Arduino Prototype of a 2-Axis Solar Tracker – Alternate Energy Source for Multi-Family Buildings

Mechatronics for Design and Manufacturing (MAE 598)

Final Project Report

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Table of Contents

List of Figures

List of Tables

1 Objective

To develop a 2-axis solar tracker controlled and powered by an Arduino Uno suitable for indoor applications.

2 Abstract

The global surge in energy demand has driven innovation in cost-effective and efficient engineering solutions. Various photovoltaic (PV) technologies have been implemented and tested across small to large-scale buildings in the U.S. Our project focuses on developing a solar-powered two-axis solar tracker to explore the correlation between power generation and tracking accuracy. This setup would include two servomotors controlled by an Arduino Uno board receiving feedback from an established circuit of photoresistors. Support structures were designed in CAD and 3D printed to meet original size requirements. The prototype could realize solar movements and respond adequately indoors, and continued energy generation from indoor light sources in the absence of solar irradiance outdoors.

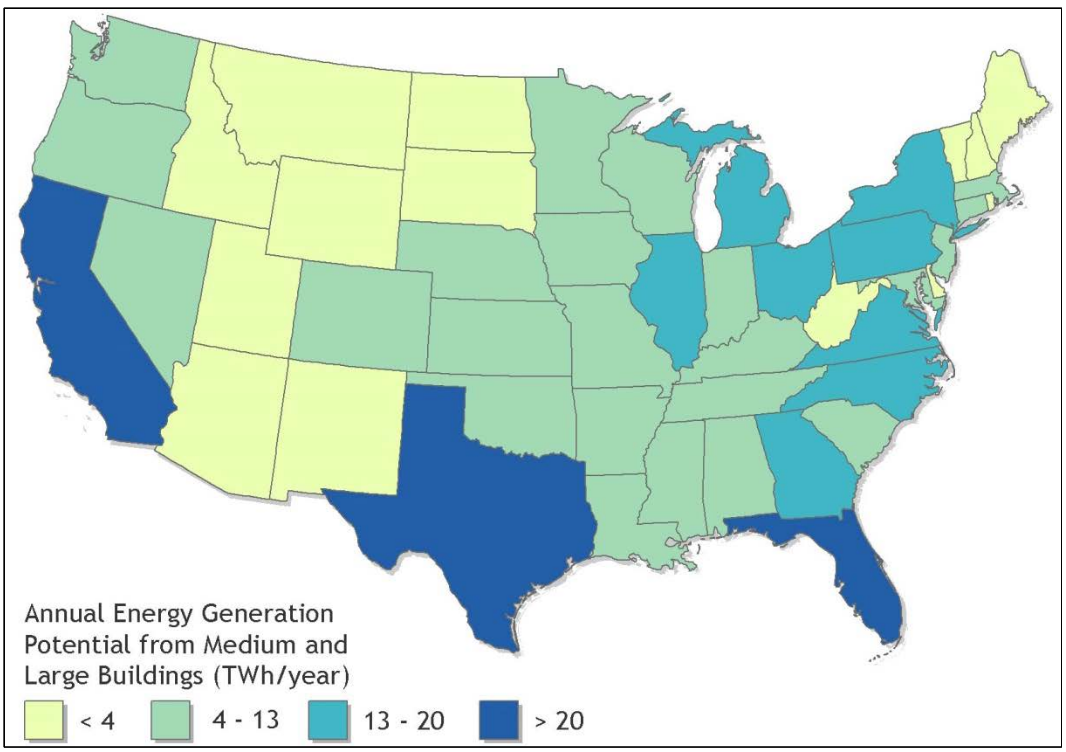


Figure 1 Annual Rooftop PV Generation in the USA [1]

3 Introduction

Photovoltaic panels made of any material require near perpendicular solar irradiance to reach its surface for maximum power generation. This comes at a cost for more moving parts for axis tracking, faster cell degeneration and higher influence of weather factors. Hence, a better application for two-axis tracking may be indoors where there may be difficulty in harnessing solar energy due to shading. A notable application would be in high-altitude buildings high-density cities where energy rates are higher, and replacement of small panels/parts would be cost-effective.

Considering the solar market share for application in building technology, currently a potential of 36% of market sales exists in the US. This could be nearly 82% if more suitable rooftops were available [1]. A considerable percentage of this energy could be harnessed by alternative solar technologies such as concentrated photovoltaic cells. This technology had been phased out in 2018 due to lack of cost-effective technology being able to concentrate solar irradiance accurately on a 2x2 $[in^2]$ solar cell [2], but advancements in tracking and improving panel efficiency to nearly 40%, has encouraged continuing its research and manufacturing efforts [3].

This project focuses on optimizing similar tracking efforts using an Arduino-based board to realize net system energy generation as a unit after meeting energy requirements by system components. This self-reliance could encourage its application as a system interlinking multiple such units to make a system ideally placed on a windowsill. Multiple such systems could be linked by an internet of things (IOT) connectivity and eventually contribute to powering at least a few LED bulbs indoors.

