Design, Fabrication, and Testing of a Dual-Axis Solar Turtle

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Abstract

A portable, light weight, low-cost, dual-axis solar turtle prototype with dynamic self-tracking solar panel was designed and fabricated using 3D printed, machined, and purchased components to charge a battery large enough to run multiple devices. The base and body of the design housing is a locking lid rolling cooler that insures if the unit is tipped over the components inside will not be damaged. The design also makes the unit slightly weather resistant. Utilizing a fixed main post made from lightweight strong material allows for the main panel to have a height of 5 feet off the ground or 1 foot off the base of the design for the solar cell to operate. PVC was chosen due to its hollow center and strong and slightly flexible body that is lightweight. All parts needed for the prototype design were purchased along with some parts being 3D printed. Some aluminum milled pieces were used in the final design due to the large amount of load needed to handle at certain points of the build. Implementing a practical “yes/no” function will verify proper angle and exposure of the panel towards the sun, using miniature solar panels that will be eclipsed by the larger solar cell whenever directly facing the sun itself. The dual-axis solar turtle built is marketable and more efficient than static panels due to auto-tracking. When tested, it collected 19.9% more solar energy than static panels.

Keywords:.

1. Introduction

In the United States, the top three energy sources of electricity in 2022 are, natural gas at 39.8%, all coal at 19.5%, and nuclear at 18.2% and (U.S. – EIA, 2023). These forms of energy are nonrenewable meaning they will eventually be depleted. For this reason, it is important to seek renewable sources of energy for they are cleaner, easier to use, require less maintenance, and will always be available. This project focuses on solar energy, which is a renewable form of energy. On average the earth surface receives about 600 W/m2 of solar energy (Kothari, 2003). This value depends on several factors such as the time of the day and the atmospheric conditions. In 2022, only 3.4% of solar energy was used to generate electricity (U.S. - EIA, 2023). It is estimated that solar energy will become the largest source of electricity by the year 2050 (Kothari, 2003). For this reason, there should be a larger investment in harnessing solar energy. People who live in secluded areas have limited access to efficient power

Submitted: June 30, 2023
Revised: November 26, 2023

because it is unavailable or too expensive. Also, with the rising cost of fossil fuel most people who live in standard-sized homes are interested in finding alternative energy sources to reduce domestic electricity costs. Solar energy is an abundant source of renewable energy which makes it a good solution for people living under these circumstances. In a single day, the amount of sunlight hitting the United States is more than 2,500 times the entire country's daily energy usage (Chandler, 2013). The most efficient solar panels of today's technology harness less than 20% of available solar energy (Solar Technologies, 2013). Although this is a small percentage, it is a helpful amount of energy that may one day allow for independence from nonrenewable forms of energy. This paper provides the description of a senior design student project including the goal of the project and the design specifications. The overall objective is to design and build a dual-axis solar turtle using a portable, light weight, low cost, and dynamic solar panel capable of charging a battery large enough to run multiple devices. Previous attempts to achieve an effective dynamic solar panel adjusting unit relied on logic or GPS coordinates to track the location of the main solar panel. The system typically did not work properly if the code was incorrect which might have caused the system to lock up. Further, GPS costs a large sum of money to buy and install.

2. Background

Installing a dual-axis solar tracker on rooftop to meet the soaring demand of energy in developing countries have been studied and discussed (Farhana et al., (2013). Deepthi et al (2013) made a comparative study on the efficiencies of single-axis and dual-axis tracking systems with fixed mounts. A solar tracking system for renewable energy is designed and built to collect free energy from the sun, store it in the battery, and convert this energy to alternating current (AC). This makes the energy usable in standard-sized homes as a supplemental source of power or as an independent power source (Juang & Radharamanan, 2014). Twisha et al. (2014) introduced dual-axis solar tracker with reflector to increase optimal electricity generation in Bangladesh. A comprehensive study on dual-axis solar tracking system was made by Chhoton & Chakraborty (2017). A discussion on how solar panels work was made by Dhar (2017). A step-by-step guide explaining how solar panels work has been presented and discussed (SVTAdmin, 2018). A solar powered phone charger was designed, built, and tested (Juang & Radharamanan, 2019). Aggarwal (2020) discussed solar panels available in the market and indicated the most efficient solar panels for purchase and installation. In this paper, the authors designed, fabricated, and tested a portable dual-axis solar turtle that is more efficient due to auto-tracking and collects about 20% more solar energy compared to static panels

3. Methodology

The visual concept design of a dual-axis solar turtle is shown in Figure 1. Building of prototype started with the proof of concept regarding eclipsing the rear control panels with the main solar panel during the beginning stages of the preliminary construction. Sizes were initially based on a 50W panel. This was not efficient for recharging the solar battery within 8 hours. Therefore, the decision was made to increase the size to an 80W panel. The preliminary proof of concept is shown in Figure 2.

