California Polytechnic State University

Senior Project

Solar Powered Single-Axis Heliostat Active Solar Tracking Device

Author:
Mason Roberts

Advisor:
Peter Schwartz

September 3, 2017
ABSTRACT

As a means of cooking food, the burning of biomass accounts for over 4 million premature deaths in third world countries ("Household Air Pollution and Health"). The focus of this project was to explore an alternative that could utilize focused sunlight to cook food. A solar tracker was designed to be affixed to a parabolic, reflective, tilted single axis heliostat to follow the sun throughout the day and focus the reflected light to the bottom of a cooking surface. This surface became hot enough to for the preparation of food or boiling/sterilization of water.

A goal for each project was to keep the price of components down in order to make the whole venture more affordable for implementing in a 3rd world country. The solar tracker would utilize a motor to turn the heliostat and a circuit was designed to locate the sun actively throughout the day using two light dependent resistors that compared the intensity of sunlight across a partition. A 3.7V, 800mAh Lithium Ion battery was picked to power the tracker based on calculations of how much power it needed to operate, and a 5V, 50mA solar panel was selected to recharge the battery based on how quickly it was being depleted. Additionally the circuit was housed in a tough, watertight container to survive rough handling and weather conditions. Difficulties encountered during the course of the project included designing the circuit to be as small and energy efficient as possible, and keeping the price reasonably low. Some considerations were how the circuit would operate at night without sunlight to guide it.

INTRODUCTION

Nearly half the world's population – 3 billion people –burn biomass to cook every day, and household air pollution is the fourth biggest health risk in developing countries, after heart disease, stroke and chronic obstructive pulmonary disease ("The stoves used by millions in developing countries are a silent killer"). In 2015 the World Health Organization estimated that over 4 million premature deaths were the result of particulate pollution caused by the burning of biomass ("Household Air Pollution and Health"). Many of these countries don’t have the infrastructure in place to allow for electric stoves or gas lines. Collecting fuel for cooking, most often performed by women and children, can take up to five hours a day ("Household Air Pollution and Health"). It is a physically demanding and time-consuming task, and their safety is also at risk.

There do, however, already exist projects that aim to reduce the amount of solid fuel burned in order to cook food with the use of cleverly designed stoves that maximize the amount of heat and minimize the amount of smoke when operating. BioLite is one such project that has been successful in creating efficient and portable stoves for cooking. Unfortunately, these stoves are impractically expensive for their originally targeted demographic, costing upwards of $80 for the baseline model and requiring that its batteries be recharged after several uses (CookStove).

This project investigated a solar substitute to gas and biomass burning. The project, as a whole, aimed to create a solar tracking parabolic mirror. However, the focus of this paper is the solar tracking portion of the design. It should be reliable,
solar-charging, inexpensive and easy to operate so as to be seamlessly integrated into the lives of those who would benefit from it most. It should improve their living environments and, additionally, reduce the amount of greenhouse gas emissions produced from burning biomass.

**METHODOLOGY**

*Theory*

A heliostat is a device that includes a mirror, which turns so as to keep reflecting sunlight toward a predetermined target, compensating for the sun’s apparent motions in the sky ("Powering A Brighter Future With Clean, Cost Effective Energy"). In order to simplify the project as a whole, the heliostat constructed had a single axis of rotation (Figure 1), as compared to dual-axis tracking structures that would require additional degrees of freedom and complexities.

![Figure 1: Cal Poly Single-Axis Scheffler Reflector Heliostat (Fuller).](image)

The axis of rotation was tilted, however, and designed to allow for future adjustments in its angle. These adjustments were to coincide with the seasonal dip and rise of the sun in the sky (Figure 2).
Figure 2: The apparent transit and angle of the Sun in the sky of a fixed point on Earth over the course of the seasons (Schimmrich).

In San Luis Obispo, the Latitudinal angle is 35 degrees North of the Equator, which is what the tilt of the heliostat reproduces twice a year, during the Vernal and Autumnal Equinoxes (Figure 3).

Figure 3: Earth's tilted axis of rotation depicted with its orbit around the Sun and the creation of the seasons as a result of the celestial body's orientation (14).

With a variance of around 23.5 degrees due to the tilt of the Earth in its rotation, the angle of the sun from directly above azimuth is observed to be between 58.5 degrees during the winter and 11.5 degrees during the summer. The manual adjustment in the tilt of the heliostat was done on a weekly or monthly basis because the effect of the seasons changing is a very slow and gradual one and did not largely diffuse the focal point of the reflected sunlight.
Concept

The tracker required a motor to adjust the angle of the array. A low voltage motor would be inexpensive, but may not be strong enough on its own to turn the heliostat. And a larger motor would have the opposite problem. It was decided that a small, low voltage motor with an attached gearbox be used. The gearbox would trade the motor’s high speed for increased torque with a series of appropriately ratioed gears to transfer force (Orthwein).

