

ECE 445

SENIOR DESIGN LABORATORY, SPRING 2026

FINAL REPORT

SolarTrack

Team #7

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May 6, 2026

Abstract

This project designs and implements a self-repositioning solar panel system that dynamically adjusts its orientation to maximize energy capture throughout the day. The system uses light dependent resistors (LDRs) to detect incident light direction and an ESP32 microcontroller to control two axis servo motors for panel alignment. Power from the solar panel is managed through a maximum power point tracker (MPPT) module and a 12V battery, with onboard voltage regulation for system components. Experimental testing compared the tracking system to a fixed position panel under similar conditions. Results show a 17.6% increase in peak power output and a 36.3% increase in total energy harvested over a full cycle. These improvements demonstrate that the repositioning system does enhance solar energy efficiency while maintaining stable operation, validating the effectiveness of an autonomous solar tracking solution.

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1 Introduction

This section outlines the limitations of fixed position solar panels and the resulting loss in energy efficiency throughout the day. It then presents SolarTrack, a self repositioning system that is able to dynamically align a solar panel with the sun to maximize energy harvesting potential.

1.1 Problem

With increasingly rising energy demands across the globe, societies are looking at renewable sources to power communities and prevent greenhouse gas emissions from climate change. For example, the International Energy Agency notes how solar is one of the most rapidly developing means of energy generation across the globe, but efficiency remains a key concern. Static solar panels only absorb the optimal amount of energy when the sun is shining perpendicular to the surface of the panel. However, the sun moves every instant of the day at around 15 degrees per hour and in a different position at different times of the year. Thus, solar panels installed in fixed locations often operate far below their theoretical power generation capabilities. Power not harnessed is energy that could have supported homes, buildings, infrastructure, and other vital systems.

Energy efficiency isn't only a matter of improved environmental conditions, it's also an economic opportunity and a matter of social benefits. If panels can absorb more energy, there's a reduced need for fossil fuels and a stabilized grid. Long term, financial output for consumers is drastically lessened. From a social benefit perspective, increased use of renewable resources in systems provides cleaner air and fewer health concerns from pollution. Furthermore, for developing countries or rural areas with minimal electrical infrastructure, supporting one solar installation to operate at maximum capacity increases potential for energy access and resiliency. Energy efficiency also supports international efforts, like the United Nations Sustainable Development Goal 7, Affordable and Clean Energy. In stark contrast to that, commercial tracking systems are often monetarily expensive or too mechanically complex to make them worthwhile. A solution must be found that meets energy generation performance and reliability without making the product overly expensive. Thus, the product must bridge the gap by creating a system that can continuously adapt to environmental variables while remaining safe and reliable.

1.2 Solution

The project detailed here creates SolarTrack, a solar panel system that positions itself to get the most energy potential through total light capture. Instead of a fixed mounting setup, this system takes constant measurements of light intensity from varied angles and uses servos to position itself. By tracking the sun as it moves, the project aims to increase power output while providing a modular, scaled approach to smart, renewable infrastructure. SolarTrack operates as an embedded system by combining sensing, computation, power and actuation. Photoresistor sensors will notice different light intensities based on angles, and a microcontroller will assess the differences and determine the ideal

setup. The microcontroller will send signals to two axis servos that will move the system to get the solar panel in the correct position. The position of the panel will also provide information to the microcontroller through power monitoring capabilities of the power subsystem, which includes two voltage regulators and power rails. The energy captured from the solar panel will be fed through an energy management portion which regulates battery charging and electronics use. These subsystems will create a resilient product with minimal human interaction thanks to a communications interface for troubleshooting during development. All of these systems function as a closed loop control system that operates without any outside interaction. Experimental testing demonstrated clear improvements in performance compared to a fixed position panel, with a 17.6% increase in peak power output and a 36.3% increase in total energy harvested. These results confirm the effectiveness and viability of the SolarTrack system as an autonomous solar optimization solution.

1.3 System Block Diagram

The system block diagram shown in Figure 1 is divided into sensing, control/compute, power, actuation, and communication subsystems, along with a power monitoring module. The system is powered by a 50W solar panel providing approximately 18-23V, which is processed by a maximum power point tracking (MPPT) module to efficiently charge the 12V battery that serves as the primary energy source for the repositioning system. The power subsystem includes DC/DC converters that generate regulated voltage rails, with 3.3V supplied to the microcontroller and sensing circuitry and a separate 6V rail designed for the servo motors to reduce electrical noise and improve stability. The sensing subsystem consists of eight light dependent resistor (LDR) sensors that measure light intensity from multiple directions with analog signals read through the microcontroller's analog digital converter (ADC) channels to determine the best panel orientation. The system was originally designed with four LDRs, but this was expanded to eight to improve directional accuracy and tracking precision. The control/compute subsystem processes sensor inputs and generates PWM signals to drive two servo motors in the actuation subsystem, enabling dual-axis positioning of the panel. The communication subsystem supports both internal and external data transfer, using a USB-to-UART interface for debugging and logging and I2C for interfacing with the power monitoring module, while ADC and PWM signals enable coordination between sensing and actuation. The power monitoring subsystem uses a current sense shunt resistor and an I2C-based monitoring IC to measure voltage and current, providing real-time feedback on system performance. The information collected by the power monitoring system is sent to a web dashboard via the microcontrollers built in WIFI module. All subsystems operate together as a closed loop system which enables autonomous solar tracking and improved energy harvesting.