4 System Design and Calculations

The design for the Arduino-based system was made on the skeleton of a paper published by Morón et al., 2017 [4]. We have considered servomotors for enabling the two-axis tracking motion, along with suitable capacities and quantities of photoresistors to detect irradiance and enable feedback to the control system. The code for the system is attached under Section 12 Appendix 1.

We selected four 1 $[k\Omega]$ resistors for our voltage dividers. When the photoresistors are dark, the measured resistance is 30 [kΩ], corresponding to a voltage of 4.839 [Volts]. When bright, the voltage reads 1.667 [Volts] which equates to nearly 0.5 $[k\Omega]$ in resistance. [6]

$$V_{out} = V_{in} \cdot \left(\frac{R_2}{R_1 + R_2}\right) = V_{in} \cdot \left(\frac{R_{photoresistor}}{1\ [k\Omega] + R_{photoresistor}}\right)$$

When bright, $R_{photoresistor} \approx 0.5\ [k\Omega] => V_{out} = 1.667\ [V]$

When dark, $R_{photoresistor} \approx 30\ [k\Omega] => V_{out} = 4.839\ [V]$

Sr No	**Components**	**Model/ Type**	**Capacity**	**Quantity**
1	Microcontroller	Elegoo Arduino Uno R3	5 [V] power supply with controller Microchip ATmeda328P	1
2	Servomotors	SG90	4.8 ~ 6 [Volts], torque of 2.5 [kg-cm].	2
3	Photoresistors	Along with Arduino Kit	Detects 0 - 300 [Ω] in our setup outdoors	4
4	Resistor	Along with Arduino Kit	500 [Ω]	4
5	Solar Module	Uxcell	1 [Watt] 6 [Volts]	1
6	3D printed components	Printed using PLA	Shading mount for photoresistors, Up-down motor mount, left-right motor mount	3
7	Miscellaneous	Along with Arduino Kit	Breadboard, Jumper wires, connector cables, etc.	As required

Table 1. Materials List for the Setup

5 Mechatronic System

The 2-axis solar tracker will be a closed-loop combination of electrical motors and mechanical components electronically controlled by an Arduino Uno programmed to perform solar tracking based on feedback from photoresistors. The photoresistors are sensitive to varying light sources and are separated by a 3D printed mount to induce shading. As a light source moves above the tracker, the feedback from the photoresistors enables the servomotors to track it and follow.

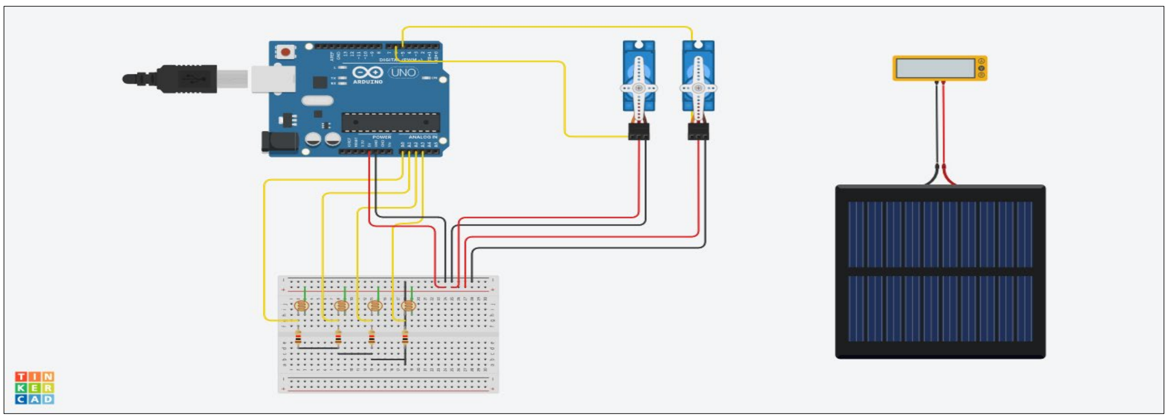


Figure 2. TinkerCAD setup of the solar tracker

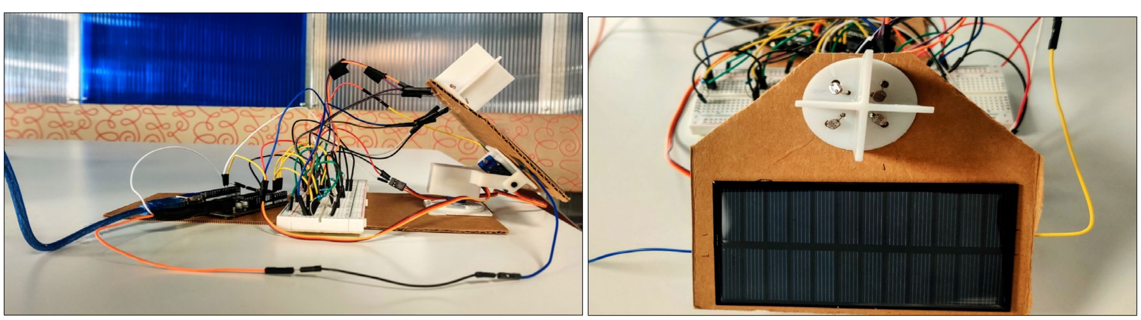


Figure 3. Physical setup of the solar tracker

The main components making up the mechatronic system are as below.