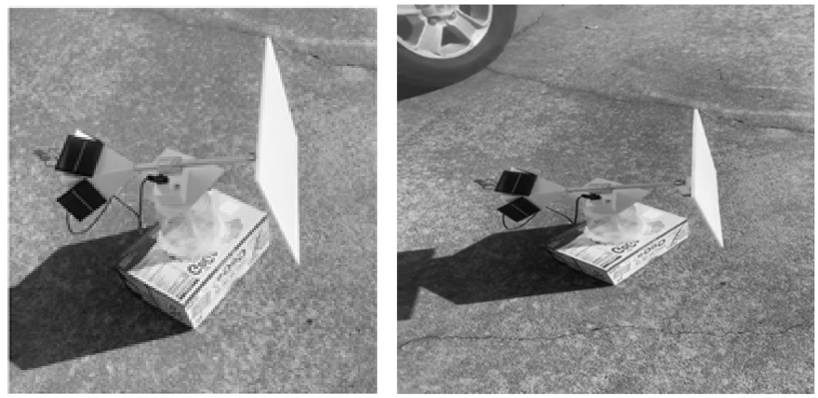

Figure 1: Visual Concept Design **Figure 2: Preliminary Proof of Concept**

3.1. Beginning Building Stage Problems

The focus was engineering a top unit that would incorporate all components needed for X and Y axis movement, while still maintaining proper structural integrity (10 pounds). The operating mechanism of the upper unit was tested/troubleshooted while simultaneously milling custom parts. Various configurations of sensor control panels were tested, with the best results coming from having 212V solar panels set in parallel to achieve a maximum current of 500mA powering multiple DC motors. Efforts were made to reduce friction by adding an axial bearing to the top of the aluminum cap, helping the motors have the least amount of friction to start the rotations. Then the bottom of the box was extended to fully enclose around the aluminum cap to better displace the weight on the bearing, all while eliminating the amount of wiggle during windy days.

3.2. Final Building Stages Problems

Still having problems with binding and motor shafts getting stuck, the other areas were looked that could throw the level off. The main pole being loose, and swaying was assessed to be a problem, one solid piece of 5-foot PVC eliminated movement and the unit was rebalanced and leveled. Weights were added to the body box as a balance for keeping the weight over the axial bearing, ensuring enough downward force is on the bearing to allow the motor to effortlessly rotate the shaft, even in the event of small winds. Finally, the solar module components were secured to the outside/inside of the rolling container and were shielded by 3D printed structures to help with slight weatherproofing. Unit housed the battery and power inverter which were secured with straps and screws to keep them stable during transportation of the unit.

3.3. Final Design and Construction: Base and Frame

The base of the unit is made from a rolling cooler with an attached handle and wheels for better portability. While also serving as the storage compartment of the unit and protecting the components from the elements. A 3D printed carbon fiber base coupling is installed using screws, holding the bottom of the main 2” PVC pipe center for added stability. Between the wheel wells, the battery is held in place with reinforced straps and screws to prevent it from sliding into the main support post. The charge controller is attached to the front side of the base cooler housing using screws and was slightly protected from weather by a flexible 3D printed awning installed with screws above the controller.

3.4. Final Design and Construction: Base and Frame 2

Next to the charge controller, still under the same awning, is the kilowatt monitor. This is used for measuring the electrical power usage of appliances the customer decides to use in the field, allowing it to be read kilowatts per hour. The DC power inverter connects the battery to the monitor and was installed with straps on the underside of the lid to allow for easy access for potential maintenance. The power outlet was connected to the monitor using a short extension cord tucked inside the cooler. The battery is connected to the inverter through securing jumper cables from the back of the inverter to the positive and negative terminals of the deep cycle battery. Figure 3 shows the final solar turtle bottom unit assembly.

Figure 3: Final Solar Turtle Bottom Unit Assembly

3.5. Final Design and Construction: Tracking Mechanism

A round aluminum cap has a cutout 3⁄4 the thickness of the axial bearing on top of it, allowing for the bearing to be secured in place, but still give enough space for the main upper unit box to float. This is placed on top of the main support pole. A set screw is bored into the aluminum cap to allow the motor stem shaft to be secured, and this is what allows our rotation of the upper unit in relation to the bearing and aluminum support cap.

