Engineering Educators Bringing the World Together
2025 ASEE Annual Conference & Exposition
Palais des congrès de Montréal, Montréal, QC • June 22–25, 2025
Paper ID #46339

BOARD #137: Bridging Theory and Practice - Empowering Student Learning through an Interactive Dual-Axis Solar Panel Tracker Platform

Dr. Hamid S Timorabadi P.Eng., University of Toronto

Hamid Timorabadi received his B.Sc, M.A.Sc, and Ph.D. degrees in Electrical Engineering from the University of Toronto. He has worked as a project, design, and test engineer as well as a consultant to industry. His research interests include the application of digital signal processing in power systems.

Yucheng Zhang, University of Toronto

Electrical Engineering student with a minor in Sustainable Energy at University of Toronto, fully passionate about renewable energy

Work In Progress: Bridging Theory and Practice - Empowering Student Learning through an Interactive Dual-Axis Solar Panel Tracker Platform

Abstract

As the drive for sustainable energy solutions accelerates, future engineers need a solid understanding of renewable energy principles and direct experience with real-world systems. This project introduces an educational platform featuring a dual-axis solar panel tracker, giving engineering students a chance to design, program, and optimize an innovative solar tracking system. By expanding beyond the simpler mechanics of fixed or single-axis trackers, the dual-axis approach encourages students to explore deeper into concepts of system efficiency and sustainability.

The main goal of this paper is not just to highlight the efficiency gains of dual-axis trackers. Instead, it aims to showcase an educational platform that emphasizes practical engagement by guiding learners through real-time data monitoring, microcontroller programming, and resolving common issues such as overcharging and equipment malfunctions.

The dual-axis tracker serves as a modular, portable educational platform with a user-friendly interface, making it accessible to students of all skill levels. It seamlessly integrates into diverse learning environments, whether within formal coursework or extracurricular research initiatives. Beyond technical skills, the platform fosters critical thinking on energy management and ecological impact, prompting students to explore the broader role of renewable technologies in society.

1.0 Introduction

The primary goal of this paper is to develop a dual-axis solar tracking platform that offers a hands-on learning experience for engineering students. We intend to bridge the gap between classroom knowledge and practical application. By designing, programming, and troubleshooting a real-world system, students gain a deeper understanding of solar energy technology, sustainability, and problem-solving methods.

Several projects exist that incorporate solar tracking at various levels of complexity. Single-axis trackers, for example, are relatively straightforward to build and maintain, requiring fewer components and less programming expertise. While single-axis trackers do illustrate how tracking can boost efficiency [1], they offer less educational value compared to dual-axis systems. Dual-axis technology not only delivers a more comprehensive learning experience but also encompasses the essential knowledge needed for building simpler tracking implementations like single-axis. Consequently, mastering a dual-axis setup inherently equips students with the skills to explore new concepts of tracking systems. On the other hand, fixed solar panel installations are even easier to set up, making them cost-effective and accessible [2]. Still, they lack any active tracking mechanism, meaning they fall short of delivering hands-on experience with real-time control, data monitoring, and advanced troubleshooting.

Building on these insights, the dual-axis platform was refined through iterative testing and continuous feedback, which included fine-tuning the hardware and improving the user interface. During the testing phase, it became clear that the original command-line-based interface was neither convenient nor intuitive for users. To address this, a Python-based graphical interface was developed, featuring control buttons and a real-time plot to display voltage, current, and power.

2.0 Technical Design

The dual-axis solar tracker system is composed of three parts: power system, control system, and tracker system as Figure 1 shows. Section 2.1 describes the circuit design and mainly focuses on the power module in the power system. Section 2.2 explains the coding for the Arduino main controller. Section 2.3 explains the structure and the control of the tracker.