5.1 Light Dependent Resistor (LDR)

The setup includes light dependent resistors (LDRs) of 500 [Ω]. LDRs are non-polar, passive components that decrease their resistance depending on increasing exposure to light (irradiance in our case). Four LDRs are used here, each separated by wall mounts to detect light variations and abundance more accurately.

Compared to photoresistors, photodiodes and phototransistors do not fare as well. Phototransistors do not function effectively under low light conditions, and photodiodes are unidirectional in setting which makes their setup more complex.

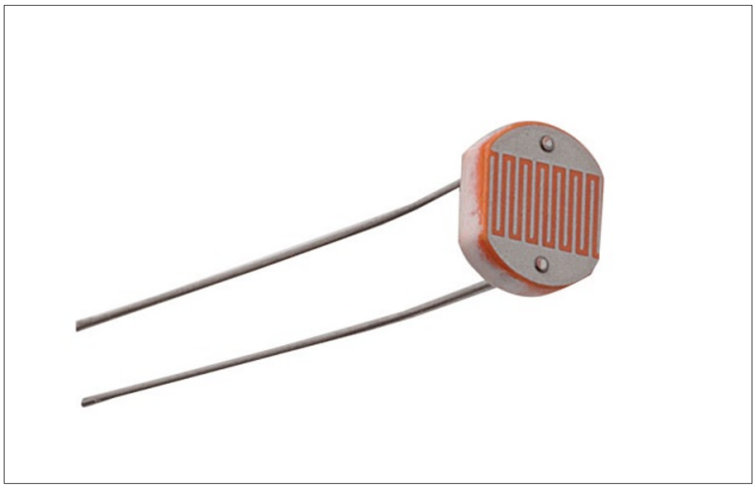


Figure 4. Light Dependent Resistor (LDR)

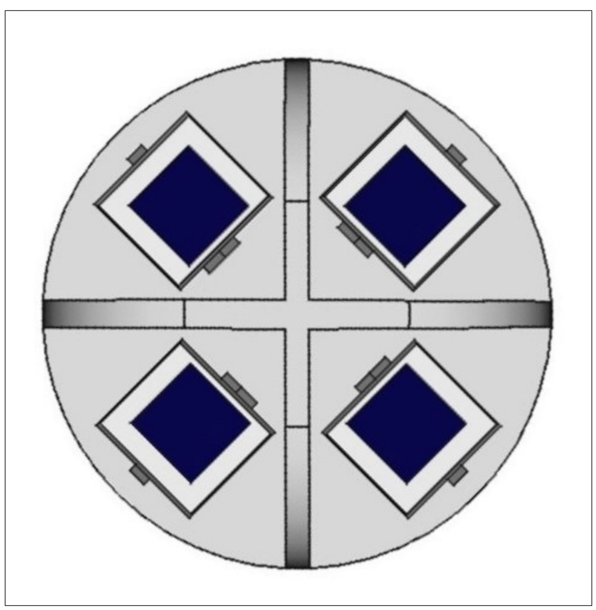


Figure 5. LDR setup with wall mounts

5.2 Servomotors

Two Micro Servo SG90 servomotors are chosen to meet the two-axis rotary-to-rotary tracking motion of this setup. It operates at a voltage of 4.8 ~ 6 [Volts] rotating up to 180-degree angles (both ways) at 0.12~ 0.15 [seconds] with a torque of 2.5 $[kg \cdot cm]$. Along with these criteria, these motors were chosen to suit the Arduino UNO setup which runs at 5 [Volts].

These motors are set up perpendicularly to each other to mimic the two-action tracking and respond to feedback from LDRs at a set delay period of 10 [seconds].

5.3 Solar Panel

A 6 [Volt] 1 [Watt] 230 [mA] solar panel with a 73% performance ratio is used to study the power generated using solar irradiance.

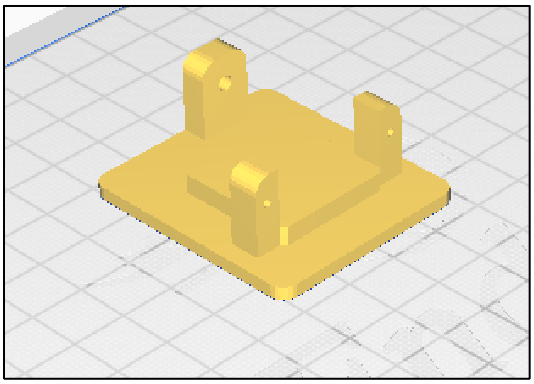
Fig 5. Uxcell's 1-Watt Solar Panel

5.4 Arduino Uno

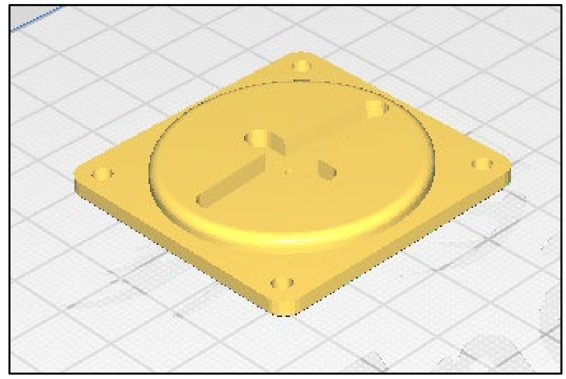
Arduino Uno is an open-source microcontroller board based on the programmable electronic controller Microchip ATmeda328P. It has 14 digital I/O pins and 6 analog I/O pins and is programmable with the Arduino IDE. The IDE easily connects a laptop to the Arduino board via a type B cable. A 5 [Volt] power port supplied power to the whole circuit.

