The orphanage's administration concerns are the high price of electricity and providing the children with a hot water supply. This device that was developed can not only generate electricity but can also be used to generate hot water for the orphans as well. This

project allowed the students to explore possible engineering solutions to real world problems that they were directly involved with.

This project included the research, design, and development of a device that would generate an electrical output from the sun utilizing a multi-junction solar cell. The desired outcome was to produce electricity at a greater efficiency than is realizable using silicon based PV. For this to be possible, an accurate parabolic dish, a functioning tracker, and a mechanical structure to facilitate the movement of the parabola assembly throughout the day were designed, constructed and tested.

Students were exposed to a wide range of engineering standards, practices, and tools. As part of The University of   Southern Maine's EGN402/403 Senior Design Capstone Projects, students were required to demonstrate the utilization of theory presented during their undergraduate education, as well as participate in extensive self-directed learning. Periodic reports were delivered to faculty advisors to ensure student were making progress, and moving in the correct direction. Students were evaluated using several metrics including: depth of research, ability to perform self-directed learning, quality of final project, as well as completion of a technical report, presentation, and poster.   The project was and will be featured at several University expositions including 2015 "Engineers Week Expo" held on March 14th, 2015, "Thinking Matters" on April 24th, 2015 . In addition to the course requirements, the resulting project will provide a theoretical and functional platform for further educational activities at the University including additional senior design work, and a platform for further study of multi-junction solar cells.

2. Design Considerations

Multi-junction cells are not commercially available to consumers in small batches. Our system design was dictated by the only multi-junction solar cells we could acquire, those manufactured by Sol-Focus [2].

From the onset of this project, budgetary considerations were always kept above all the other; the materials chosen during development largely reflect efforts to reduce the overall cost of the system rather than selection for optimal performance. The following sections detail the design process, limitations, and considerations while developing the final proof of concept.

2.1 The Parabolic Dish

A parabolic dish was necessary to concentrate the solar radiation to a focal point where the multi-junction cell was located. Manufacturing of a parabolic dish is particularly difficult without extremely specialized tools. The design goal was to develop a concentrator that would be realizable with the equipment and materials available at the University. The dish's geometry was designed to provide the proper energy density resulting in the maximum performance of the solar cell.

Multi-junction cells designed for concentrating solar applications performance varies as the concentration level increases. As shown in Figure 2, the efficiency of each layer of the multi-

junction cell increases as the concentration increases to maximum, at which point the efficiency begins to drop off. It has been shown in laboratory testing that the optimum performance of such cells occurs at concentration levels of approximately 400 times the power of the sun.
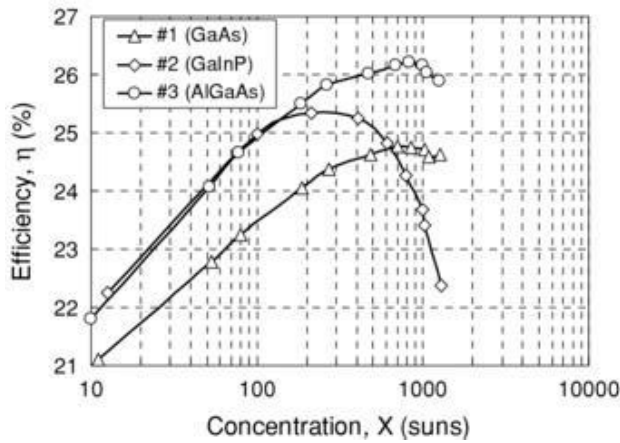

Figure 2. Efficiency of Gallium based solar cells over a range of solar concentration levels.

The dimensions of the parabolic dish were chosen to produce a focal region with a concentration of approximately 400 times the power of the sun to achieve maximum efficiency. The dish was oversized addressing several concerns. A larger dish would help to account for losses and imprecision in the manufacturing process. The resulting focal point would also be larger, ensuring the cell remained energized when the tracking device was not actively moving.

The parabolic dish was chosen to be a size of 50 cm by 50 cm to provide a focal area of 2.5 cm by 2.5 cm with the desired 400X concentration. The parabolic curve was determined after selecting a focal distance of 50 cm by using Equations 1 and 2 [3].

$$Parabolic\ equation\ y = (ax)^2 \tag{1}$$

$$Focal\ Point = \frac{1}{4a^2} \tag{2}$$

Using these two equations and the selected focal length the value of $a = 0.7$ was determined to provide a focal distance of 50cm above the lowest point of the parabolic dish. Using SolidWorks a conceptual model was developed. The parabolic dish consisted of two main components, the rib and the support, shown in Figures 3 and 4 respectively. Both of these pieces are two dimensional so they were easily machined using the CNC at the University's Skunk Works laboratory. Each of these pieces follows the parabolic equation $y = (0.7x)^2$.

Figure 3. Rib component parabolic in one dimension

Figure 4. The support structure displaying slots which mate with the rib
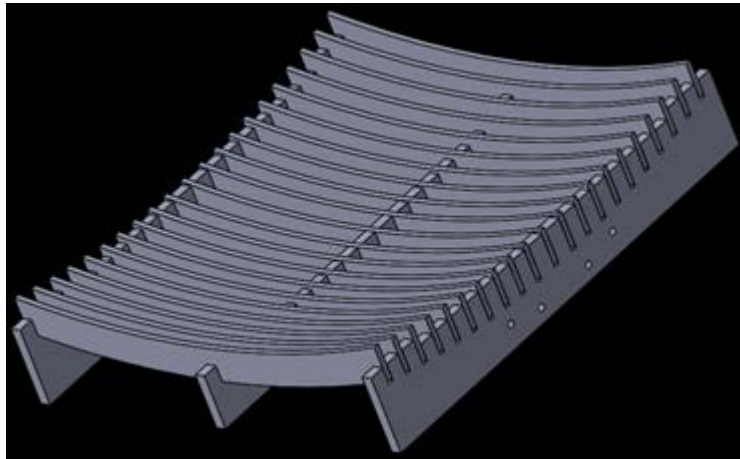to form a parabola in two dimensions

Figure 5. Completed assembly of parabolic frame

These two pieces were designed to slot into one another to create a parabolic surface in two dimensions. The completed parabolic dish of 21 ribs and 3 supports is shown in Figure 5. A reflective surface was obtained using an array of mirrors 2 cm wide affixed perpendicular to the ribs. The polycarbonate mirrored strips conformed to the guiding ribs creating a parabolic shape in the one dimension. The cumulative effect of these mirrors generated a parabola in the second dimension. The mirrors cut into 2 cm wide strips generated a 2 cm long focal line as opposed to a focal point. Then by positioning the solar cell slightly closer to the dish, the focal line comes out of focus and generates a rectangular shape. The proper position was chosen to produce a square focal area of 6.25 cm^2 which effectively generates 400X concentrated sunlight on that plane.