To increment the motor, there were several different single-axis solar tracking techniques that the circuit could have employed. It could have tracked the sun actively or as an estimate. A circuit designed to estimate the path of the sun in the sky could utilize a simple timer: turning the heliostat a full 180 degrees over the course of a 12 hour day. While this would work to move the heliostat in the general area of the sun, it would require calculating the exact increment that the motor would need to move the array in the precise degrees required. However, if the circuit had sensors to detect the sunlight there would be feedback telling the motor when it had turned enough. For this reason, sensors were used for tracking the sun.

Sensors add the ability to detect the presence of the sun and remove any guessing. The single-axis Heliostat would require two sensors in order to follow the sun throughout the day and return facing East again during sunrise. A circuit designed to actively track the sun would compare the readings across both sensors. If one sensor received less light than the other, then the Heliostat would be turned in the direction that optimized the readings on both. Depending on the circuit configuration and the sensitivity of the sensors, minute corrections could have happened many times a minute. The high number of corrections per minute would waste too much energy. And while adjusting with the sun so often is very precise, the parabolic Scheffler reflector allowed for a variance of about one degree. This would translate to a displacement of the reflected light by two degrees, and at a distance of around a meter the result would be a displacement in focus of around 3.4cm, which would still be within the radius of the cooking surface.

If the device were designed to actively track the sun with a partition added between the two sensors, and configured to react to large changes in the detected light, then the circuit would waste much less energy by adjusting less frequently. This partition would cast a shadow on the East-facing sensor as the sun tracked West during the day, and vice-versa when resetting at sunrise (Figure 4).
Figure 4: Two light sensors used to compare readings across a shadow casting partition (Kashatria).

Compared to monitoring the minute differences between the sensors, this approach would only react to a relatively larger change in the sensors’ readings. This was the best configuration for the tracker because it gave an acceptable amount of precision without wasting a lot of energy on constant angle adjustments.

The sensors used were light dependent resistors (LDR). An LDR’s resistance changes as the incident light on it gets brighter. If light on a photoresistor exceeds a certain frequency, photons absorbed by the semiconductor give bound electrons enough energy to jump into the conduction band. The resulting free electrons conduct electricity, thereby lowering resistance (“Light Dependent Resistor – LDR”). And in order to compare the LDRs' values, an Operational Amplifier (Op-Amp) would be used. In the correct configuration an Op-Amp acts like a comparator: outputting from one of its two power connections based on which input voltage is greatest (“Low-Power, Dual-Operational Amplifiers”).

If the two LDRs were used on a single Op-Amp (Figure 5) – directly comparing their ever-fluctuating values – the concentrator would oscillate back and forth around the optimal angle, wasting energy.

Figure 5: Single Op-Amp configuration comparing readings between two light sensors.
To compensate for this, a threshold voltage would be needed to indirectly compare the voltages on the LDRs using two separate Op-Amps so that the only time the angle changed was when the reading on the LDR passed a certain, pre-designated voltage. The resistance values for a voltage divider would need to be calculated.

A voltage divider is a passive linear circuit that produces an output voltage that is a fraction of its input voltage. Voltage division is the result of distributing the input voltage among the components of the divider. A simple example of a voltage divider is two resistors connected in series, with the input voltage applied across the resistor pair and the output voltage emerging from the connection between them (Ulaby). Additionally, each LDR would be apart of its own voltage divider circuit whose voltage would vary with the intensity of light on the photoresistor (Figure 6).

![Figure 6: Two Op-Amps configured to compare readings of LDRs to threshold voltage.](image)

The resistance of each R1 would be the same to allow for the value of R2 to be based on the resistance of an LDR at a desired illumination. So no matter what the voltage across the circuit is, the ratio of compared resistances would always be the same.

The tracker would require power to run, but there were several options from where it could get it. One option would have been to just use a battery. The battery would have run the tracker and kept the circuit simple, but it would not have lasted very long before it needed to be replaced or recharged elsewhere. If it was large it could have lasted longer, but would also have been more expensive and cumbersome.

Another option would have been to power the circuit with just a solar panel. Ideally, this method of powering the circuit would not require replacing components for very long periods of time, but the solar panel would need to be large to power the tracker and that would not be cheap.