5.5 3D-printed support structures

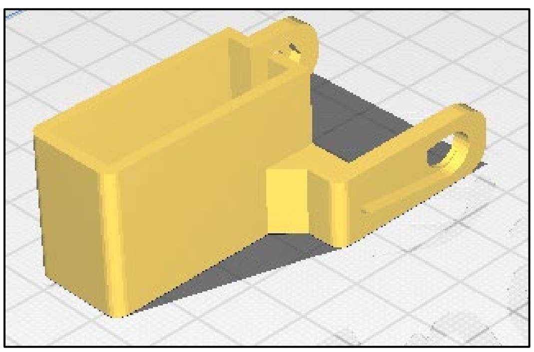
Support structures were identified, designed in CAD and 3D printed using Polylactic Acid (PLA) at Professor Cindy's Laboratory in ASU.



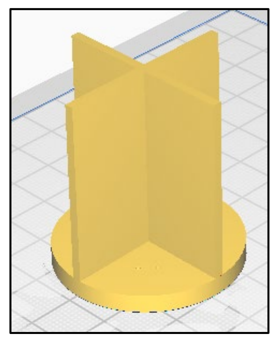
(a)



(b)



(c)



(d)

Figure 6. 3D designs of structures
(a) *Attachment for servo (Top - Down) (b) Base attachment*
(c) Attachment for servo (Left - Right) (d) LDR separation mount

5.6 Software

Arduino IDE is a platform employed to write commands for the tracker. It is primarily programmed in C language and provides feedback outputs to calibrate the tracker.

TinkerCAD is used to create a digital version of the Arduino IDE and is used to set up a CAD model of the actual setup. This allows us to run simulations to verify our code and calculations, along with ensuring that appropriate connections are established, and the feedback system is complete and operational.

6 Methodology/ System Operation

The algorithm for the solar tracker is based on one which works in a closed loop system with feedback from four photoresistors mounted separately with a physical barrier in between to ensure accuracy.

The feedback from the top two photoresistors is averaged and compared to the bottom two to determine up-down motion which gets communicated to its servomotor. Correspondingly, the two on the left and right each get averaged and compared to determine left-right motion which gets communicated to its servomotor.

Based on the LDR reading values printed while executing the code, we found that a threshold value of approximately 70 [Ω] would enable the photoresistor to trigger in indoor lighting conditions, variations in lighting provided by a light source at approximately 100 lumens.

An appropriate step size of 10 $\left[\frac{seconds}{minute}\right]$ was chosen which enabled fair motion without damaging the setup, along with a delay of 50 [milliseconds].

Mechanical Systems:

Servomotors: These are used to control the up-down and left-right motion of the solar tracker based on feedback received from the photoresistors.

Control Systems:

Feedback Loop Algorithm: The algorithm, which operates in a closed-loop system, processes the input from the photoresistors to control the servomotors. It computes average readings, compares them, and determines the motion needed to optimally align the solar tracker.

Step size and delay settings: These settings in the control algorithm dictate the timing and extent of motions, ensuring smooth and safe operation without damaging the mechanical components.

Electronic Systems:

Photoresistors (Light Dependent Resistors, LDRs): These sensors detect light intensity and provide the necessary feedback to the control system about the position of the light source.

Arduino Uno: This is the electronic unit responsible for providing signals, power and controlling the entire circuit.