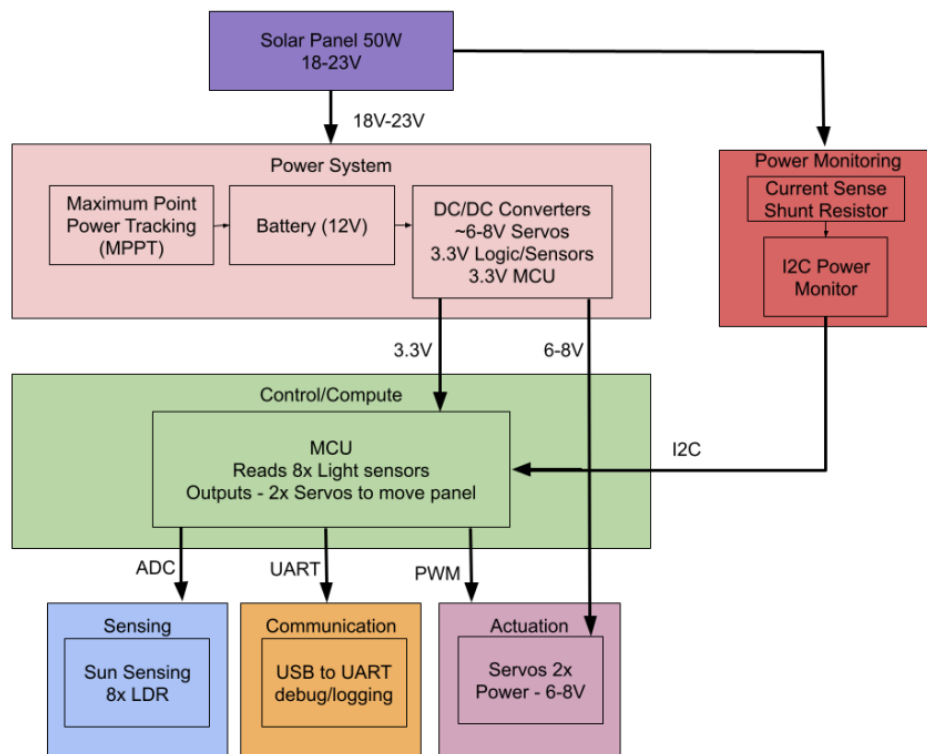


Figure 1: The SolarTrack block diagram.

2 Design

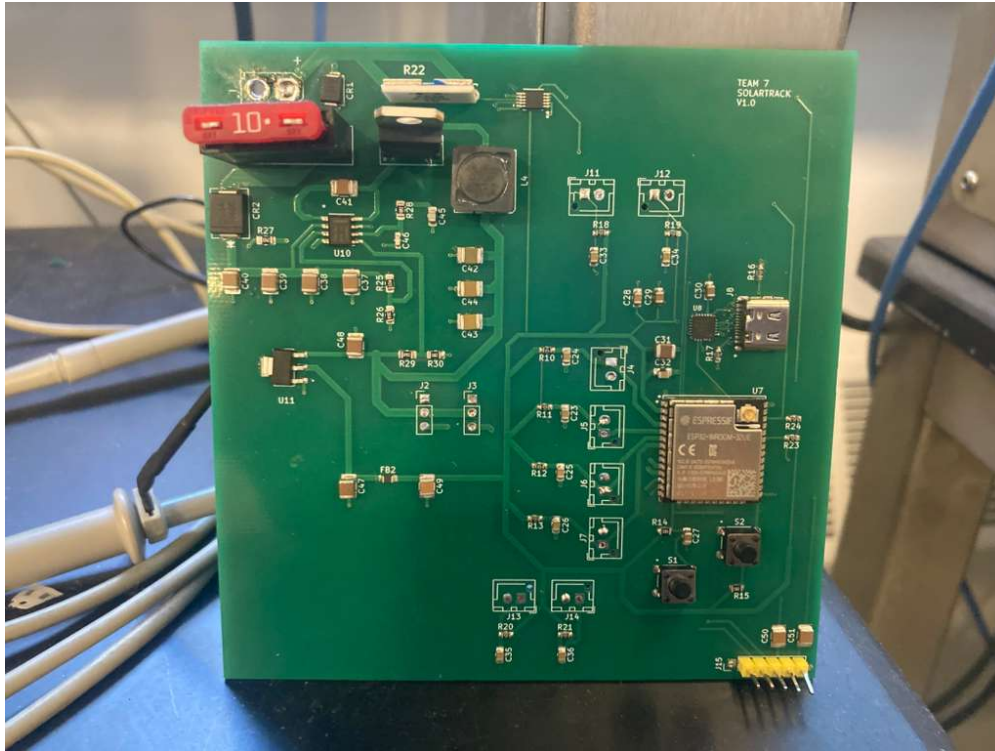


Figure 2: The SolarTrack PCB.

2.1 Solar Panel

The solar panel is the main energy source of the entire system. The solar panel we selected produces 50 Watts of power with an operating voltage between 18 and 23 Volts and an operating current between 2 and 3 Amperes. The power harvested by the panel is monitored by the power monitoring system, and the energy goes to the MPPT, charging the battery, which in turn powers all the electronics.

One of the main design challenges with the solar panel was the tradeoff between energy harvesting and the size/weight of the panel itself. While a larger panel would allow for increased energy capture, this would come with the drawback of needing far more powerful servos to allow it to move, along with a larger assembly to mount it and facilitate its rotation. This would lead to significant increases in cost and power draw from the servos. On the other hand, a smaller solar panel, while reducing costs and power draw, would, for obvious reasons, harvest far less energy than a larger solar panel would. The panel we selected, at its 50 Watt power output, represents a compromise between these needs, being large enough to provide a meaningful amount of energy without forcing us to use more expensive, more power-hungry servos.

2.2 Power System

2.2.1 MPPT

The MPPT module (Maximum Power Point Tracking) is a commonly used system in solar charge controllers. Ordinarily, a solar panel is forced to operate at the battery voltage to charge properly. Especially given that our solar panel operates in the 18-23 Volt range while the battery operates at 12 Volts, this is suboptimal. The MPPT continually adjusts the panel voltage to keep it at the power-maximizing point of its I-V curve before stepping down the voltage to allow the battery to charge. This results in efficiency gains usually of the order of 20 to 30 percent. The MPPT takes the solar panel's energy and uses it to charge the battery.

2.2.2 Battery

The battery subsystem connects to the DC-DC converters, which, in turn, connect to the circuit itself. We use a 12 Volt, 9 Amp-hour sealed lead acid battery for this subsystem. Between an SLA battery and a lithium-ion battery, while lithium-ion batteries are lighter, they are also more expensive, and given that the battery is stationary in our system, the weight is not a meaningful consideration. SLA batteries are also more robust and can handle adverse weather conditions (especially the cold) better than lithium-ion batteries, which makes an SLA battery preferable.