Two 12V 500 mA DC motors are responsible for causing the rotation once a control panel was exposed to sunlight generating power. These motors are installed in their own 3D printed mounts located on the main body box. The first DC motor is inside the bottom of the head unit; a stem shaft extension was fixed to the motor shaft, which is then secured to the aluminum cap with the set screw. The stem shaft was fit into the hole found in the center of the axial bearing.

The second DC motor is inserted into a shaft that rotates a spool turning a wire that moves the y-axis up and down, holding the unit in place as well as keeping constant tension. The opposite end of the spool is held in place with a rod running through the entire frame. A guide pulley is mounted on a rear rod to keep tension on the wire where the main horizontal support pole was fed through a vertical pivot mount and secured with a steel rod through the body.

3.6. Final Design and Construction: Tracking Mechanism 2

The attached main 80W solar panel was placed on the tip of the horizontal 1” PVC pipe support pole. Using a simple set pin and a predrilled hole that holds the main panel in place during operation. Toward the mid-section of the horizontal support pole, a vertical predrilled hole serves as the anchor point for the wire and spool y-axis unit. The wire was fed through the vertical hole and the excess was wrapped around the pole to ensure a tight no slip hold on the wire.

From the rear of the support pole, a 3-way collar was slid into place just behind the wire anchor, this 3-way collar is what holds the 3 control panels. The control collar is fixed into place with a predrilled hole and set pin as well. Three equal length 1” diameter poles slide into the slots in the 3-way collar and are faceted with set pins. The control panel housings were installed. Within each housing unit is a 12V 500mA solar panel set up.

The left and right panels are connected to the same control circuit to allow for proper clockwise and counterclockwise movement. The bottom horizontal movement motor is connected to the same breadboard where the top panel is directly connected to the vertical movement motor attached to the wire spool.

3.7. Final Design and Construction: Tracking Mechanism 3

Using the steel rods ran through the main body box of the motor housing assembly allows for attaching the small weights using a tension cable. This provides enough downward force to keep the unit from tipping in windy conditions and ensures the center of mass is full on the axial bearing. Light emitting diodes built into the control circuit will both become illuminated indicating the left and right panel are providing power as a check for the customer. If the left panel is covered, the left LED should turn off. This test ensures the connections were made correctly. In the event the opposite LED or the covered panel shuts off, then the connections are backwards. This is simply fixed by swapping opposite solar panel positive and negative terminal wires.

3.8. Final Design and Construction: Monitoring System

Kilowatt monitor will display the current power consumption of any electrical appliances connected to it when the customer needs electricity. The main power capacity can then be divided by the number indicated on the monitor to calculate the amount of energy available in hours remaining on the battery.

$$\frac{Indicated\ Battery\ Capacity * Percentage\ of\ Charge}{Kilowatt\ Monitor\ Indicated} = Power\ Available\ in\ Hours$$

3.9. Final Design and Construction: Monitoring System 2

With an upgraded 80W solar panel the power supply is capable of recharging within 8 hours of direct sunlight. If the electrical load is less than 80W per hour, then the appliance used will run directly off the solar panel and will not draw power from the battery power bank. Both the battery and main solar panel could be increased in capacities if desired in future models. Figure 4 shows the final prototype of solar turtle solar charge unit.

3.10. Future Recommendations: 1

3D printed parts made it possible to implement quick design changes ready to test daily. This helped to find the proper performance needed in tandem with the already machined mechanical parts. If possible, machining these final 3D parts out of a metal would ensure a tighter fit of components and increased stability.

Figure 4: Final Prototype of Solar Turtle Solar Charge Unit

3.11. Future Recommendations: 2

Some of the parts that were 3D printed were prone to breaking under any non-ideal movement. The DC motors had a small amount of free space in the mounting frame that would cause a shift in angle of them operating, causing the motor to have an unacceptable amount of strain coming from the spinning shaft. This could be fixed by using larger and more structurally enforced motors, which is highly recommended for the next iteration of the solar turtle.

The size of panel to motor ratio is linear, so with stronger parts everything can be upsized. Meaning if a bigger panel or larger power supply needs to be added, the size of the sensor panels will increase along with the size of the motors that run the unit itself.