Solid birch plywood was used during manufacturing to reduce cost. Polycarbonate strips were used for the reflective surface. Polycarbonate provides a durable, inexpensive, flexible mirrored material that was optimal for this application. Figure 6 shows a photo of the assembled wooden parabolic dish, both with the polycarbonate mirrors (right) and without (left).

Figure 6. Parabolic mirror dish during assembly (left), after mirror strips are attached (right)

Designing the dish had many obstacles and challenges to overcome. The first consideration was how to design the lens to reflect light onto a smaller surface. In Physics II there was a section on optical lenses and their properties. As Physics II was completed in freshmen year digging through the textbook was necessary and provided the equations for the parabolic function along with the focal point location equation for reflective lenses. With those two equations in mind we set out to design a parabolic dish in two dimensions that would concentrate the solar energy 400X onto the multi-junction PV cell.

The biggest obstacle to the parabolic dish was how to acquire the parabolic shape in two dimensions. Creating a parabolic trough would be easier and was considered but the desire to have a focal point to match the dimensions of the multi-junction PV cell was favored. After a week of brainstorming and drawing designs two ideas emerged. One was to have evenly spaced steps that followed the parabolic equation on the X and Y axes and the other developed design was to have a curved piece on the X axis with angled slots cut into it for the curved pieces on the Y axis to slot into. Once both of these designs were discussed it was concluded that the combination of the two designs would be the best fit. As one can see there are slots cut in an evenly spaced step pattern following the parabolic equation on the X axis portion and the curved pieces that make up the Y axis portion slot into this piece thusly creating a parabolic dish in two dimensions.

To design the parabolic dish the use of SolidWorks would be needed. This was because the CNC machine available to the students can take SolidWorks designs and cut out the desired custom pieces. With limited working knowledge of SolidWorks several weeks of tutorials needed to be followed to gain the expertise to complete the design. After using the tutorials the ability to design prototypes was achieved and designs were sent to the CNC machine. The first downfall to the process was not setting strict dimensions to the design in SolidWorks which resulted in skewed dimensions in the custom made parts. The design was reprocessed and resent to the CNC machine and the custom made parts were now available for assembly.

To test the assembly it was brought out into full sunlight to see if there was a focal point. A piece of cardboard was placed a half meter above the surface and a clear focal point was visible. The focal point was also strong enough to set the cardboard on fire. During testing it was discovered

that the assembly was too weak and was starting to fall apart after minimal use. To fix the problem the slotted piece was thickened from quarter inch plywood to half inch plywood as well as extensions to deepen the slots at the far ends of this piece. After these modifications the assembly was stable and creating a strong focal point.

2.2 Multi-Junction Cell

The acquisition of a multi-junction cell was paramount to the success of this project. In an effort to obtain cells that would be suitable for our purposes, several US based manufacturers were contacted. All companies were unwilling to provide samples for academic research, or sell solar cells in small quantities. After searching for other possible sources, cells were located on E-bay. The cells were overstock from a company called SolFocus which had developed a concentrated solar array for retail sale. Because the cells were intended to be sold as an array, limited data was available about the material composition and individual performance. A data sheet was obtained specifying the output of a SolFocus array, VOC, ISC and other key parameters are presented in Table 1 below. The data sheet presented provides information pertaining to an array of 20 solar cells. The complete data sheet is available as a pdf [2].

Panel Specification	
Power	345 W ±5%

Panel Characteristics	
Nominal Performance Characteristics	
(850 W/m² DNI, 20°C Ambient, On-Sun)	
Voltage	51 Vmp
Current	6.8 Imp
Open Circuit Voltage	60.5 Voc
Short Circuit Current	7.4 Isc
Max System Voltage (US)	600 V
Max System Voltage (Europe)	1000 V
Power	-0.15 %/°C
Voltage	-0.086 V/°C
Multi-Junction Cells	20
By-Pass Diode	20
Length	1101 mm (43.35 in)
Width	1366 mm (53.78 in)
Area	1.50 m² (16.19 ft²)
Weight	32 kg (70.5 lbs)
Connector	MC Type 4

Table 1. SolFocus datasheet

Solar cell physics is a topic that is introduced in several courses including Electronics and Materials Science. This fundamental knowledge was utilized and expanded through the design and the solar tracker system.

2.3 MicroController

A Microcontroller was needed to process the signals generated by the tracking device and then send the desired signals to the motor drivers. The motor drivers provided power to the motors, orienting the parabolic dish normal to the sun. Several microcontrollers were considered, including the Arduino Uno, the MSP430, and Microchip's XLP PIC. These microcontrollers were investigated based on usability, low power features, and signal processing capabilities.

The Arduino Uno has become a popular choice for hobbyists in the recent years, primarily because of the vast amount of open sourced code available to its users. This microcontroller was sufficient to operate our device, including necessary features such as an analog to digital converter (ADC) and an associated multiplexer. The Arduino Uno lacks a debug feature which was desirable during code development and product testing. The Arduino Uno also lacks an attractive low power mode that is available in TI's MSP430 and Microchip's XLP PIC.

Microchips XLP PIC or extreme low power PIC, also had the necessary features to implement the solar tracker, and included the low power mode, which would be necessary to complete a device that would use as little power as possible during operation. In addition, Microchip also provides a powerful debugging tool that allows for efficient code development. However, in order to use Microchips products a programmer was necessary, which was not available without an additional purchase.

Ultimately TI's MSP4302553, shown in Figure 7, was chosen. The MSP430 is equipped with 16 digital and analog input/output pins, an ADC and multiplexer that will handle up to 8 inputs, and the lowest power consumption of any microcontroller available. In addition, the University of Southern Maine instructs a course using the MSP430, and thus the development platform is familiar to students. As this project was intended to be developed and used for academic purposes the MSP430 was the optimal choice.