To minimize the cost and keep the circuit operating indefinitely, without relying on replacement batteries, the tracker would utilize both a small rechargeable battery and a small photovoltaic cell. The solar panel would charge the battery and be located on the circuit itself in order to maximize the amount of attenuated sunlight over the course of the day as it tracked the sun. Figure 4 pictures a simulated plot of the attenuated sunlight of different solar panel mounting techniques. Based on the simulation, placing the solar panel on the tracker
itself would maximize its output. To select a solar cell that would output an appropriate voltage and current, the average energy required to power the tracker – circuit and motor – would need to be measured.

![Figure 7: Simulated energy production of one-kilowatt solar photovoltaic (Comstock).](image)

A charge regulator circuit was not added to the design both because it would have increased the cost and complexity, and because it was unnecessary. Such a circuit would have closely monitored the current through the battery and made sure that it was not too much. Overcharging would have damaged the battery and shortened its lifespan. The selected solar panel’s rated current would be small and close to the battery’s average so the battery would receive a “trickle charge” which would be slow enough not to overcharge it (Simpson). A zener diode would be considered if the voltage of the solar cell was much larger than the voltage of the battery.

Calculations

The resistance values for different light intensities were found on the LDR’s Data Sheet, but were also measured in order to determine a range of values to be used for a comparative Op-Amp design, and can be seen in Table 1 below.

<table>
<thead>
<tr>
<th>Light Conditions</th>
<th>Resistance Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Sunlight</td>
<td>200Ω</td>
</tr>
<tr>
<td>Shade</td>
<td>600Ω</td>
</tr>
<tr>
<td>Dark</td>
<td>2000Ω</td>
</tr>
</tbody>
</table>

Table 1: Several resistance values of the LDR type used in different light intensities.

A resistance of less than 600Ω (470Ω) was selected for one of the resistors in the threshold voltage divider. The LDR would share this resistance when it becomes partially shaded and makes for the ideal point at which the circuit would react and turn the heliostat to realign with the sun.
Table 2: Records of the seasonal Sunset and Sunrise times for San Luis Obispo used to determine how many hours the sun is up/down (“San Luis Obispo”).

The average number of hours the sun is up during the year in San Luis Obispo, and thus detectable by the tracker, was calculated to be 12.175 hours.

Table 3: Measurements of the durations of current drawn by each device over a 24-hour day.

Based on the motor’s voltage requirement and the values in Table 3 for the current usage of the tracker, a battery would have to be between 3VDC and 10VDC, and have a capacity greater than the highest recorded consumption rate of 121mAh to avoid the possibility of damaging the battery by overdrawing current during this period.

In Table 3, for each of the possible states the tracker was in over the course of 24 hours, the milliamps required were recorded and the average duration of the states were totaled. These values were used to calculate the total milliamper hours required by the tracker each day. 200mAh is the smallest charge a solar panel must provide in order to fully recharge the battery each day. Its voltage must also be greater than the battery’s in order to charge it at all. Small solar cells rated within these criteria range from 15cm² to 25cm².
Design

The Arduino microprocessor board (Figure 8) was used solely to prototype different methods of detecting the sun. Such a device was too excessive and expensive – relative to the entirety of the project – to be used for the logic of the tracker.

Figure 8: Prototype with Arduino Microprocessor. Small motor for debugging.

For both efficiency and cost, the number of components were kept to a minimum and salvaged from old and broken computers and electronics whenever possible.

Figure 9: Picture showing dual op-amp IC and H-Bridge during circuit tests and development.
A shallow, wide mouth jar was used to house the circuit. Its rubber gasket seal kept it watertight (Figure 11). The jar was made of glass and allowed for light to make it through to the LDRs, but it was thick enough to remain sturdy under rough handling. The motor and its internal torque conversion system were not directly affixed to the tracking circuit, and instead were attached to the bottom of the concentrator, requiring minimal weatherproofing.

The two LDR were bent facing slightly away from each other (Figures 9 & 11). This was so that in the morning, when the sun was still low in the East and the array remained where it lost site of the sun in the West, the LDR was already facing slightly back towards the East where it would detect the sun and reset the array in the morning.

A 3.7V, 800mAh lithium ion battery was used to power the tracker. It was positioned in the center of the jar between structural components.
Based on the calculated energy requirements of the tracker, a small 5V, 50mA solar cell was adhered to the glass bottom of the jar where it both tracked with the heliostat – maximizing the attenuated sunlight – and acted as the sensor partition – casting shadows on the photoresistors inside the enclosure.