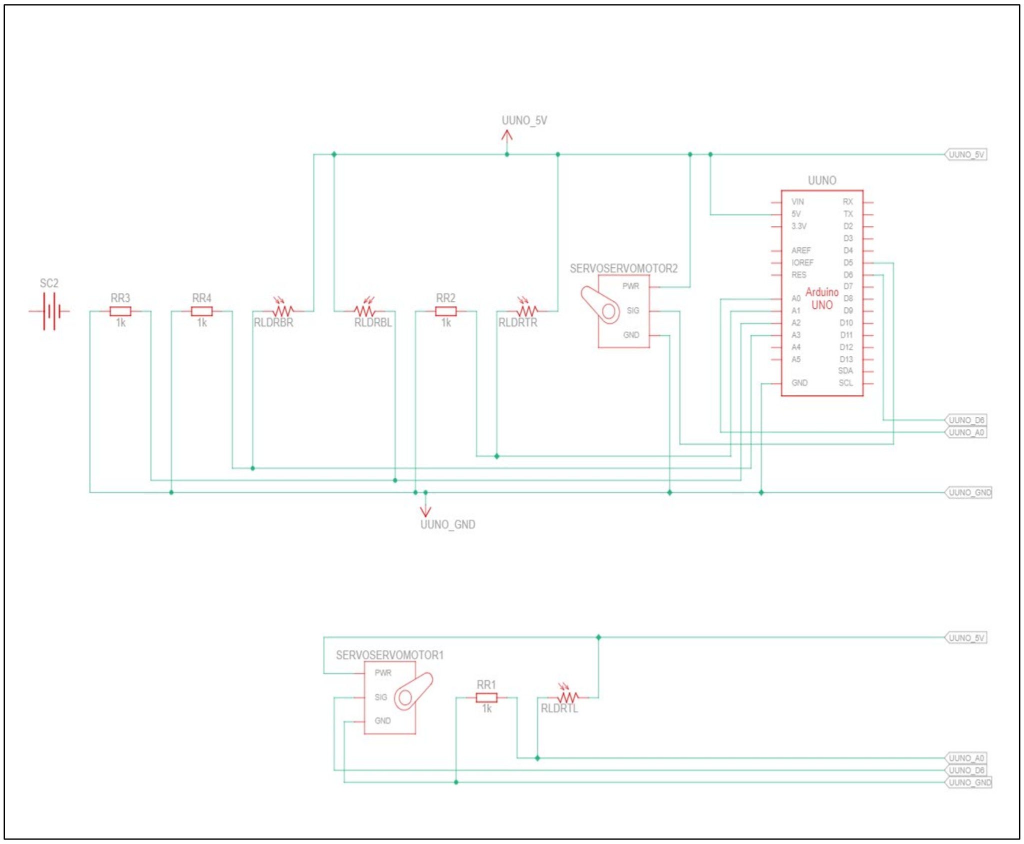


Figure 7. Wiring Diagram of the Solar Tracker Circuit

7 Challenges

- The components used for the prototype were 3D-printed. They were brittle and would easily break during installation. Using flexible materials like Thermoplastic Polyurethane (TPU) or subtractive manufacturing can be more efficient for fabricating support structures.

- Calibrating the system indoors varied the threshold value depending on lighting conditions, leading us to alter values in the setup code.

8 Summary and Conclusion

The tracker was designed based on the Arduino-based system on the skeleton of a paper published by Morón et al., 2017 [4] and other class homework. We have designed the system after calculations and sizing necessary components. After setting up the circuit, the tracker was able to follow the light source as reflected by varying photoresistor output data as attached under Section 12 Appendix 3. A video of the tracker working is also submitted under 'Application project development video' in Canvas.

The 2-axis solar tracker is a miniature solution to generating small amounts of electric power intended for indoor applications. The tracking system was successfully assembled as per the circuit diagram and generated a positive power output. A system made of a few such trackers could potentially generate electricity to power a few LED bulbs. Application of newer technologies like concentrated photovoltaics along with improved accuracy via Fresnel lens could provide an advanced concentration ratio of approximately 1000 [suns], generating sufficient energy to power all light sources in a household with only 4 sun hours.

9 Improvements and Evaluation

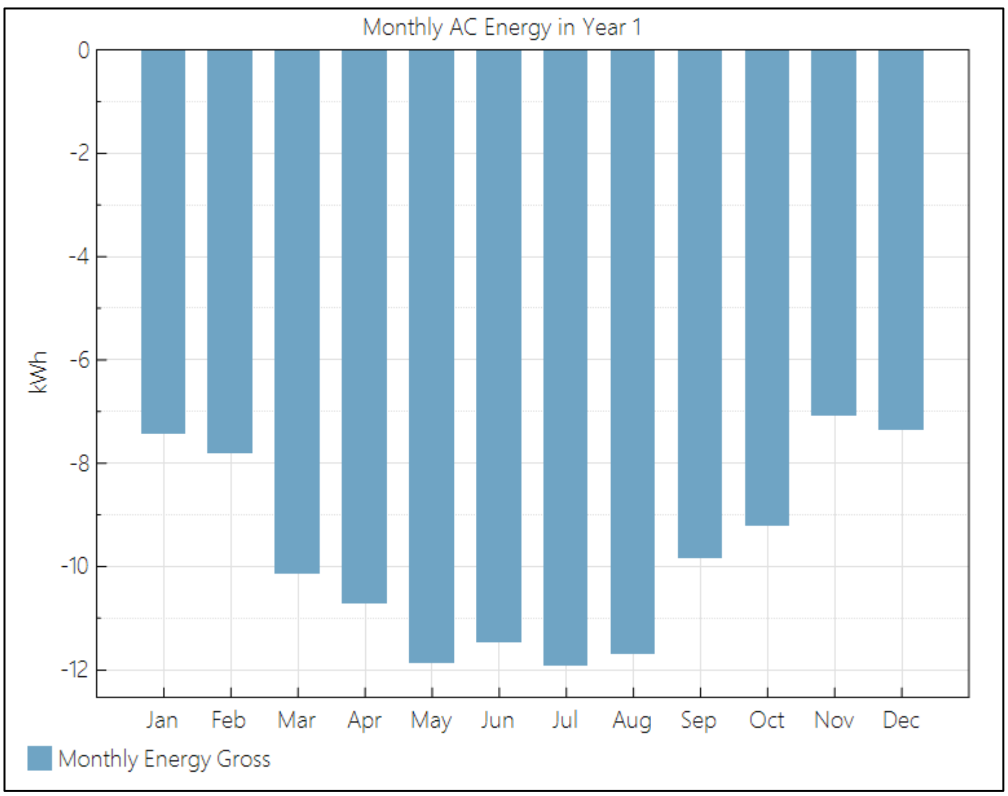
Based on our literature review and experience working with the tracker, the following improvements could be made on the model:

1. Adding a data logger would calculate how much solar energy is effectively generated by the panel by 2-axis tracking in Arizona.