Figure 7a. MSP430 (large black chip) mounted on TI's LaunchPad
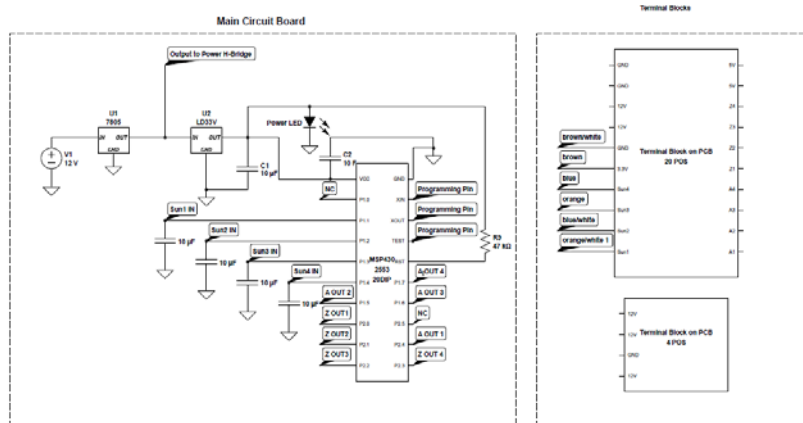
Figure 7b. MSP430 Control Circuit Diagram

The program that was developed to control the tracker will form the basis for a project that will be completed by all electrical engineering students in there coursework for the undergraduate class Microcontrollers and Embedded Systems. This course aims to introduce students to the architecture, function, applications, and programming of embedded systems, namely the MSP430. A simplified version of this project will provide a framework for future students to explore microcontrollers through a hands-on project.

2.4 Control Logic

A "C" based program was developed using the Code Composer Studio (CCS) platform to operate the motors and receive data from the tracker. It was necessary in certain instances to use assembly code to initiate the inputs and outputs, activate the ADC, and generate interrupt routines. The ADC on the MSP430 was used to convert the voltage signal generated by the photo-diode into a binary number between the values of 0-1023. This data was then manipulated using software to produce the desired movements in the stepper motors.

Presented below in Figure 8 is a simplified flow diagram of the control logic. The program is initialized by sending a binary code to the motors. This energizes the motors and ensures that the device remains static during startup. Signals are then processed from the solar tracker using the ADC. Because the precision of the ADC far exceeds the photo-diodes accuracy, the raw values were then rounded to a value between 1 and 12 using the floor command. Using the floor command reduces the gain on this control loop ensuring equilibrium will be reached when the tracker is in the correct position.
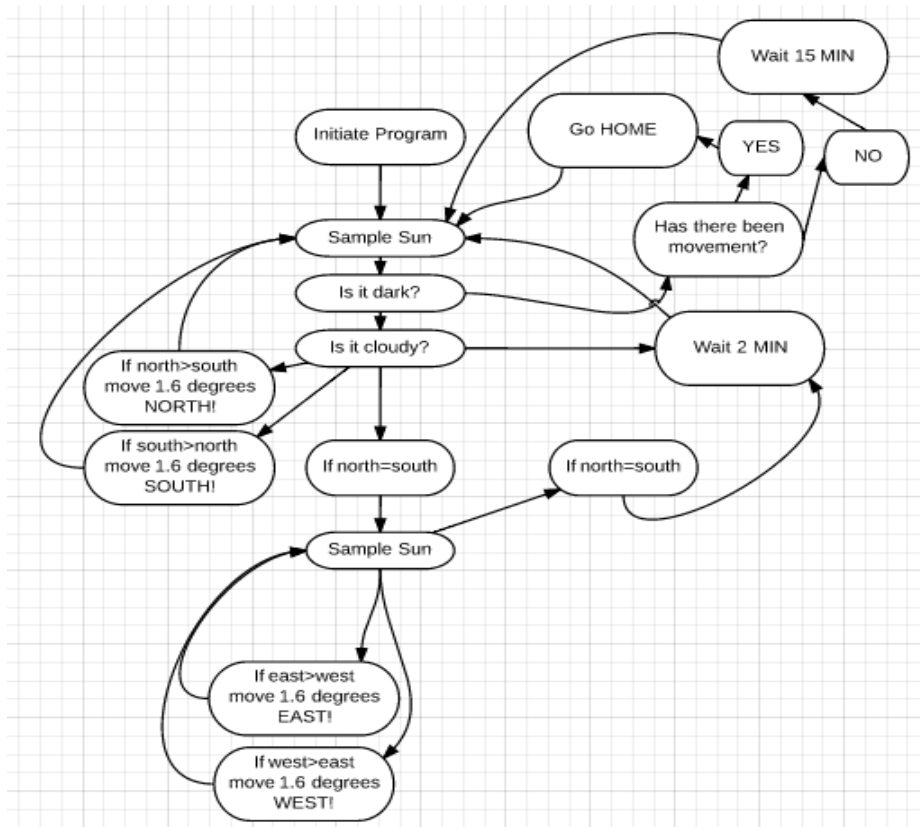
Figure 8.   A simplified flow chart of the microcontroller logic

Within the program two thresholds are initialized, these include the "dark" condition and the "cloudy" condition. In the case of the dark condition, if the sum of the inputs is below the "dark" value, the program will enter a waiting state of 15 minutes before sampling the sun again. As the program enters this 15 minute waiting state, a check is made to see if there has been any movement previous to the last time the state had been entered. If there has been movement, the device will enter the "go HOME" function.   The "go HOME" function will cause the motors to move back the number of steps that have been taken in order to reposition and orient to where the sun is expected to rise the next day.

The "cloudy" threshold ensures that the solar tracker will not endlessly search for the sun during cloudy conditions. If there are clouds in the sky, the diffuse light does not produce a strong focal point for the multi-junction making it undesirable to operate. The diffuse light does not produce a clear shadow making it difficult to track subsequently, a waiting state is necessary during these conditions. Because the diffuse light will illuminate the four photo-diodes relatively evenly, each individual photo-diode is compared with the cloudy value. If none of the four sensors read a value greater than the "cloudy" threshold, the program will enter a 2 minute waiting period before sampling the sun again.

If both the "cloudy" and "dark" thresholds are exceeded, then the tracker will utilize the data from the four photo-diodes to begin orienting itself towards the sun is step increments of 1.6 degrees (slightly greater than the accuracy of the tracker). The north and south values are compared, if one value is greater, than the horizontal axis motor will move the device in that

direction. This loop will repeat in this fashion until both values are equal, which equates to an alignment with the sun with respect to the axis of movement.