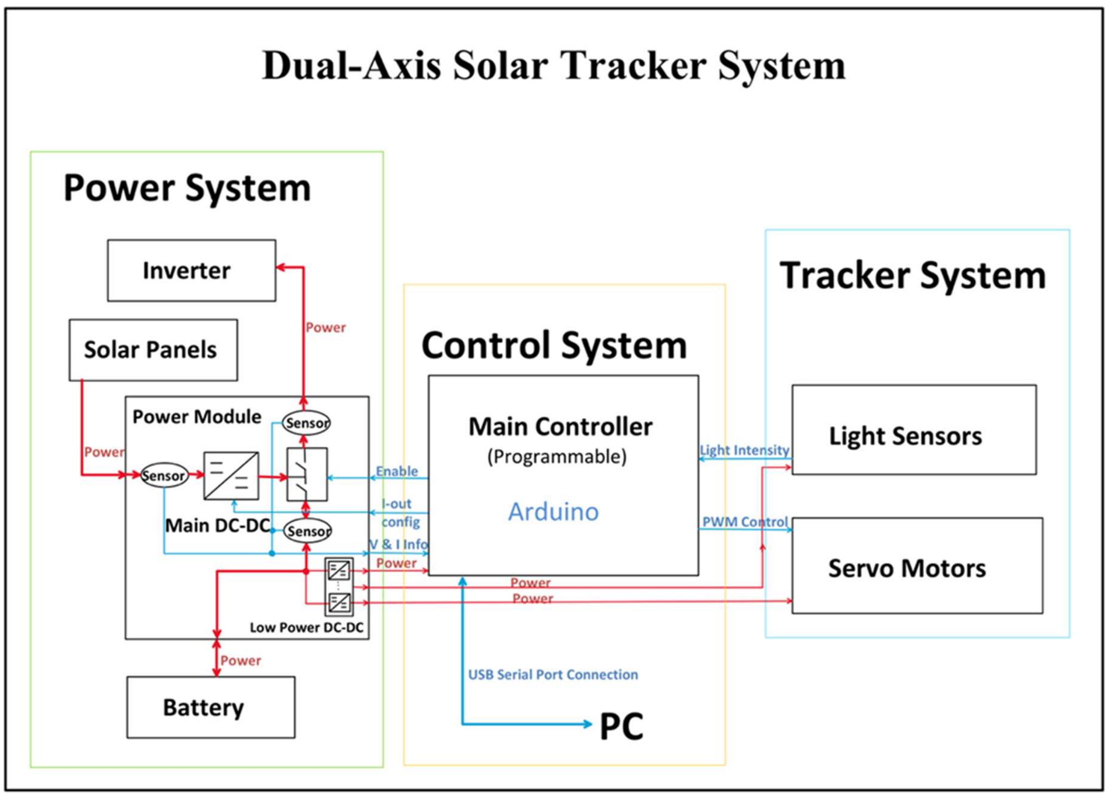

Figure 1. Dual-Axia Solar Tracker System Block Diagram

2.1 Circuit Design

The circuit design for this project focuses on the design of the power module inside the power system in Figure 1. The 1500W 30A rated main boost converter collects the power from the solar panels, providing stable 28V for the inverter and battery through two double pole relays (4 channel 30A rated relay). Lower-power DC-DC converters get the power from the battery power rail, so they can continue operating when sunlight becomes unavailable, but the battery still has energy. The current flowing to the main boost converter, the battery, and the inverter (load) are measured by 3 ACS712 30A rated hall effect current sensors. In this design, the battery is connected to the relay's normally closed (NC) contacts. Even if the Arduino is powered off due to a low battery, the solar panel can still charge the battery because the relay remains in its default (unenergized) position, maintaining a direct connection between the battery and the panel. Since the Arduino relies solely on the battery for power, once the battery has enough charge from the solar panel, it can power the Arduino again. However, the load cannot be powered up without reading the current sensors (over-current protection is active), as the load is connected to the NO (typically opened) pins.

As the ground could be isolated by the double pole relay during operation, three differential op-amp-configuration-based resistively isolated voltage sensors are used to measure the voltages at the load, the solar, and the battery power rail respectively. These voltage sensing signals are sent to ADC_0, which can be read by Arduino through the I2C bus. Moreover, battery and solar voltage sensing signals are sent to op-amp comparators, which output low signals when both the battery voltage and solar voltage are lower than the thresholds configured by potentiometers. If both the battery voltage and the solar voltage go below the threshold, the circuit will go to over-discharge protection mode, turning off all components in the design except for the op-amp module which consumes only about 30mW from the battery.

Except for the over-discharge protection triggered by the op-amp module, the Arduino main controller controls all other circuit behaviors (Figure 2). The current sensing signals from ASC712 are directly read by analog input pins A1, A2 and A3. Voltage sensing signals from the op-amp are read by the I2C bus at 0x48 for ADC_0 (default address for ADS1115 [3]), and the light intensity (output of light sensor TEMT6000) are read by I2C bus at 0x49 for ADC_1 (address for ADS1115 when ADDR is shorted to VDD [3]). The angle of two servos in the tracker is controlled by the PWM signal (one for rotation, another for tilt). The connection of 30A relays is controlled by two digital GPIO pins (one for battery power rail double pole relay, another for load power rail double pole relay). The key information can be sent to the LCD screen by I2C bus.

To provide sufficient power to the inverter (load) without charging the battery with a current that is above the safe level, the output current limit of the main boost converter needs to be adjusted dynamically based on the current sensor reading, which is implemented by a digitally controlled potentiometer MCP4018. However, the digitally controlled potentiometer cannot work properly until there is 5V between VDD and GND, which happens after the boost is powered up, so the current configuration is switched to the mechanical potentiometer before powering down by a latching relay.