**Data**

![Figure 12: Plot of change in LDR resistance, voltage at divider and voltage of motor over time.](image)

Figure 12 was measured during the circuit’s testing to ensure that all of its separate components were responding to each other as the light shown on the tracker changed. The circuit was slowly turned, manually, into and out of the sun – shown on one of its LDRs. The resistance of the LDR can be seen dropping at first as it was slowly moved from the dark. When its resistance dropped to 470Ω the voltage across it passed the comparative threshold voltage and allowed for the output of the Op-Amp to go high during this period of time. And as it was slowly moved back into darkness the resistance increased passed 470Ω and the voltage dropped below the Op-Amp compared threshold limit, dropping its output back to zero.

The charge of the battery was measured over several days in order to determine if the small solar panel was sufficient enough to keep it charged and it was consistently reading 3.7V.

<table>
<thead>
<tr>
<th>Itemized Receipt</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
<td>Cost (USD)</td>
<td>Quantity</td>
<td>Total (USD)</td>
</tr>
<tr>
<td>Battery Case</td>
<td>$0.85</td>
<td>1</td>
<td>$0.85</td>
</tr>
<tr>
<td>Lithium Battery</td>
<td>$2.39</td>
<td>1</td>
<td>$2.39</td>
</tr>
<tr>
<td>Solar Cell</td>
<td>$1.58</td>
<td>1</td>
<td>$1.58</td>
</tr>
<tr>
<td>Diode</td>
<td>$0.01</td>
<td>1</td>
<td>$0.01</td>
</tr>
<tr>
<td>LDR</td>
<td>$0.07</td>
<td>2</td>
<td>$0.14</td>
</tr>
<tr>
<td>IC Socket</td>
<td>$0.09</td>
<td>2</td>
<td>$0.18</td>
</tr>
<tr>
<td>L9110H IC</td>
<td>$0.87</td>
<td>1</td>
<td>$0.87</td>
</tr>
<tr>
<td>Component</td>
<td>Price</td>
<td>Quantity</td>
<td>Total</td>
</tr>
<tr>
<td>---------------</td>
<td>-------</td>
<td>----------</td>
<td>--------</td>
</tr>
<tr>
<td>LM358N IC</td>
<td>$0.35</td>
<td>1</td>
<td>$0.35</td>
</tr>
<tr>
<td>Resistor</td>
<td>$0.06</td>
<td>4</td>
<td>$0.24</td>
</tr>
<tr>
<td>Motor</td>
<td>$12.95</td>
<td>1</td>
<td>$12.95</td>
</tr>
<tr>
<td>Perfboard</td>
<td>$0.60</td>
<td>1</td>
<td>$0.60</td>
</tr>
<tr>
<td>Jar</td>
<td>$0.00*</td>
<td>1</td>
<td>$0.00</td>
</tr>
<tr>
<td>Wires</td>
<td>$0.00*</td>
<td>N/A</td>
<td>$0.00</td>
</tr>
<tr>
<td>Hot Glue</td>
<td>$0.00*</td>
<td>N/A</td>
<td>$0.00</td>
</tr>
<tr>
<td>Solder</td>
<td>$0.00*</td>
<td>N/A</td>
<td>$0.00</td>
</tr>
</tbody>
</table>

Table 4: Breakdown of the prices of all the tracker components. (*Salvage/free)

The prices on Table 4 were eBay item purchases.

**DISCUSSION**

*Analysis*

The jar that was used to house the circuit worked very well. It had very thick glass to prevent it from being easily broken, but still allowed for light to reach the LDRs. It was water tight with the addition of hot glue where the wires had to be lead through the lid for the solar panel and motor. It was compact so it didn’t have to take up much space to be implemented in a project. And it was practically free because it was once garbage.

In Figure 12, once the LDR reached a resistance of around 470Ω, the voltage across it changed enough to reach the threshold voltage of 3.1V. After surpassing the threshold voltage, the Op-Amp’s comparative configuration allowed for current to flow through to the H-Bridge and on to power the motor.

A lithium Ion battery was the ideal choice to meet the criteria of the tracker when compared to other battery types such as NiCd, NiMH and Lead Acid. It had the largest voltage (3.7V) and capacity (800mAh) for its size. This allowed it to power the motor responsible for turning the array, while keeping the size of the tracker small. However, this came at the cost of being more expensive. Additionally, with Lithium batteries, it’s cautioned that they be kept above an optimally rated voltage in order to prevent over-discharging (“Lithium Ion Battery”). As long as it continues to be recharged it has a very long life span.