The east and west values are then compared and a process similar to the one described above occurs. Again, once both these values are equal, the tracker is aligned with respect to that axis. The tracker program then goes into a two minute waiting period before checking the values of the tracker again. For each step of the motor a variable's value is increased corresponding to the direction of movement. It is this value that is used during the "go HOME" command when the "dark" program is tripped. For testing purposes, the speed of the motors, and time of the waiting periods can be adjusted, which facilitates ease of testing.

The authors can be contacted for a copy of the complete "C" based program developed for the MSP430, using Code Composer Studio.

2.5 Stepper Motors and Motor Drivers

Motors were necessary to orient the parabolic dish normal to the sun, and keep the resulting focal point directly on the solar cell. Stepper motors provide extremely accurate movement, with high torque. Adding an additional gear ratio to the stepper motors decreased the effective step size, and increased applied torque. The selection of the NEMA 17 was based on the torque to cost ratio. The model selected provided the highest torque with the lowest cost. The selected NEMA 17 has a rated holding torque of 65 N.cm, phase resistance of 1.6 ohms, maximum current draw of 2.2 Amps, and an operating voltage of 12-24V (NEMA 17).

Motor drivers were also necessary to provide sufficient voltage and current to the motors in the required sequence. The motor drivers selected shown in Figure 9 utilize the Keyes L298 H-bridge, which provides 12V-24V and is rated for currents up to 2.5 amps per coil. The driver PCB also includes the necessary heat sink ensuring the chip doesn't overheat.
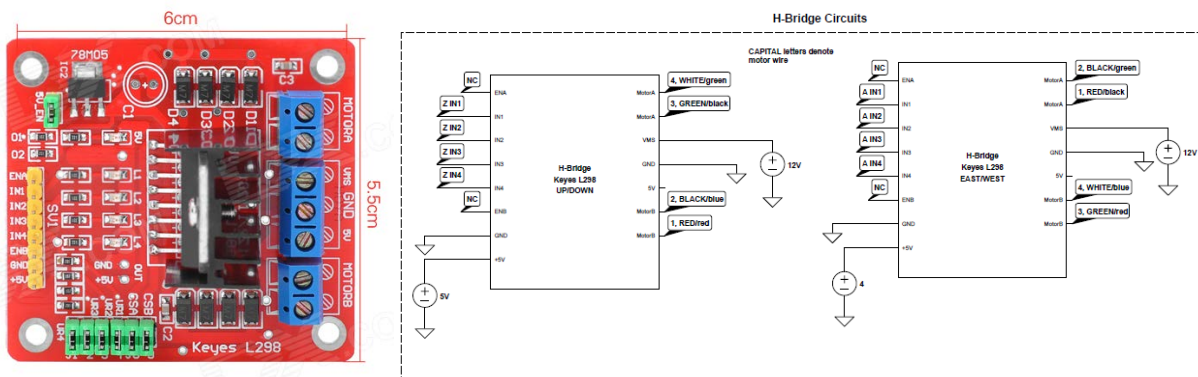

Figure 9. Pre-assembled motor driver circuit board containing the L298 H-bridge

2.5 Quadrant Tracker

A quadrant tracker was chosen as the method of collecting data describing our position relative to the sun. Presented below in Figure 10 is the circuit diagram and in Figure 11 two images showing the solar tracker from two orientations.

The tracker consists of three primary components the quadrant divider, the operational amplifier circuit, and the small photo-diodes located in all four quadrants. The quadrant divider is used to cast shadows on the four photo-diodes producing a variation in the voltage developed. These voltages can then be used to determine which direction to move to orient the parabolic dish normal to the sun. When all four values are equal, the quadrant divider will not cast shadows on any of the photo-diodes.
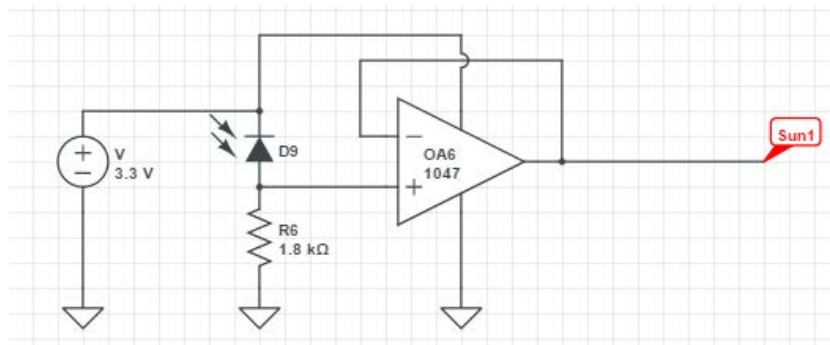

Figure 10. Buffer amplifier circuit utilizing a single rail operational amplifier

$$\text{Accuracy} = \tan^{-1} \frac{Width \; of \; Sensor}{Length \; of \; Shadow} = 1.43 \; degrees$$
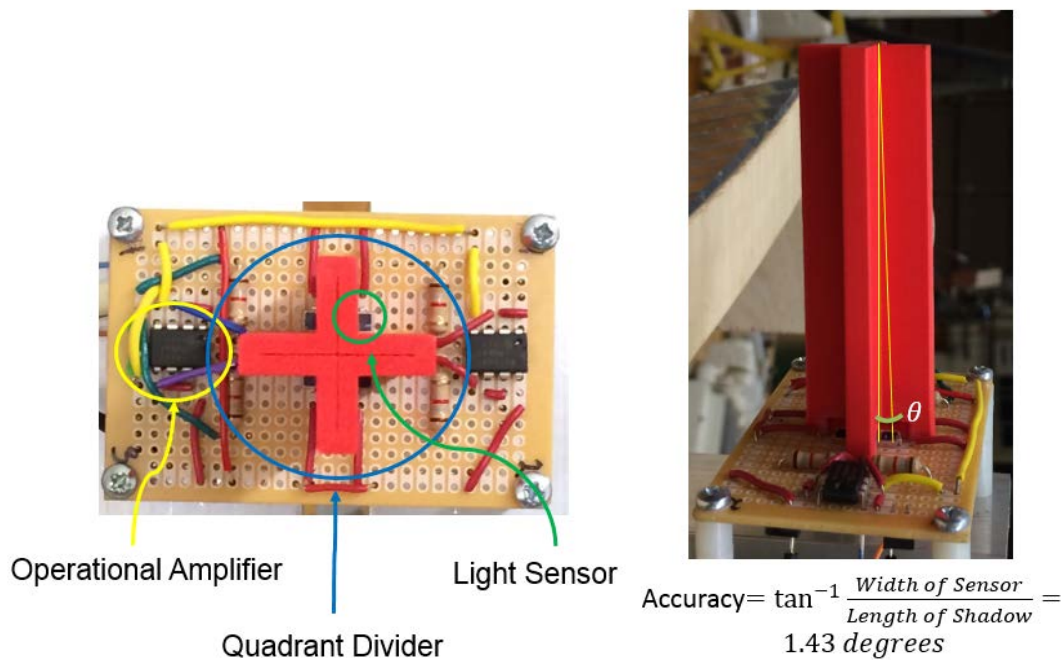
Figure 11. The quadrant tracker: A view of the tracker looking perpendicular to the parabola (left), A view displaying the angular accuracy (right)