2. Initially, we planned on using a HCPV module, but it's limited availability and inactive testing in lower power made it difficult to procure. This, along with a Fresnel lens, would have been ideal for our project. An energy study conducted for such a unit is modeled in System Advisor Model (SAM) and attached under Section 12 Appendix 2.

3. Our intention was to demonstrate the solar tracking capabilities of the tracker, but the next step after the energy studies of the prototype unit would be to link up more such units with HCPV units to generate more energy.

Appendix 2 is the energy study for a 2-axis tracking high-concentrated PV unit made on NREL's System Advisor Model (SAM) software. A standard HCPV cell of 12 cm^2 with 36% efficiency and a 1000x sun concentration ratio could generate 117 kWh annually, which equates to 320 Whrs/day. Four such units could generate as much power as a Silicon-based solar panel of 1m^2 which covers 90% of the current global market. The levelized cost of energy for a single unit would be 28 cents/kWhr considering the higher prices locally in the USA but was found to be nearly 13 cents/kWhr if Chinese components were considered. With the US solar markets and government policies closing these cost differences via the Inflation Reduction Act (IRA), these LCOEs are soon achievable. Such LCOE rates could also meet the SunShot 2030 initiative of the U.S. DOE to make solar energy more cost competitive for residential units [5].



(a)

Metric	Value
Annual AC energy (year 1)	-117 kWh
DC capacity factor (year 1)	-4.1%
LCOE Levelized cost of energy	-28.00 ¢/kWh

(b)

Metric	Value
Annual AC energy (year 1)	-117 kWh
DC capacity factor (year 1)	-4.1%
LCOE Levelized cost of energy	-13.00 ¢/kWh

(c)

Figure 8. SAM simulation for a single HCPV unit
(a) Energy Output Annual Distribution (b) Energy Output Annually + LCOE in USA
(c) Energy Output Annually + LCOE for Chinese components

10 Contribution Table

Tushar Vishwanath	Planned the design and prototyping of components; assisted in assembling, planning, sourcing of all components and equipment required for the setup. Formulated and troubleshot code, setup connections. Organized video presentation.
Anand Anil Kumar	Prepared literature review, report writing, SAM energy study, presentation. Assisted in model setup, troubleshooting code.
Sobha Srujana Patri	Assisted with circuit setup, presentation demo. Included challenges, improvements in report. Made class presentation, video editing.
Tolemy Nibi	Assisted with writing and checking the report for grammar and spelling. Helped assemble the solar tracker.

Table 2. Contribution Table

11 References

1. Gagnon, P., Margolis, R., Melius, J., Phillips, C., & Elmore, R. (2016). Rooftop solar photovoltaic technical potential in the United States: A detailed assessment (Technical Report NREL/TP-6A20-65298). National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy16osti/65298.pdf
2. Horne, S., & Lasich, J. (2021). Concentrating photovoltaic systems and applications. *In Concentrating Solar Power Technology* (pp. 357-379). Elsevier. https://doi.org/10.1063/1.5053493
3. Jones-Albertus, R., Feldman, D., Fu, R., Horowitz, K., & Woodhouse, M. (2016). Technology advances needed for photovoltaics to achieve widespread grid price parity. Progress in Photovoltaics: Research and Applications, 24(10), 1272-1283. https://doi.org/10.1002/pip.2755
4. Morón, C., Ferrández, D., Saiz, P., Vega, G., & Díaz, J. P. (2017). New Prototype of Photovoltaic Solar Tracker Based on Arduino. Energies, 10(9), 1298. https://doi.org/10.3390/en10091298
5. U.S. Department of Energy. (n.d.). SunShot 2030. Office of Energy Efficiency & Renewable Energy. Retrieved April 29, 2024, from https://www.energy.gov/eere/solar/sunshot-2030
6. Makeability Lab. (n.d.). Photoresistors. Retrieved from https://makeabilitylab.github.io/physcomp/sensors/photoresistors.html