The battery we chose is also preferable due to its high capacity. With 12 Volts and 9 Amp-hours, this battery provides a "buffer" of 108 Watt-hours. That is, in conditions where the solar panel is unable to generate energy (extreme inclement weather, nighttime, obstruction on the panel itself), the system has 108 Watt-hours of available energy before the battery is drained. In our tests, we saw a power draw of roughly 1.8 Watts during rotation (which only happened for a few seconds every hour in total), meaning that this battery can sustain 60 hours of rotation, which is more than enough to sustain it through such conditions.

2.2.3 DC/DC Converters

Although the battery provides a 12 Volt potential difference, this is insufficient for the electronics of the system. The servos operate between 6 and 8.4 Volts, and the MCU requires both a 3.3 Volt input and that all ADC pins, when in use, are supplied a voltage between 0 and 3.3 Volts. To that end, we use two DC-DC converters: a 12V to 6V buck converter, and a 6V to 3.3V LDO (low-dropout regulator). The 6V rail is then used by the actuation system, while the 3.3V rail is used by the control/compute and sensing systems. For going from 12 Volts to 6 Volts, a buck converter is preferred because buck converters offer high efficiency, especially given the high step-down and the potentially high current draw (which can go up to 5 Amps if both servos are on and facing resistance) from the actuation subsystem. For going from 6 Volts to 3.3 Volts, an LDO is preferred specifically because an LDO offers a low-noise signal. This is critical for the control/compute subsystem, as the MCU requires a stable input to avoid brownouts from the voltage momentarily

dipping too low. Given the requirement that the ADC pins do not receive voltages above 3.3 Volts, this is also important for the sensing subsystem, as any fluctuation that causes the voltage input to the sensing subsystem to increase could lead to damaging the ADC pins. Figure 3 below is a schematic of the DC-DC converters - the buck converter is on top, the LDO is on the bottom. Notice how much buffering and protection is needed for the buck converter as compared to the LDO.

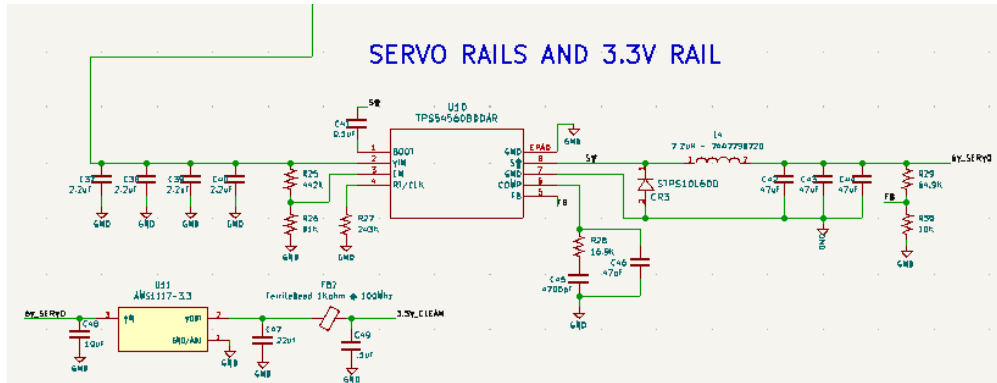


Figure 3: The DC-DC converters.

2.3 Power Monitoring

To monitor the power generated by the solar panel, we place a current sense shunt resistor in series with the panel output, which creates a small voltage drop. An I2C power monitor uses this voltage drop to compute the current, thus measuring the panel voltage. The voltage and current readings are sent to the MCU over I2C. When multiplied, the current and voltage readings provide the power harvested from the solar panel, allowing for long-term monitoring of the solar panel's performance.

2.4 Control/Compute

We use an ESP32-WROOM series microcontroller for the control/compute subsystem. This microcontroller runs the tracking algorithm, which takes input data from the sensing subsystem and outputs data to the actuation subsystem. The input is read as 12-bit ADC (values between 0 and 4095) from eight different light sensors – four mounted on the corners of the panel, four mounted on the corners of the base. The output is a PWM signal to each servo – one servo controls elevation; one controls azimuth. The sensors on the base inform the direction in which the system must position the solar panel, and the sensors on the panel allow the system to stop rotation once all the sensors read identical (within a margin of error) values. We specifically chose this microcontroller because of its built-in Wi-Fi capabilities. The Wi-Fi capabilities, along with USB to UART, are used for communication, elaborated on in the communication subsystem. Perhaps most importantly, the USB to UART connection allows for flashing programs onto the MCU, which enables us to run the previously-described tracking algorithm. The control/compute subsystem is powered by the 6V to 3.3V LDO.

2.5 Sensing

The eight light sensors are each a voltage divider consisting of a 4.7 kOhm resistor and an LDR / photoresistor. As LDRs have high resistance in the dark and low resistance in the light, the LDR will thus have a significantly lower potential difference over it when in light. The sensing subsystem is also powered by the LDO.