The quadrant tracker was assembled on a solderable breadboard using two single-rail dual op-amp chips, and a 3-D printed quadrant divider. 3-D printing provided an inexpensive method of developing a working prototype which could be easily modified in SolidWorks and then reprinted pending necessary changes. The accuracy of the device is a function of the shadow length as well as the width of the photo-diodes. This was later improved by recessing the photo-diodes slightly under the quadrant divider (as seen in Figure 11, right), which reduced the effective angle necessary to cast a shadow on the photo-diodes. The overall accuracy of the device was determined to be approximately 1.4 degrees.

The electrical components were assembled in a NEMA rated outdoor enclosure with water tight wire glands. The entire system operates on a single 12V power supply, utilizing two voltage regulators to provide 3.3V and 5V. The solar tracker and the microcontroller circuits operate on 3.3V and the LN-298 H-bridge is powered using 5V. 12V is provided to the motors, which is regulated by the LN-298. The complete circuit diagrams showing all components and connections were given in Figures 7 and 9 above.

2.5 Mechanical Assembly

The mechanical assembly design was determined after the above individual components were designed. Out of all the components the mechanical assembly was the most fluid, and this design had several iterations through the process as the tracker was developed. As changes were made to the parabolic dish and motor configurations, the assembly was redesigned to accommodate.

The assembly was required to allow motion with two axis of freedom for the dual-axis tracking effect. An industrial turntable was utilized for the azimuth movement, and two pillow blocks with a shaft were used for the zenith movement. The full assembly is shown in Figure 12.
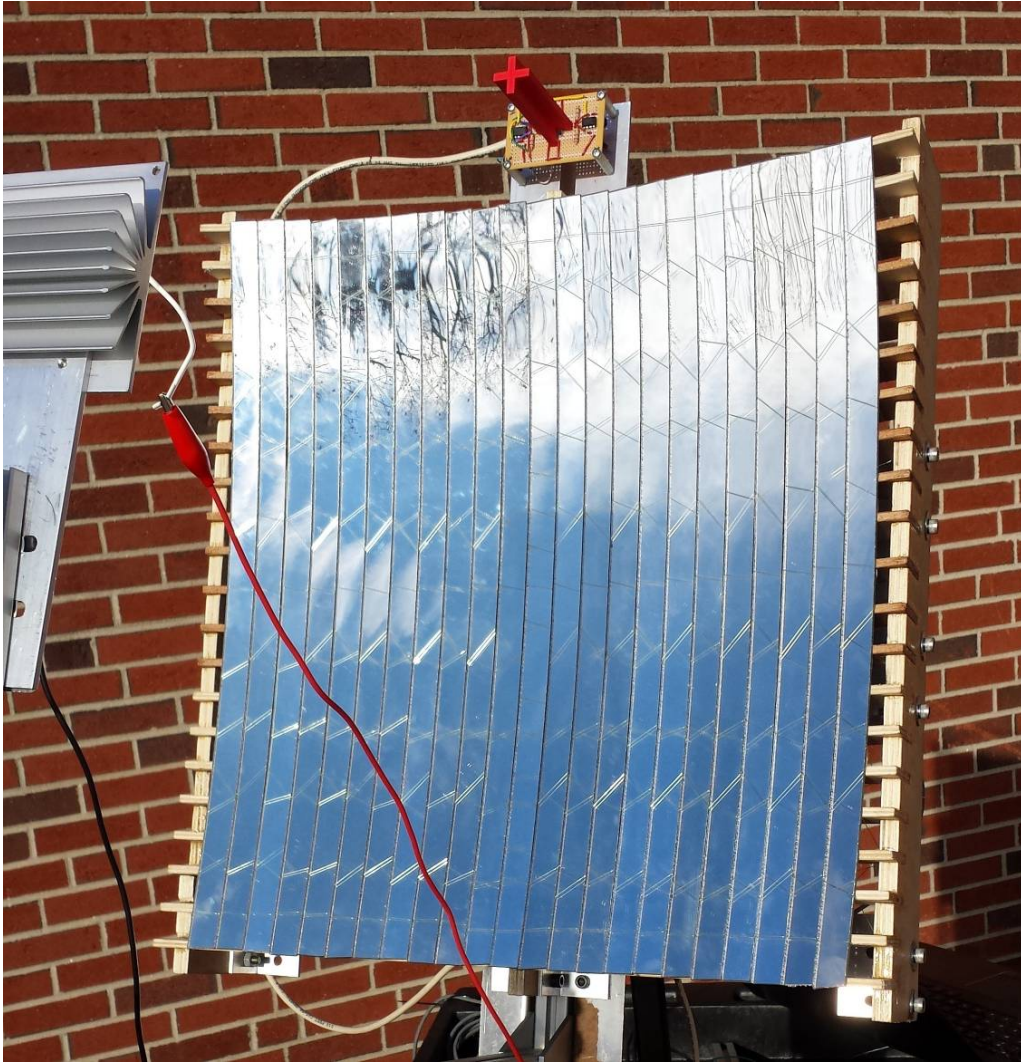
Figure12. Completed proof of concept design of the concentrated solar PV assembly

3. Experimental Setup

The project's separate components detailed above were then assembled into a functioning device. Tests were performed on the device under a variety of conditions. The first test conducted was designed to evaluate the tracking performance. Tracking testing was performed at an ambient temperature of 22 degrees Celsius using artificial sunlight with the parabolic dish assembly disconnected. This reduced the load on the motors, minimizing the potential damage if a failure resulted. Artificial sunlight was provided by a flashlight, and a PC was used to monitor the CCS program.