12 Appendix 1

```
#include <Servo.h>

// Initialize variables
int ldrtopr = A0;    // Top-right LDR
int ldrtopl = A1;    // Top-left LDR
int ldrbotr = A2;    // Bottom-right LDR
int ldrbotl = A3;    // Bottom-left LDR

Servo servo_updown;
Servo servo_rightleft;

int threshold_value = 30;  // Threshold value for sensitivity
int step_size = 10;        // Adjust the step size for even faster movement

void setup() {
  Serial.begin(9600);  // Serial communication setup

  servo_updown.attach(5);     // Servo motor for up-down movement
  servo_rightleft.attach(6);  // Servo motor for right-left movement
}

void loop() {
  int topr = analogRead(ldrtopr);
  int topl = analogRead(ldrtopl);
  int botr = analogRead(ldrbotr);
  int botl = analogRead(ldrbotl);

  // Calculate average values for elevation and azimuth
  int avgtop = (topr + topl) / 2;
  int avgbot = (botr + botl) / 2;
  int avgleft = (topl + botl) / 2;
  int avgright = (topr + botr) / 2;

  // Calculate differences in elevation and azimuth
  int diffelev = avgtop - avgbot;
  int diffazi = avgright - avgleft;

  // Adjust servo position for azimuth
  if (abs(diffazi) >= threshold_value) {
    if (diffazi > 0) {
      if (servo_rightleft.read() < 180 - step_size) {
        servo_rightleft.write(servo_rightleft.read() + step_size);
      }
    } else {
```

```
    if (servo_rightleft.read() > 0 + step_size) {
      servo_rightleft.write(servo_rightleft.read() - step_size);
    }
  }
}

// Adjust servo position for elevation
if (abs(diffelev) >= threshold_value) {
  if (diffelev > 0) {
    if (servo_updown.read() < 180 - step_size) {
      servo_updown.write(servo_updown.read() + step_size);
    }
  } else {
    if (servo_updown.read() > 0 + step_size) {
      servo_updown.write(servo_updown.read() - step_size);
    }
  }
}

delay(100); // Adjust delay as needed
}
```

13 Appendix 2

System Advisor Model Report

High Concentration PV	0.32 kW Nameplate	33.45, -111.98
LCOE Calculator		UTC -7

Performance Model

Modules	
Concentration ratio	1,000 X
Cell area	12 cm²
Module area	1.2 m²
Module capacity	321.9 DC Watts
Quantity	1 Modules
Total area	1.2 m²
Total capacity	321.9 DC Watts

Inverters	
<null>	
Unit capacity	384 AC Watts
Input voltage	38 - 43 VDC DC V
Quantity	1
Total capacity	384 AC kW
DC to AC Capacity Ratio	0.00
AC losses (%)	0.99

Array	
Modules per tracker	1 Modules
Trackers	1 Units
Shading	no
Soiling	yes
DC derate factor	0.93

Performance Adjustments	
Availability/Curtailment	0.12%
Degradation	none
Hourly or custom losses	none

Annual Results (in Year 1)	
DNI	7.00, kW/m²/day
POA irradiance on cell	0.00, kW/m²/day
Gross from array	10 DC kWh
Net to inverter	0 DC kWh
Gross from inverter	0 AC kWh
Net to grid	-110 AC kWh
Capacity factor	-4.14%

Financial Model

Project Costs	
Capital cost	$205
Fixed operating costs	$5
Variable operating costs	$0

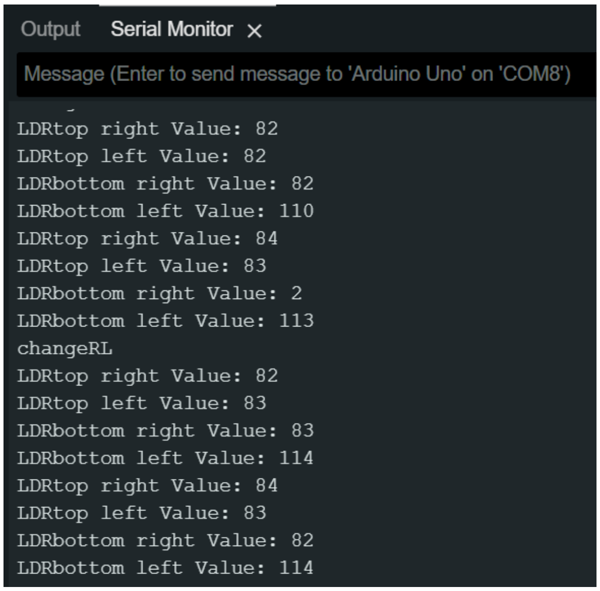
Financial Parameters	
Fixed charge rate	13.51%
Capital recovery factor	0.125
Project financing factor	1.065
Construction financing factor	1.012