It is necessary that the sensing system produces stable output to the ADC pins, as small fluctuations and occasional jittering could result in massive losses in energy efficiency. At best, the servos unnecessarily move, increasing the power draw, and at worst, the solar panel is facing the wrong direction, leading to an overall efficiency loss. As energy efficiency is so pivotal to this project and noisy input directly threatens that, we include a capacitor as part of the overall light sensor circuit. This capacitor effectively creates a low-pass filter with a cutoff frequency ($1 / 2\pi RC$) of around 1500 Hz, which is sufficient for removing noise without tampering with the actual signal of the sun's movement. Figure 4 shows the schematic for one of these light sensors, complete with the resistor, capacitor

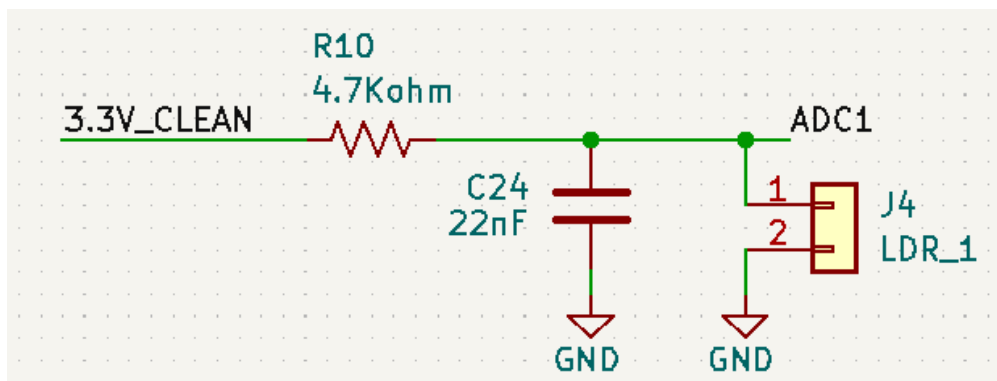


Figure 4: The light sensors.

2.6 Communication

There are two primary methods of communication used in the communication subsystem. The first method is USB to UART. This allows us to connect a laptop/PC to the MCU, thus allowing us to flash programs onto it and debug through print statements. This significantly eases the development and testing cycle on the software side. Without the ability to debug via print statements, development of the algorithm in the initial stages would have been significantly harder. As the MCU receives all the sensor data and outputs the motor PWM signals, practically all the internal information of the system is available through print statements. The ability to see all this data also made searching for hardware problems easier. For example, if an LDR was consistently reading no value or garbage data, it likely meant that a connection had popped loose. Likewise, if a signal was being sent to a servo but the servo was not rotating, it meant that the servo wires were disconnected. As the project has many moving parts and many wires, such errors are not

always obvious at first glance, and having a way to immediately notice this through the print statements significantly sped up the development process.

The other method, and the main reason we specifically chose the MCU we did, is Wi-Fi through an antenna. This allows for long-term data collection and the usage of a web UI to actively display the collected data. Without the Wi-Fi connection, overall, field testing would have been more difficult, as we would have had to have left a laptop next to the panel all day as we collected data, feeding the MCU's readings (from the USB to UART connection) into another program to perform calculations and create graphs. As we tested over long periods of time (6+ hours), leaving a laptop next to the solar panel was not feasible. Thus, the Wi-Fi made the overall setup for our experiments possible.

2.7 Actuation

Actuation is done with two servo motors, one for elevation and one for azimuth. These motors are powered by the 12V to 6V buck converter, and the PWM signal is received from the control/compute subsystem. The primary design consideration for this subsystem was the use of servo motors vs stepper motors. Stepper motors have a higher power draw when resting than servos do. The specific servos we chose (DS5160) have a relatively low current draw (in most cases, only 1.8 Watts in motion) and have 60 kg*cm torque when powered at 6 Volts, which was sufficient for moving the solar panel assembly. Additionally, unlike in most scenarios, the servo speed was nearly irrelevant for SolarTrack, so long as the servos could move the panel. This is because the Sun moves quite slowly in the sky. On a twelve-hour or longer day (any day between March 22nd and September 22nd), the Sun moves, at most, 15 degrees per hour. Servo speeds are typically measured in seconds per 60 degrees. This means we need at least 14,400 seconds per 60 degrees rotation. The servos we chose rotate at 0.17 seconds per 60 degrees, so they are indeed sufficient, as 0.17 is less than 14,400.

3 Design Verification

As part of the design verification for SolarTrack, we conducted testing to evaluate whether the final system met the functional requirements outlined during the design process. This included the validation of individual subsystems as well as testing full system performance under realistic operating conditions. Testing focused on energy generation, power regulation, sensing accuracy, actuation reliability, and overall system efficiency. Detailed requirement and verification procedures are provided in Tables 1 through 4 in the Appendix A. The following sections present the testing methodology, measured results, and analysis used to verify that each requirement was satisfied.

Outdoor testing was conducted over two clear sky days with similar sunlight conditions to ensure a fair comparison between the static and self positioning systems. The same 50W solar panel and 12V battery were used for both tests with the battery starting at approximately 60% state of charge. Each test was conducted from 9:00 AM to 3:00 PM and system performance was recorded at 10 minute intervals over the full six hour test window. Metrics used for comparison included total harvested energy over time, net energy gain from tracking, and energy overhead introduced by our tracking system.

3.1 Solar Panel and Energy Harvesting Verification

The solar panel subsystem was verified by measuring output voltage under direct illumination under various sun conditions while confirming operation within the expected range of 18-23 volts. System level testing was then conducted to compare a fixed position panel with the SolarTrack system. As shown in figure 2 and Figure 3, both systems showed similar performance during early morning hours with nearly identical cumulative energy up to approximately 11:00 AM. As the sun's position changed throughout the day, the tracking system maintained much better alignment which resulted in increased power output and far greater energy accumulation. By the end of the test period, the fixed system produced approximately 146 watt hours, while the SolarTrack system produced approximately 199 watt hours of net energy after accounting for tracking losses. This translates to a net energy gain of approximately 53 watt hours, representing a 36.3 percent increase in total harvested energy. Peak power output was also much higher in the tracking system with a maximum observed improvement of approximately 17.6 percent over the fixed configuration. These results demonstrate that dynamic tracking provides a substantial improvement in energy capture particularly during mid day and afternoon periods when misalignment losses are greatest in the static panel setup.

3.2 Power System Verification

The power subsystem was rigorously tested to ensure stable voltage regulation and sufficient current delivery under ever changing operating conditions. The 3.3 volt rail supplying the microcontroller remained within acceptable tolerance throughout the test period including during servo actuation events. To further validate the robustness of the system, stress testing was performed by gradually increasing the load on the servo power rails.