Tracking capabilities were then tested under the full load of the parabolic dish, in full sunlight and for an extended period of time. The test was conducted at an ambient temperature of 2 degrees Celsius with light and variable winds. This test provided an opportunity to observe the

location of the focal point relative to the parabolic dish and to do basic heat generating testing on combustible materials. A GoPro camera was used to monitor the tracking for the duration of the test.

Once it was confirmed that the tracking system was working properly and there was a stationary focal point relative to the parabolic dish, the first focal point test was performed. The test was conducted with an ambient temperature of 2 degrees Celsius beginning under full sunlight and transitioning to a mostly cloudy sky with light and variable winds. An infrared thermal camera was used to monitor the temperature of a thin metal plate painted black. A welding helmet was used to provide a safe method to view the concentrated light.

The final test was to gather power output from the solar panel. This test was done under the conditions of full sunlight in an ambient temperature of 2 degrees Celsius with light and variable winds. The materials required were a variety of power resistors, a multi-meter and a PC to store the gathered data and perform calculations.

4. Procedure

To ensure design criteria were met, several experiments were designed and executed. Key functionality was examined using both artificial light and natural light. The fully assembled device was tested using a flashlight to ensure that the motors aligned the tracker in the correct position. The data collected during this test was purely qualitative.

The tracker was then brought outside and allowed to track for a period of approximately 4 hours. During this period photos were captured every 10 seconds to monitor the position of the device. The photos were then assembled into a time lapse video, allowing a qualitative evaluation of tracking performance and focal positioning.

The focal point was examined using a thermal camera and a very thin black metal sheet. The metal sheet was placed at the focal point while the device was in direct sunlight. The focal point was captured using the thermal imager. The size and temperature of the focal point was extracted from the images and was compared to analytical results. Open circuit voltage and short circuit current measurements were collected for the solar panel with and without the lens that came with the purchased panels.

Finally the device was again placed outside in direct sunlight on a clear day. The output of the device was monitored recording both the voltage and current. For each test a different resistance value was used as a load. Voc, the voltage across the resistor and Isc, current through the resistor were measured. The product of the voltage and current provided a calculated output

power. The results produced a power curve identifying the maximum power output, the fill factor, and the efficiency of the device.

5. Results

During the motion testing of the tracking device, video evidence confirmed acceptable tracking behavior. The video of the device tracking over a four hour period is available on YouTube using the following link, Time Lapse Video. This tracking behavior was also exhibited during power testing, as all measurements were obtained while the device was self tracking, and the power output was verified continuously during testing by measuring Voc and Isc to normalize the results.

During the temperature evaluations several measurements of interest were collected, including the temperature of the heat sink during operation and the temperature of the metal sheet used to analyze the focal point. It was determined that during operation the temperature of the heat sink was approximately 48 degrees Celsius. The temperature of the plate reached a maximum of 350 degrees Celsius. Figure 13 displays the maximum temperature of the heat sink during operation, 47.9 degrees Celsius. Figure 14 displays a white region, representing the focal point. The white reading indicates that the maximum temperature was out of range of the thermal camera when the image was captured.   During subsequent tests a maximum temperature of 350 degrees Celsius was measured.
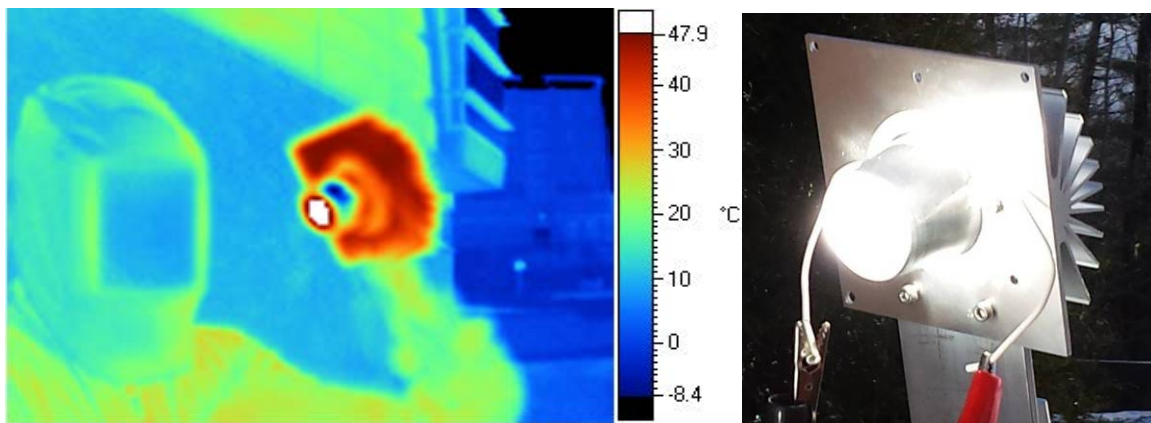

Figure 13. (Left) Thermal image of student observing the multi-junction cell with lens attached, student is wearing personal protective equipment, (Right) Photo of the PV cell and its heat sink assembly being illuminated with concentrated sun light
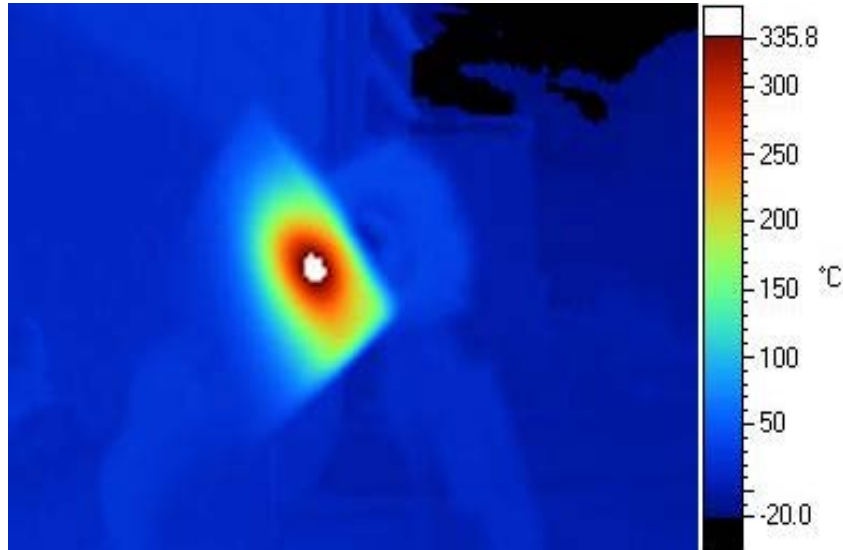
Figure 14. Thermal image of a thin metal plate, showing approximate size of focal area

During all test conditions it was assumed 500 Watts/m^2 of insolation which equates to approximately 20 Watts/cm^2 in the focal region. Preliminary power tests were performed on the solar panel with and without the lens. With the lens on the device the open circuit voltage was 3.2 volts and the short circuit current was 3.43 amps. No tests were performed under load, however using the calculated fill factor it is estimated that the cell's output with lens would produce a maximum power output of 8.25 watts. The lens area was 4.91 cm^2 leading to an overall system output efficiency of approximately 8.4%.