The measured voltage remaining at 3.7V means that the battery received enough energy, on average, to remain charged enough to power the tracker indefinitely. Further monitoring of the voltage would be needed to ensure that it does not drop over time, which would suggest the solar cell was just shy of being powerful enough to recharge it forever.

It was difficult finding other solar trackers for sale that had all the same features as were included in this project. The least expensive units were tracker controllers available for around $60 (Figure 13A), but didn’t include any motors or means by which to power itself. And there were also a few kits for around $150 (Figure 13B) that included everything but the ability to power itself. Compared to these prices, the $20.16 it cost to assemble this tracker is very reasonable.
Perhaps most important of all, it was hard to imagine how the tracker could have been any easier to use. As long as the jar was affixed to the heliostat being controlled by the motor, it practically ran itself. Because it had the LDRs to detect the presence of sunlight, the active feedback between the motor and controller allowed for unsupervised assurance that the unit would always be facing the sun during a cloudless day.

**Conclusion**

The larger goal of this project is to develop solar cooking as a substitute for biomass stoves. The focus of this paper in particular was to design, test and construct the solar tracking element. In the end it was a small, durable, inexpensive, self-charging, easy to use, solar tracking device. With that being said, there were still things that could have been done differently.

The motor used met the energy and torque requirements of the project, but it was salvaged from an old machine, and the gear’s teeth were very worn. Without a proper grip on the chain used to orient the concentrator it easily slipped if it were bumped or a breeze picked up. Adding that to the fact that the apparatus was top-heavy and it was quite a problem keeping the reflector stationary during the day. In the future, counter weights would need to be added to balance the load and a new cog should be attached to the motor for better grip on the chain.

Among the many traits the tracker was desired to have, it was to be rugged so it could remain sturdy under rough handling, which was accomplished well by the glass jar, but, if this project was done differently, a clear plastic jar would have been easier to come by, accomplished the same job and be less prone to shattering than the glass one. And while it worked to allow the light to hit the LDR, the thick glass distorted the light just enough that resetting during sunrise was not possible: both the angle of the concentrator and the diffuse light prevented the LDR from detecting the sun for several hours. Further research would be needed to see if the circuit could be designed to reset on its own at dusk in preparation for dawn. Additionally, because the enclosure was transparent, it acted like a small
greenhouse. Long-term monitoring of the condition of the circuit would need to be done to ensure the heat wasn’t damaging it over time.

The light dependent resistors did their jobs perfectly in the active solar tracking configuration and were relatively cheap compared to the whole tracker. But if there was more time to investigate other solar detection electronics, then it would be worth looking into light emitting diodes. While under normal conditions an LED emits light when current is passed through it in a specified direction, if light is shown on an LED a very small current can be measured as a result (Dietz). LEDs are cheaper than LDRs and their operational quiescent power is almost nothing. That means if they are used as sensors in a reverse bias orientation, they use almost no power, compared to the 12.4mA required by the existing design with LDRs. It would be worth investigating in the future to determine if a circuit could be designed to last longer periods of time without recharging, if this project was visited again.

The solar panel in combination with the lithium ion battery worked great to keep the price of the project low and allow the tracker to power itself indefinitely. The only concern would be if the device was left in the shade for long periods not being used, at which point the battery may no longer hold as much capacity for charge. A solution to this, which would need further investigation, would be to use capacitors instead; they will not lose capacity overtime after being left depleted.

One particular problem encountered with the project, and the constant problem with solar energy in general, was that at night the system couldn’t perform its job. It was not the subject of this paper to discuss it, but a thermal storage unit could be used to capture the energy of the system during the day and release it after the sun goes down just long enough for a diner meal to be made with the residual heat. Otherwise, the single-axis solar tracking device did an excellent job at meeting many of the goals set out in this project.
Work Cited


http://www.srh.noaa.gov/srh/jetstream/global/images/seasons.png


http://inst.eecs.berkeley.edu/~ee16b/fa17/note/circuits/VoltageAndCurrentDividers.pdf

“San Luis Obispo.” TimeandDate.com, 
https://www.timeanddate.com/sun/usa/san-luis-obispo

“Motor Control Driver Chip.” DataSheet4U, 
http://www.datasheetspdf.com/PDF/L9110/839657/1

Fuller, Nick. “Cal Poly Scheffler Reflector.” Cal Poly, Apr. 3, 2013, 
https://sites.google.com/site/cpschefflersolar/project-definition


Kashatria, Mridul. “Knowing Sun Tracker.” A Sun Energy World, Apr. 17, 2006, 
http://sunenergyworld.blogspot.com/2006/04/knowing-sun-tracker.html