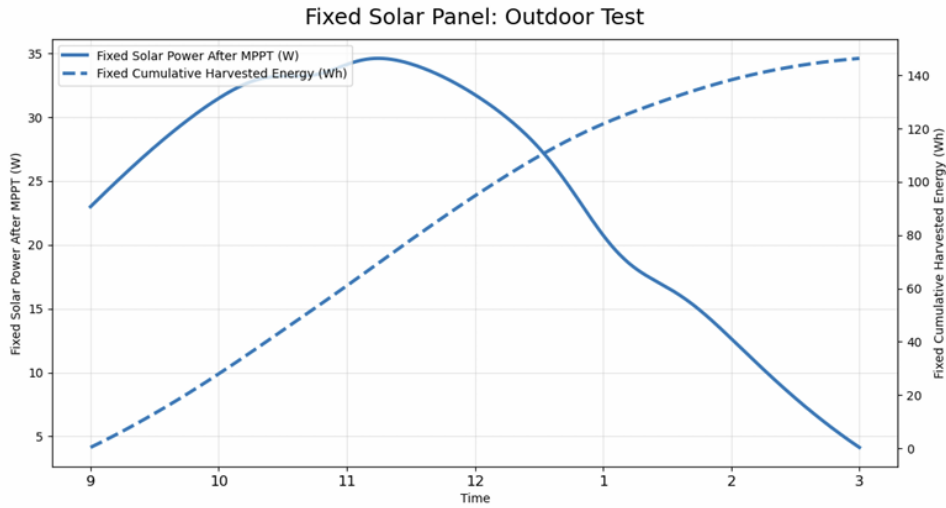


Figure 5: Fixed solar panel outdoor test.

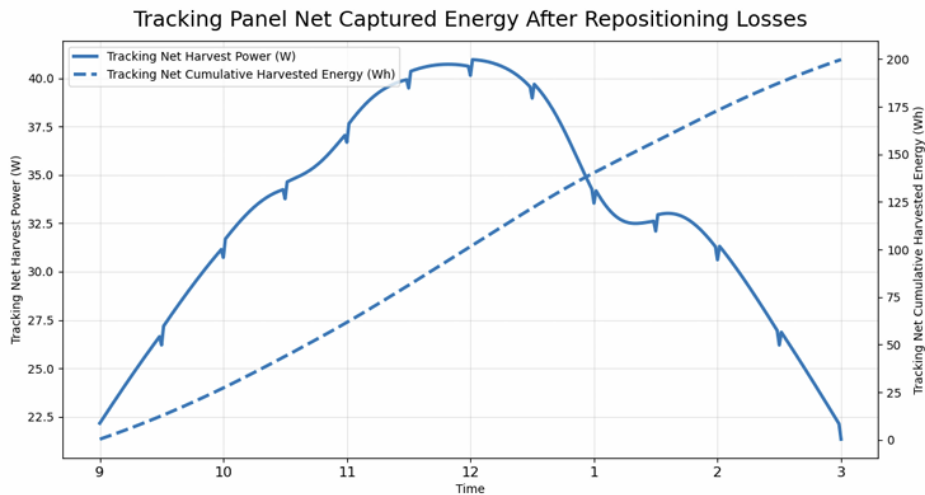


Figure 6: Tracking panel net captured energy after repositioning losses.

A single servo was first driven from low to high load conditions, including rapid position changes to simulate worst case current draw. This process was then repeated with both servos operating simultaneously to replicate peak system demand even though out system would only have one servo active at a time. During these tests, the system was monitored for voltage instability and microcontroller resets. Each servo was estimated to draw up to approximately 1.5 amperes, resulting in a combined peak current demand of approximately 3 amperes. The DC to DC converters successfully supported this load without observable voltage droop or instability, and the microcontroller maintained continuous operation with no evidence of brownout or unintended resets. This confirms that the power subsystem is capable of handling transient current spikes associated with

Time	Fixed Power (W)	Fixed Cum Harvest (Wh)	Track Gross (W)	Tracker Use (W)	Track Net (W)	Track Cum Net (Wh)	Fixed SOC (%)	Track SOC (%)	Net Gain (Wh)
9:00	22.99	0.38	22.99	0.89	22.10	0.37	58.4	60.3	-0.01
9:10	24.61	4.36	24.59	0.88	23.71	4.20	62.0	63.9	-0.16
9:20	26.17	8.61	26.14	0.86	25.28	8.30	66.0	67.7	-0.31
9:30	27.66	13.11	27.85	1.85	26.00	12.63	70.1	71.7	-0.48
9:40	29.06	17.85	29.38	0.88	28.50	17.27	74.5	76.0	-0.58
9:50	30.34	22.81	30.80	0.86	29.94	22.15	79.1	80.5	-0.66
10:00	31.48	27.97	32.38	1.82	30.56	27.25	83.6	84.7	-0.72
10:10	32.42	33.31	33.64	0.89	32.75	32.62	87.4	88.3	-0.69
10:20	33.02	38.77	34.58	0.88	33.71	38.17	90.5	91.3	-0.60
10:30	33.21	44.30	35.41	1.77	33.64	43.84	93.0	93.7	-0.46
10:40	33.22	49.83	35.93	0.88	35.05	49.64	95.1	95.7	-0.20
10:50	33.52	55.39	36.78	0.87	35.91	55.55	96.6	97.1	0.16
11:00	34.13	61.03	38.33	1.65	36.69	61.64	97.6	98.0	0.60
11:10	34.56	66.77	39.59	0.87	38.72	68.01	98.4	98.7	1.24
11:20	34.55	72.53	40.38	0.88	39.50	74.54	98.9	99.2	2.00
11:30	34.17	78.26	41.14	1.70	39.44	81.15	99.2	99.5	2.90
11:40	33.55	83.90	41.45	0.87	40.58	87.90	99.5	99.7	4.00
11:50	32.74	89.42	41.54	0.89	40.65	94.87	99.8	99.8	5.25
12:00	31.76	94.79	41.79	1.79	40.00	101.43	99.7	99.9	6.64
12:10	30.60	99.88	41.62	0.86	40.76	108.24	99.8	99.9	8.26
12:20	29.22	104.95	41.14	0.88	40.26	114.99	99.9	99.9	10.04
12:30	27.54	109.88	40.54	1.79	38.75	121.61	99.9	100.0	11.94
12:40	25.44	114.08	39.07	0.85	38.22	128.10	99.9	100.0	14.02
12:50	23.03	118.10	36.94	0.87	36.07	134.28	99.9	100.0	16.18
1:00	20.69	121.72	35.06	1.84	33.22	140.07	100.0	100.0	18.35
1:10	18.88	124.99	33.75	0.87	32.88	145.64	100.0	100.0	20.64
1:20	17.69	128.02	33.45	0.88	32.57	151.00	100.0	100.0	23.05
1:30	16.75	130.89	33.91	1.80	32.11	156.51	100.0	100.0	25.62
1:40	15.63	133.58	33.90	0.87	33.03	162.02	100.0	100.0	28.44
1:50	14.24	136.06	33.23	0.86	32.37	167.47	100.0	100.0	31.41
2:00	12.66	138.29	32.28	1.74	30.55	172.75	100.0	100.0	34.46
2:10	11.05	140.25	30.87	0.87	30.00	177.86	100.0	100.0	37.61
2:20	9.48	141.95	29.29	0.85	28.43	182.72	100.0	100.0	40.77
2:30	8.00	143.39	27.85	1.78	26.07	187.29	100.0	100.0	43.90
2:40	6.60	144.60	26.22	0.89	25.33	191.64	100.0	100.0	47.04
2:50	5.31	145.58	24.52	0.87	23.65	195.70	100.0	100.0	50.13
3:00	4.14	146.35	22.99	1.74	21.25	199.48	100.0	100.0	53.12