Further testing was conducted to examine the performance of the lens. It was determined that the geometry of the lens was creating hot spots on the solar cell chip. This is due to the fact that this lens was designed for light coming in at a specific angle which is nearly perpendicular to the solar panel. SolFocus developed a system using a primary and secondary mirror resulting in rays nearly perpendicular to the lens. In contrast to this device, where there is only one parabola and an arm that holds the panel above the parabolic dish. In this configuration reflected light will not enter the lens at the appropriate angle.

The lens did increase the amount of light collected as well as increase the power output, however the efficiency was reduced. The decrease in efficiency is attributed to uneven distribution of the light due to the complex geometry of the lens. The inability to measure the lens's effects accurately lead to testing without the lens on the solar cell.

Without the lens on the solar panel, open circuit voltage was measured at 3.01 volts and the short circuit current was measured at 0.762 amps. These collected measurements were used to normalize the values for voltage and current gathered during power output testing.

Power output data collected is presented in Table 2 below, which displays the value of the resistor load, the voltage across the resistor and current through the resistor. The final column shows the output power in Watts.

Power Testing Results			
Resistance	Voltage	Current	Power
0.0001	0	0.762	0
1.303	0.965	0.75893566	0.73237291
2.14	1.51	0.75373984	1.13814715
2.5	1.852	0.762	1.411224
3	2.18	0.75045455	1.63599091
3.33	2.45	0.74465863	1.82441365
3.75	2.545	0.68952717	1.75484666
5	2.732	0.55455526	1.51504496
7.5	2.74	0.37424284	1.02542538
10	2.883	0.29220325	0.84242198
15	2.868	0.20457102	0.58670969
20	2.845	0.16615038	0.47269782
10000	3.01	0	0

Table 2, output data collected during power testing

6. Discussion of Results

Testing of the device confirmed that the microcontroller logic and overall design was sufficient to produce power and keep the focal point centered on the multi-junction cell. Presented below in Figure 15, is a representation of the power output. The curve generated displays the output behavior of the solar cell for a variety of load resistances. The point on the graph which is marked with a yellow star denotes the point at which the maximum power was generated. This maximum output of 1.82 Watts was found with a resistance of 3.33 Ohms. The point on the graph marked with a yellow dot is the product of the Voc and Isc. From these two values the fill factor can be determined using Equation 3.

$$Fill\ Factor = \frac{Maximum\ Power\ Output}{Voc*Isc} \tag{3}$$

From the output data collected the efficiency of the solar cell was able to be confirmed. This is measured by the percentage of incoming solar energy hitting the cell compared to total electrical output. With an estimated $500 Watts/m^2$ the efficiency of this cell was approximately 36.4%. It should be noted that a pyrometer was not available during testing and that a more accurate measurement of the insolation could not be obtained to verify this result.
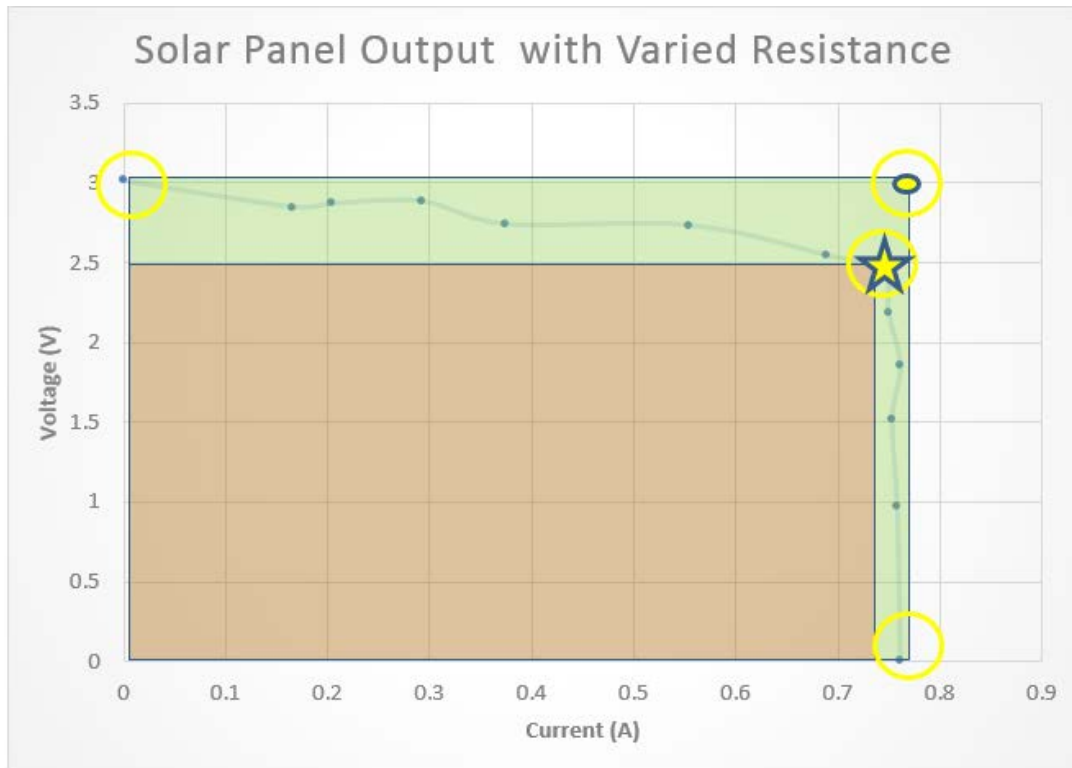
Figure 15. PV cell's I-V curve measured highlighting its Voc and Isc values
and the maximum power point,

During indoor testing the dark threshold value function worked correctly and the tracker would consistently travel back to its starting position. The cloudy value was also shown to work correctly during hazy and cloudy conditions.