3.12. Future Recommendations: 3

For better performance and large scaling of components, a microcontroller might be more suitable. If an Arduino were running directly off the main solar panel, it could be used as a digital switch. Using a digital switch would allow the current to build to max in the solar panel before passing through the DC motors. A larger current is needed to torque a larger motor. Regulating when and how much current passes would make the system operate with the same components but be able to facilitate moving a larger panel and increase the structural integrity of the top tracking unit. No photoresistors or sensors will be needed because the control solar panels will still do the sensing of the sun and power the motors directly. The Arduino would be nothing more than a simple programmed switch if larger motors were required.

Additionally, DC to DC converters could be used to alter the voltage and currents being produced by the control panels. This would allow the user to match the specifications of the DC motor exactly and then control the flow of current through the digital switch.

These simple changes would cost no more than $30, making these upgrades relatively feasible. However, this method would use code to operate and if the sun were not optimal, then the Arduino may never get enough power to run.

3.13. Future Recommendations: 4

It is important to remember to keep the power sources separate when making this change, to keep the main power source unaffected by the new code used in the tracking mechanism. A small battery could be used in this system in conjunction with the sensor panels to maintain a regulated input voltage and current to the Arduino, which would help fix this problem. If in the event the sensor panels are too weak to run a larger motor, then the use of a DC-to-DC converter off the main panel can be used to temporarily route power from the main solar panel through the DC motor.

The Arduino would still act as a digital switch, but the larger solar panel DC supply connects to an H-Bridge (Figure 5). An H-Bridge is made of 4 BJT transistor current controlled devices. The Arduino would only send a base signal to the current controlled device to allow flow of larger power to the motor without messing up the Arduino. Figure 6 shows H-bridge addition movement.

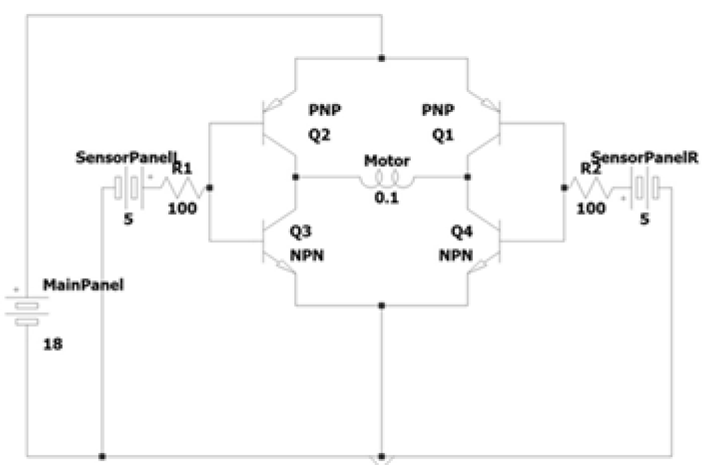

Figure 5: Circuit Diagram of an H-bridge

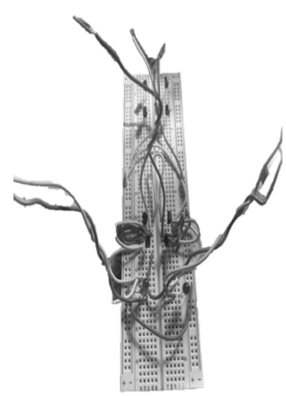

Figure 6. H-bridge Addition Movement

4. Results and Discussions

4.1. Checking the Battery Charge State

For checking the battery, one can use the solar charge controller or a multimeter. Initially checking the battery with a multimeter showed 11.2V. A trickle charger for battery was used. Table 1 shows the charge state of gel battery and AGM battery.

Safety Precautions

Use proper protective equipment such as gloves and protective eyewear when connecting the inverter to the battery. Use a two-pin switch instead of a three-pin switch. Solar inverter is strapped to prevent sliding or falling. Battery is strapped to the inside right-hand side of the cooler.

Charge State	Gel Battery Voltage	AGM Battery Voltage
100%	12.85+	12.8+
75%	12.65	12.60
50%	12.35	12.30
25%	12.00	12.00
0%	11.80	11.80

Table 1: Charge State of Gel Battery vs AGM Battery

4.2. Human Acceptance Test

The process was modeled on how to set up the system. 14 students agreed setting up the system was easy while another 5 disagreed. 73.68% agreed that the set-up process was easy.