Figure 7: Outdoor test data of fixed and self-repositioning solar panels.

servo actuation while maintaining stable logic level operation. Battery state of charge data shown in Figure 4 further confirmed proper system operation. Both systems reached full charge during the test window however, the tracking system reached maximum charge earlier and maintained higher net energy accumulation thereafter. This indicates that the system not only meets power delivery requirements but also improves overall energy use efficiency.

3.3 Power Monitoring Verification

The power monitoring system was validated through continuous measurement during system operation. Current and voltage readings were successfully captured across the full operating range, including when testing under maximum load conditions during dual servo movement. To verify measurement accuracy the monitoring outputs were compared against measurements that were obtained using an oscilloscope. The voltage across the current sense element and system supply rails was probed directly and the resulting calculated values closely matched the readings reported by the monitoring system. This helped to confirm that the system provides reliable and accurate real time power data. As shown in the recorded data in Figure 4, tracking system power usage remained relatively low compared to total harvested energy. The tracking subsystem consumed approximately 0.85 to 0.90 watts during normal steady operation, with short peaks up to approximately 1.8 watts during repositioning events. These increases in power consumption are visible as small dips in net power in Figure 3 which correspond to servo actuation intervals. The system also maintained net harvested power levels of approximately 30 to 41 watts during peak sunlight hours which proves that tracking overhead is negligible relative to total energy generation. Over the test duration, the system harvested approximately 199.48 watt hours of net energy, while the cumulative energy consumed

by tracking remained a very small fraction of this total. As a result, the additional energy required for repositioning had minimal impact on overall system efficiency, confirming that tracking overhead does not significantly reduce net energy gain and proving our power monitoring system can accurately monitor power.

3.4 Control and Sensing Verification

Our sensing and control subsystems were validated through real world testing across many different solar positions throughout the day. The system continuously measured light intensity differences across the 8 sensor array and translated these values into control signals for the servos. In testing, the panel was able to consistently move toward the direction of highest incident light, demonstrating correct interpretation of sensor inputs and proper execution of the control algorithm. Repositioning occurred at regular intervals and the system was able to reliably adjust orientation without unsteady oscillation or overshoot which indicates stable control behavior. Tracking behavior shown in Figure 3 demonstrates smooth movement in changing light conditions, with periodic adjustments resulting in sustained high power output. Our first design was initially based on four light sensors positioned at orthogonal directions however, this configuration produced limited resolution and occasional malfunctions when light intensity differences were small or uneven. Expanding the system to eight sensors provided much better spatial resolution of the light field and allowed our algorithm to make more precise directional decisions. This improvement reduced jitter in panel movement and resulted in smoother tracking.

3.5 Communication Verification

Our communication subsystem was verified through real time data logging during testing. Sensor data, power measurements, and system outputs were successfully transmitted and recorded at 10 minute intervals. Internal communication between subsystems operated reliably which enabled continuous monitoring of system performance throughout the six hour test duration. In addition to local logging, the system utilized the ESP32 microcontroller's built in WIFI module to send data to a web based dashboard. This allowed remote monitoring of system behavior in real time where key metrics such as power output, energy accumulation, and system status were successfully displayed. The reliable transmission of data over both wired and wireless interfaces confirms that the communication subsystem meets its design requirements and supports effective system validation and monitoring.

3.6 Full System Verification

Through full system testing, we were able to confirm that SolarTrack meets its primary design objectives. The tracking system consistently outperformed the fixed position configuration achieving a total energy output of approximately 199 watt hours compared to 146 watt hours for the static system. This is a net gain of approximately 53 watt hours

and a 36.3 percent improvement in energy harvesting efficiency. In addition, the system demonstrated higher sustained power output throughout the day and reached battery saturation earlier than the static system. The relatively small energy overhead associated with repositioning confirms that the benefits of tracking significantly outweigh its costs. All in all, these results validate the effectiveness of the closed loop solar tracking system and demonstrate that SolarTrack provides a meaningful improvement in solar energy efficiency in real world conditions.

4 Costs

This section summarizes the cost of the SolarTrack system, including both the physical components required to build the prototype and the estimated labor required for design, assembly, testing, and verification. The total estimated cost of the project includes parts, shipping, sales tax, machine shop labor, and team labor.