7. Conclusions, Discussions and Summary of Educational Impact

7.1 Conclusions and Remarks

The resulting assembled device met the design requirements set forth at the beginning of the project. The concentrated cell efficiency was estimated to be greater than 36% which far exceeds the efficiency of a silicon PV cell. The tracking device worked as designed, and kept the focal point on the multi-junction cell during operation.

The project presented here provided an excellent opportunity to investigate many of the key skills developed in an undergraduate electrical engineering program. Analytical and computer aided electrical design techniques were utilized. Mechanical modeling programs such as SolidWorks played a vital role in the design and manufacturing of many of the key components of the device.

Students were exposed to many of the tools commonly found in an engineering and manufacturing setting including manually operated mills and computer operated milling machines.

Concepts of project management, and budgeting both time and money were essential to the success of this project. Standard engineering tools such as Gantt charts, and design journals were developed and utilized to ensure the project was completed on time and within budget. Design journals were created for multiple aspects of the project including, mechanical design, electrical design, code development, and CAD development.

Standards are an important aspect of any engineering project. Standards presented by OSHA were observed when ever working in dangerous settings, personal protective equipment was worn at all times.

When solar panels are manufactured for sale to consumers, the data regarding output and cell characteristics must be tested and clearly displayed. Two popular standards are used for testing solar devices, the STC or Standard Test Conditions and the NOCT or Normal Operating Cell Temperature. These test conditions, although not realistic in normal operating conditions, do provide the consumer with the ability to compare products with some level of consistency. During testing these conditions were not obtainable for several reasons. First, without extremely specialized equipment concentrating solar arrays cannot be tested in laboratory conditions, because a light source producing parallel rays is required. When testing the device outside, it was winter in December, and the ambient temperature was far less than the STC and the cell temperature was higher than that specified in the NOCT. Despite these restrictions the data obtained is presented below in Table 4 with a format similar to what one would find on a solar panel for retail sale.

Parameter	Rating
Voc	3.01 (V)
Isc	0.764 (A)
Max Power Current	0.745 (A)
Max Power Voltage	2.45 (V)
Max Power Output	1.82 (W)
Max Cell Efficiencey	36.40%

Table 4, standard presentation of solar cell performance

Perhaps the most significant shortfalls stated earlier, the material selection for this project was largely dictated by cost, availability, and ease of machining, rather than optimal performance. Significantly greater monetary investments would be required to execute an operational product. Imperfections and inconsistencies inherent cutting the plywood were the limiting factor in the existing design. Replacing the plywood with plastic (acrylic) materials which can be laser cut

with CO2 laser for precision and smooth parabolic edges and fuse bonded to each other will help improve the manufacturing accuracy, dimensional stability and also durability of the mirror assembly in outdoor environments. Decreasing the width of the mirror strips and using thinner mirror material will improve the size and the light uniformity of the focal area. A new team of students have already committed to make these improvements and make the system viable for continuous operation outdoors.

The power consumption of the device was also significant. Because the motors were required to apply current continuously even when the device was not in motion, the device actually used more energy than it produced. The output could be increased by including an array of cells at the focal point, as only 1/24th of the total solar energy collected was absorbed by the multi-junction cell. The power consumption could also be greatly reduced by including a locking mechanism that would allow the motors to cut power when the tracker positioned the array correctly. Thus for the majority of the time, the array would not be consuming power. One concept that was developed to address this issue was a pair of normally closed solenoids which could "lock" the device in positions while not actively tracking. A second possible solution is to utilize a worm gear, which has the advantage of resisting non-motor driven motion. These two improvements could greatly increase the efficiency of the overall device.

In addition to addressing the complications with this design, there are many additional features that could be added to this product. One of which would be an active cooling system which would extract heat from the heat sink, which could be used for productive purposes, such as space heating water heating, or water purification. As stated earlier the system designed with its sun-tracking mechanism will serve as a platform on which other concentrated solar energy conversion devices (solar-thermo-electric, solar-thermo-mechanical, solar-thermo-chemical) can be tested for research and development, and for educational use, as well.

7.2 Summary of Educational Impact on Students and Public

This project was completed as a senior capstone design project utilizing all of the education gained thus far in the engineering curriculum along with a large amount of self-directed learning. Every stage in the design and development of the project was an educational test that had to be overcome.

The students completing the project are members of "Engineers Without Borders" and had gotten a project approved for the installation of solar energy collectors at an orphanage in Guatemala. The orphanage's administration concerns are the high price of electricity and providing the children with a hot water supply. This device that was developed can not only generate electricity but can also be used to generate hot water for the orphans as well. This project allowed the students to explore possible engineering solutions to real world problems that they were directly involved with.

Students were exposed to a wide range of engineering standards, practices, and tools. As part of The University of Southern Maine's EGN403 Senior Design Capstone Project, students were required to demonstrate the utilization of theory presented during their undergraduate education, as well as participate in extensive self-directed learning. Periodic reports were delivered to faculty advisors to ensure student were making progress, and moving in the correct direction. Students were evaluated using several metrics including: depth of research, ability to perform self-directed learning, quality of final project, as well as completion of a technical report, presentation, and poster.

In addition to the course requirements, the resulting project will provide a theoretical and functional platform for further educational activities at the University including additional senior design work, and a platform for further study of multi-junction solar cells and alternative ways of utilization of the concentrated solar radiation such as solar-thermo-electric, solar-thermo-mechanical, and solar-thermo-chemical.

After the completion of the project, the results and the physical product were demonstrated to students, faculty and the general public in several venues. An oral and visual presentation was prepared and delivered to the Engineering faculty and students highlighting the research methods, implications of the work and design challenges, as part of the grading and assessment of the project. The project was also exhibited at the 2015 "Engineers Week Expo" held on March 14[th,] 2015, an annual function held to raise interest in the public and to promote the profession of engineering. The solar tracker exemplified meaningful engineering work and offered an interactive experience for the attendees of the Expo, particularly K-12 students. The project will also be featured at several other venues including 2015 "Thinking Matters" Conference on April 24th, 2015.

The impact this project has had reaches far beyond the experience the students had, and the walls of the University.

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