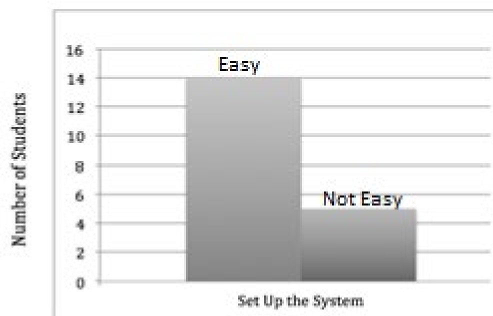

Figure 7: Human Acceptance Test Data

4.3. Performance Tests: 1

The advantage of the tracking system is that the solar panel maintains its most effective tracking angle throughout the day. Table 2 shows voltage, current and power values for fixed panel for different times whereas Table 3 shows these values for tracked panel. Figure 8 shows the relation between time and power for fixed and tracked panels.

Time	Voltage (V)	Current (A)	Power (W)
8	12.7	2	25.4
9	12.9	2.5	32.25
10	14.1	3	42.3
11	14.2	4.2	59.64
12	14.2	5.3	75.26
13	14.2	5.2	73.84
14	14.2	5	71
15	13	4.8	62.2
Total			441.89
Mean			55.23

Table 2: Fixed Panel vs Time

Time	Voltage (V)	Current (A)	Power (W)
8	13	3.4	44.2
9	13.1	3.5	45.85
10	14.2	4.8	68.16
11	14.2	5.2	73.84
12	14.2	5.4	76.68
13	14.2	5.3	75.26
14	14.3	5.3	75.26
15	14.1	5	70.5
Total			529.75
Mean			66.22

Table 3: Tracked Panel vs Time

The formula used to track the improvement of the collected solar energies is shown below:

$$\% \textbf{ Improvement in Power } = \frac{\textbf{Power of Tracking Panel} - \textbf{Power of Fixed Panel}}{\textbf{Power of Fixed Panel}} \textbf{ x } \mathbf{100\%}$$

$$\% \textbf{ Improvement in Power } = \frac{\mathbf{66.22 - 55.23}}{\mathbf{55.23}} \textbf{ x } \mathbf{100\%} = \mathbf{19.9\%}$$

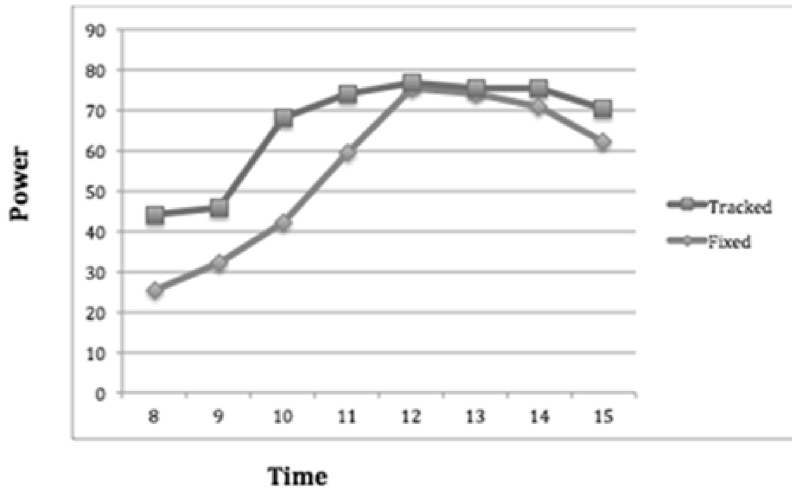

Figure 8: Time vs power

5. Conclusions and Recommendations

The final prototype build came in slightly over the initial budget of $300. The total amount spent building the prototype was $406.89. There would be more possibilities with cutting costs when it comes to functionality and overall build quality with having parts milled and manufactured wholesale, purchasing complete solar modules is more cost effective compared to getting the components individually. It is recommended that a microcontroller of some sort is powered through its own independent solar panel. This microcontroller would detect voltages at the smaller control panels and appropriately route power through a larger DC motor. This recommendation comes from size ability in mind. A system that could be used on a larger tracking system could reduce production cost because the control panels will not need to be increased in size to facilitate a larger DC motor and increased generator capacity. If the scale of the module was increased, then it could be used as a more permanent solar power generator capable of auto-tracking the sun. This could potentially increase the effectiveness of all solar panel powered systems including the industrial sized arrays.

In conclusion, the dual-axis solar tracking system contains significant components in comparison to the fixed system. The mini control panels were used to provide current to rotate the DC motors. The mini panel wires are connected inversely to turn the motor clockwise or counterclockwise to help the panel to maximize the absorption of energy. This resulted in generating a higher wattage than the fixed panel. Overall, the dual-axis solar tracking system is more effective in providing the best electrical performance.

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