Results	
LCOE (FCR Method)	-28 cents/kWh

14 Appendix 3

Screenshot of Output Values from 4x LDRs at varying light intensities

1. Bottom Left LDR lit

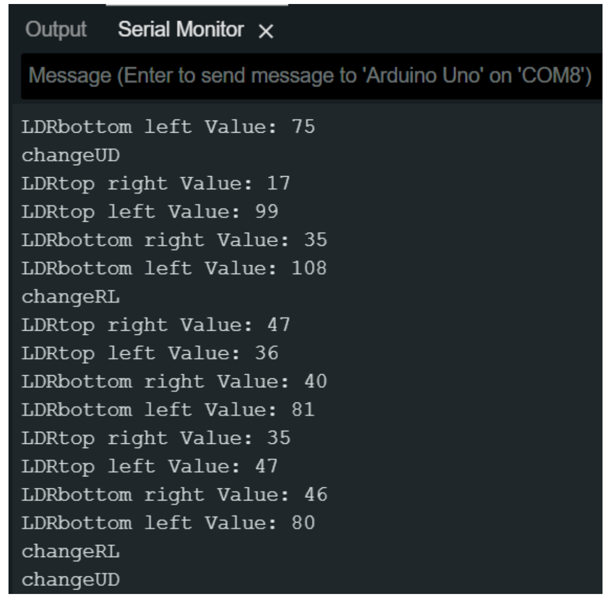


```
Output   Serial Monitor ×
Message (Enter to send message to 'Arduino Uno' on 'COM8')
LDRtop right Value: 82
LDRtop left Value: 82
LDRbottom right Value: 82
LDRbottom left Value: 110
LDRtop right Value: 84
LDRtop left Value: 83
LDRbottom right Value: 2
LDRbottom left Value: 113
changeRL
LDRtop right Value: 82
LDRtop left Value: 83
LDRbottom right Value: 83
LDRbottom left Value: 114
LDRtop right Value: 84
LDRtop left Value: 83
LDRbottom right Value: 82
LDRbottom left Value: 114
```

2. Bottom Right LDR lit

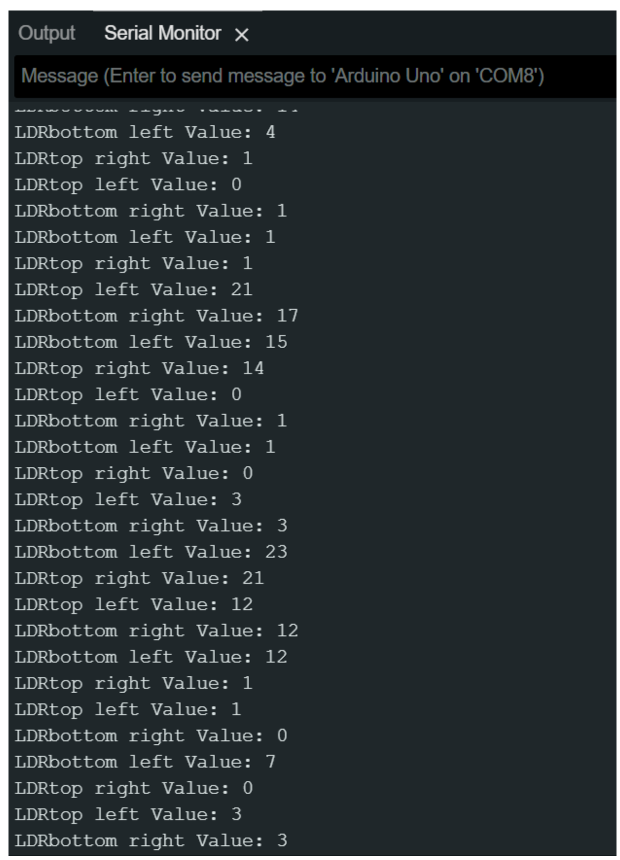
```
Output   Serial Monitor ×
Message (Enter to send message to 'Arduino Uno' on 'COM8')
LDRbottom right Value: 107
LDRbottom left Value: 83
changeUD
LDRtop right Value: 43
LDRtop left Value: 47
LDRbottom right Value: 25
LDRbottom left Value: 41
LDRtop right Value: 39
LDRtop left Value: 46
LDRbottom right Value: 32
LDRbottom left Value: 33
LDRtop right Value: 44
LDRtop left Value: 30
LDRbottom right Value: 39
LDRbottom left Value: 55
LDRtop right Value: 20
LDRtop left Value: 35
LDRbottom right Value: 28
LDRbottom left Value: 40
```

3. Top Left + Bottom Left LDR lit



```
Output   Serial Monitor ×
Message (Enter to send message to 'Arduino Uno' on 'COM8')
LDRbottom left Value: 75
changeUD
LDRtop right Value: 17
LDRtop left Value: 99
LDRbottom right Value: 35
LDRbottom left Value: 108
changeRL
LDRtop right Value: 47
LDRtop left Value: 36
LDRbottom right Value: 40
LDRbottom left Value: 81
LDRtop right Value: 35
LDRtop left Value: 47
LDRbottom right Value: 46
LDRbottom left Value: 80
changeRL
changeUD
```

4. Close to 0 illumination



```
Output   Serial Monitor ×
Message (Enter to send message to 'Arduino Uno' on 'COM8')
LDRbottom left Value: 4
LDRtop right Value: 1
LDRtop left Value: 0
LDRbottom right Value: 1
LDRbottom left Value: 1
LDRtop right Value: 1
LDRtop left Value: 21
LDRbottom right Value: 17
LDRbottom left Value: 15
LDRtop right Value: 14
LDRtop left Value: 0
LDRbottom right Value: 1
LDRbottom left Value: 1
LDRtop right Value: 0
LDRtop left Value: 3
LDRbottom right Value: 3
LDRbottom left Value: 23
LDRtop right Value: 21
LDRtop left Value: 12
LDRbottom right Value: 12
LDRbottom left Value: 12
LDRtop right Value: 1
LDRtop left Value: 1
LDRbottom right Value: 0
LDRbottom left Value: 7
LDRtop right Value: 0
LDRtop left Value: 3
LDRbottom right Value: 3
```