4.1 Parts

Description	Manufacturer	Quantity	Extended Price	Link
Solar Panel	LEPITERY	1	56.99	Link
60V Rated Wiring	Remington Industries	1	17.79	Link
Inline Fuse	YNZDRWA	1	7.18	Link
MC4 Connectors	BougeRV	1	9.99	Link
MPPT Charge Controller	Powerwerx	1	29.99	Link
SLA Battery	ExpertPower	1	24.99	Link
10A 40V Schottky Diode	Panjit International Inc.	1	0.9	Link
1000 μ F electrolytic capacitor	Vishay Beyschlag	2	2.21	Link
10 μ F ceramic (X7R) capacitor	Samsung Electro-Mechanics	8	0.3	Link
0.1 μ F ceramic (X7R) capacitor	Samsung Electro-Mechanics	18	0.3	Link
Ferrite Bead	Eaton	1	0.1	Link
TVS Diode	Littelfuse Inc.	1	0.16	Link
220 μ F electrolytic capacitor	Rubycon	1	0.39	Link
Current Sense Shunt Resistor	Ohmite	2	1.76	Link
I2C Pull-up Resistor: 4.7k Ω	Ohmite	4	4.68	Link
1 μ F ceramic (X7R) capacitor	Taiyo Yuden	1	0.08	Link
0.012 μ F ceramic (X7R) capacitor	Knowles Syfer	10	4.86	Link
ESP32-WROOM-32E-N16	Espressif Systems	1	5.71	Link
47 μ F electrolytic capacitor	Rubycon	1	0.28	Link
3.3V regulator	Diodes Inc.	1	0.31	Link
6V buck converter	Pololu	1	31.95	Link
Pull-up resistor 10k Ω	YAGEO	10	0.1	Link
Push Button	Same Sky	2	0.2	Link
6-pin header	Würth Elektronik	1	0.35	Link
FT232 USB-to-UART bridge	FTDI	1	4.8	Link
USB-C Connector	Amphenol ICC	1	0.61	Link
Series register 22 Ω	TE Connectivity Passive Product	2	0.1	Link
ESD Protection Diode array for USB	Texas Instruments	1	1.05	Link
Series register 220 Ω	TE Connectivity Passive Product	2	0.2	Link
CdS photoresistor LDR 5mm	Advanced Photonix	4	6.16	Link
Heavy Duty Servo Motor	DFRobot	2	81.8	Link
XT60 Connector	SparkFun Electronics	1	2.5	Link
2200 μ F electrolytic capacitor	Rubycon	2	1.07	Link
5.1k Ω resistors	YAGEO	1	0.2	Link
Servo Power Switching MOSFET	Toshiba Semiconductor	1	0.61	Link

Figure 8: Bill of materials.

The bill of materials for SolarTrack is shown in Figure 5. The main hardware costs came from the solar panel, heavy-duty servo motors, MPPT charge controller, SLA battery, 6 V buck converter, wiring, connectors, sensors, and the ESP32 microcontroller. Smaller electrical components such as capacitors, resistors, diodes, headers, MOSFETs, and protection circuitry were also included in the parts cost because they were necessary for stable power

regulation, sensing, communication, and motor control.

The total cost of all parts before shipping was \$300.67. A 5% shipping cost added \$15.03, and a 10% sales tax added \$31.55. Therefore, the total cost of purchased parts, including shipping and tax, was:

$$\$300.67 \times 1.05 \times 1.1 = \$347.25$$

Thus, the final parts cost for the SolarTrack prototype was \$347.25. This cost represents the direct material expense required to build the system, not including labor or machining support.

4.2 Labor

In addition to the parts cost, labor was included to estimate the full project cost. The SolarTrack chassis was built with assistance from the ECE machine shop. Assuming an hourly rate of \$50/hr and approximately 25 hours of machine shop work and material preparation, the estimated machine shop labor cost was:

$$\$50/\text{hour} \times 25 \text{ hours} = \$1250$$

This gives a machine shop labor cost of \$1,250.

Student labor was also estimated for the design, implementation, testing, debugging, documentation, and verification of the project. Each team member worked approximately 2 hours per day for 60 days at an hourly rate of \$40/hr. Thus, the labor cost per team member was:

$$(\$40/\text{hour}) \times (2 \text{ hours} / \text{day-person}) \times 60 \text{ days} = \$4800 / \text{person}$$

Since the team consisted of three members, the total student labor cost was:

$$(\$4800/\text{person}) \times 3 \text{ people} = \$14400$$

This gives a total student labor cost of \$14,400.

Combining the parts cost, machine shop labor, and student labor, the total estimated project cost was:

$$347.25 + 1250 + 14400 = 15997.25$$

Therefore, the total estimated cost of the SolarTrack project was \$15,997.25.

5 Conclusion

5.1 Accomplishments

SolarTrack succeeded in achieving its overall goal of increasing the amount of solar energy that can be harvested by the solar panel through the use of autonomous repositioning. The system successfully integrated sensors, actuation systems, power systems, power monitoring systems, and communication systems into a cohesive automated solar tracking system. The system utilized an ESP32 microcontroller to gather data from an array of eight LDR sensors to measure the intensity of the incoming light to the panel, and used that information to control two servo motors that enabled the solar panel to be repositioned to track the sun throughout the day. The system also collected data from the solar panel of the voltage, current, harvested power, and energy that was collected by the panel, all of which was sent to a web-based dashboard for observation.

The major accomplishment of the project is that the SolarTrack system was able to produce significantly more energy than a fixed solar panel. During testing of the systems outdoors, the SolarTrack system produced 199 Wh of energy, while the fixed positioned solar panel produced only 146 Wh. Thus, the SolarTrack system produced 53 Wh more energy (a 36.3% increase) than the fixed positioned panel. Furthermore, the SolarTrack system also exhibited a 17.6% increase in the power that the panel was able to output at peak times. These increases in the energy that is produced by the SolarTrack system indicate that the energy that is gained by the panel through repositioning is significantly more than the energy that is consumed by the actuators that allow the panel to reposition.

5.2 Uncertainties

Despite meeting the design goals, there are some uncertainties regarding the system. For instance, the tests were performed on a limited number of clear-sky days. While the system worked well in the direct sunlight of those days, additional testing would be required to determine if the same system would work in less sunny conditions.

In addition, although the servos were able to reposition the solar panel during the testing period, the long-term reliability of the servos is yet to be determined. For instance, the motors may wear with continued use of the panel, the panel may be subjected to weather conditions that will impact its durability, and the energy required to reposition the panel may increase with the size of the panel.

Finally, although the concept has been validated with the relatively small 50 W solar panel, uncertainties exist regarding the potential use of such a system for larger panels. For instance, larger panels would require more powerful motors to counteract the increased load of the panels. Thus, while the system has been validated for the small panel, additional testing would be required before implementing the same system to the potentially much larger solar panel installations on residential or commercial properties.

5.3 Ethical Considerations

SolarTrack aims to support the ethical goal of increasing access to clean and renewable energy. By increasing the amount of energy that can be harvested from a solar panel, SolarTrack can lead to a reduction in the reliance upon fossil fuel energy sources and the greenhouse gases that are released into the atmosphere as a result of their use. Furthermore, increasing the efficiency of solar panels can lead to an increase in their usefulness in areas that are rural, remote, and underdeveloped.

However, considerations of the safety of the system are also part of the ethical discussion of the project. Any system that incorporates moving parts must be designed in a way that will not cause injuries to the individuals who may use the system. For instance, the solar panel itself should not be constructed in a way that it can move in a way that is potentially harmful to individuals or the environment, and the system should be constructed to avoid overheating or damaging its components through the use of its electrical systems.

Finally, additional considerations regarding the environment in which the system operates include the potential impact of the system upon the environment beyond the harvesting of solar energy. For instance, the system is composed of components that may have environmental impacts when they are eventually discarded. These components can be replaced with components with increasing longevity and with considerations of their potential to be recycled, as well as to minimize the negative impact that the system can have upon the environment altogether.

5.4 Future Work

In the future, focus should be placed upon improving the robustness, scalability, and intelligence of the current SolarTrack system. One area of potential improvement would be to test the system under different environmental conditions to determine its long-term performance and reliability of the system.

The mechanical design of the system could be improved to incorporate components that can better support the solar panel and provide more efficient movement of the panel. Potential improvements to the actuation system would include the use of geared motors, stepper motors, or linear actuators instead of the hobby servos that are currently used. Additionally, the design of the enclosure of the system would need to be improved to weatherproof the system for long-term outdoor use.

The control algorithm could also be improved. Instead of using only the measurements of the LDR array, the system can incorporate a time-based algorithm that calculates where the sun will be in the sky at any given time of day and year. The system could then use these two algorithms together to determine the best way to orient the panel to the sun. Additionally, the system could be programmed to only move the panel when the energy that is gained by turning the panel is of greater value than the energy required to actuate the panel to that new position.

Finally, the monitoring system could be improved by introducing long-term data storage,

trend analysis, battery health indicators, and other performance metrics to the current dashboard of the system. This would convert the current project into a complete monitoring system for solar panel energy.

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Appendix A Requirements and Verification Tables

Requirement	Verification	Status (Y/N)
Must produce energy when exposed to direct light.	When the solar panel is connected to the MPPT and in sunlight, verify that power is being generated by the solar panel.	Y

Table 1: Solar Panel R&V.

Requirement	Verification	Status (Y/N)
Must provide sufficient energy for the entire system to be self-sustaining.	Once the full system is assembled, let the system operate for 24 hours in normal conditions and verify that the battery gains charge over the day.	Y
Must provide a stable 3.3V to the MCU.	Once the full system is assembled, probe the input voltage to the MCU continuously over 24 hours of operation. Ensure that this voltage is consistently 3.3V.	Y
Must provide 6.0V to servos under motion.	Once the full system is assembled, probe the input voltage to the servos while sending a PWM signal to the servos. Ensure that the servos are receiving a stable 6.0V during this process.	Y

Table 2: Power System R&V.

Requirement	Verification	Status (Y/N)
Must measure up to system's peak load without saturation.	In isolation, connect the subsystem to a current source, gradually increasing the current to 10 Amperes and verifying that operation remains consistent.	Y

Table 3: Power Monitoring R&V.

Requirement	Verification	Status (Y/N)
Given input from eight light sensors, must output signal to two servos to ensure the solar panel remains aligned.	In isolation, connect the subsystem to eight voltage sources that mimic the light sensors. Using realistic test cases (consisting of both input data fed to the system and expected output) representing various possible positions of the sun relative to the system, ensure that the algorithm operates correctly.	Y
Must support debugging by logging through UART.	Include print statements / debug messages throughout the code to make the internal state clear. Verify that these messages are visible.	Y

Table 4: Control/Compute R&V.

Requirement	Verification	Status (Y/N)
Must output signal between 0 and 3.3 Volts to the ADC pin.	Once the subsystem is assembled, probe the output voltage (middle of the voltage divider) when completely covering and when completely illuminating the LDR, verifying that the voltage stays within range in both cases.	Y
Must provide a usable contrast (10% difference) between sensors when in misaligned sunlight.	In testing with a 100,000 Lumen flashlight, move the flashlight around the sensors while they are mounted to the base and panel. As the flashlight is moved around, probe the voltages to the ADC pins, ensuring that the specified difference is observed.	Y

Table 5: Sensing R&V.

Requirement	Verification	Status (Y/N)
Must provide UART at 3.3 Volts. Must support stable serial communication at 115200 bps.	Flash a simple "Hello World" program onto the MCU, a program which consists of nothing other than a single print statement. Verify that the message is printed correctly.	Y

Table 6: Communication R&V.

Requirement	Verification	Status (Y/N)
Must operate under load at 6 Volts.	With the servos connected to the 6 Volt rail and mounted in the overall assembly, ensure that the solar panel moves when the servos are powered.	Y
Must prevent EMI noise from affecting the MCU.	With the servos and MCU connected to the board, send an arbitrarily high PWM signal to the servos while continually probing the 3.3 Volt power rail. Ensure that even at peak servo utilization, the 3.3 Volt rail stays stable.	Y

Table 7: Actuation R&V.