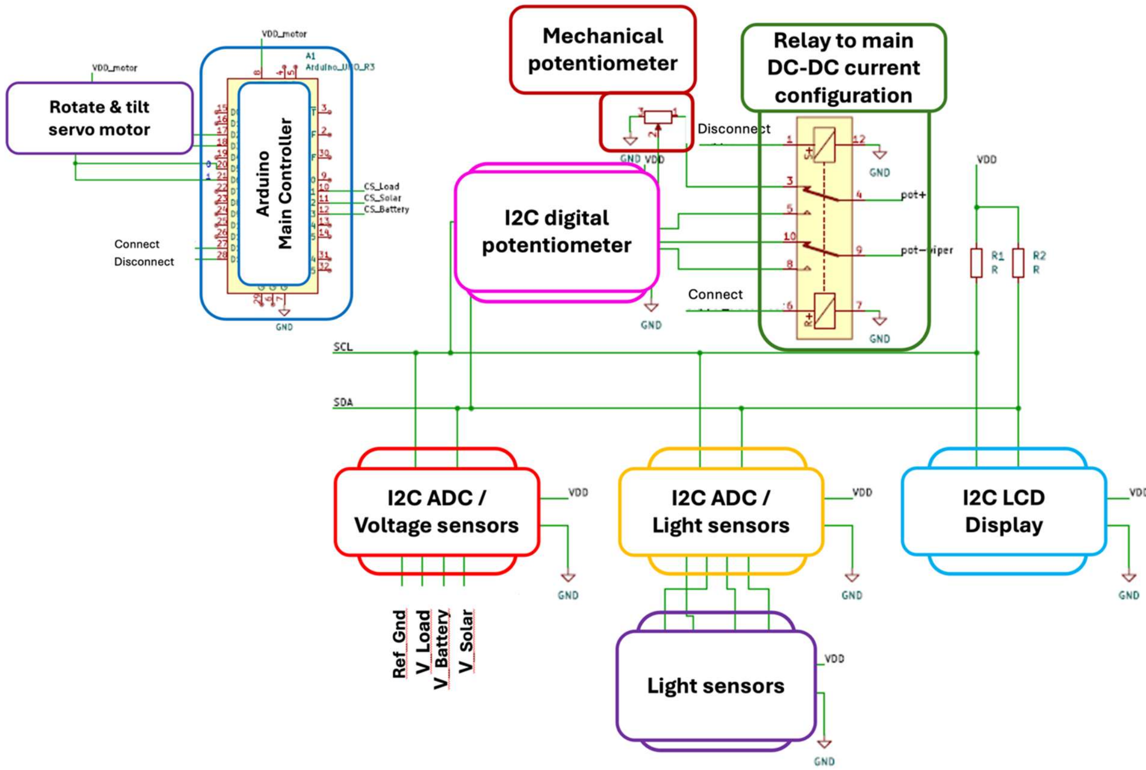

Figure 2. Dual-Axia Solar Tracker Controller and I2C Schematic

2.2 Controller Programming

The main controller, programmed on the Arduino, governs the majority of the circuit's behavior and communicates with a PC via a USB serial connection. When the controller receives a command through the serial interface, it triggers the appropriate handling code to interact with the user, and a brief response message is sent back to the PC through the serial port.

Aside from battery over-discharge protection, which is managed by the op-amp module, most of the power module's protection features are implemented through the controller's programming. The controller samples voltage and current sensor data 100 times per second and displays the calculated power information on the LCD screen. If the measured current exceeds the predefined limit (currently set to 20A), the over-current protection mechanism is activated. This disconnects the affected power rail, which is then automatically reconnected after 2 seconds. If the over-current condition persists, the rail will be disconnected and checked again after another 2 seconds. The system will only resume normal operation once the current falls below the defined threshold.

Moreover, the state of charge (SOC), estimated through Coulomb counting based on current measurements, is used to trigger various protection modes for the battery. When the SOC reaches 100%, the double-pole relay on the battery power rail is disconnected to prevent overcharging. Sixty seconds after this disconnection, the open-circuit voltage (Voc) is measured and used to calibrate the SOC estimation. If the measured Voc at full charge is lower than the predefined threshold (e.g., 28.4V for $LiFePO_4$ batteries [4]), the battery relay will briefly reconnect for 20 seconds. After another 60-second disconnection, the Voc is measured again. This process repeats until the measured voltage aligns with the expected value for 100% SOC.

In addition, while the op-amp module provides over-discharge protection by cutting off circuit power, the controller offers a more proactive measure. When the solar input voltage drops below 5V and the battery SOC falls below 10%, the controller disconnects the load power rail to reduce battery drain and minimize the risk of over-discharge. If the SOC drops below 5%, the controller initiates a shutdown procedure. This includes resetting the latching relay, reconfiguring the main boost converter via the mechanical potentiometer, and saving critical system data.

The picture of the power module and controller is attached below.

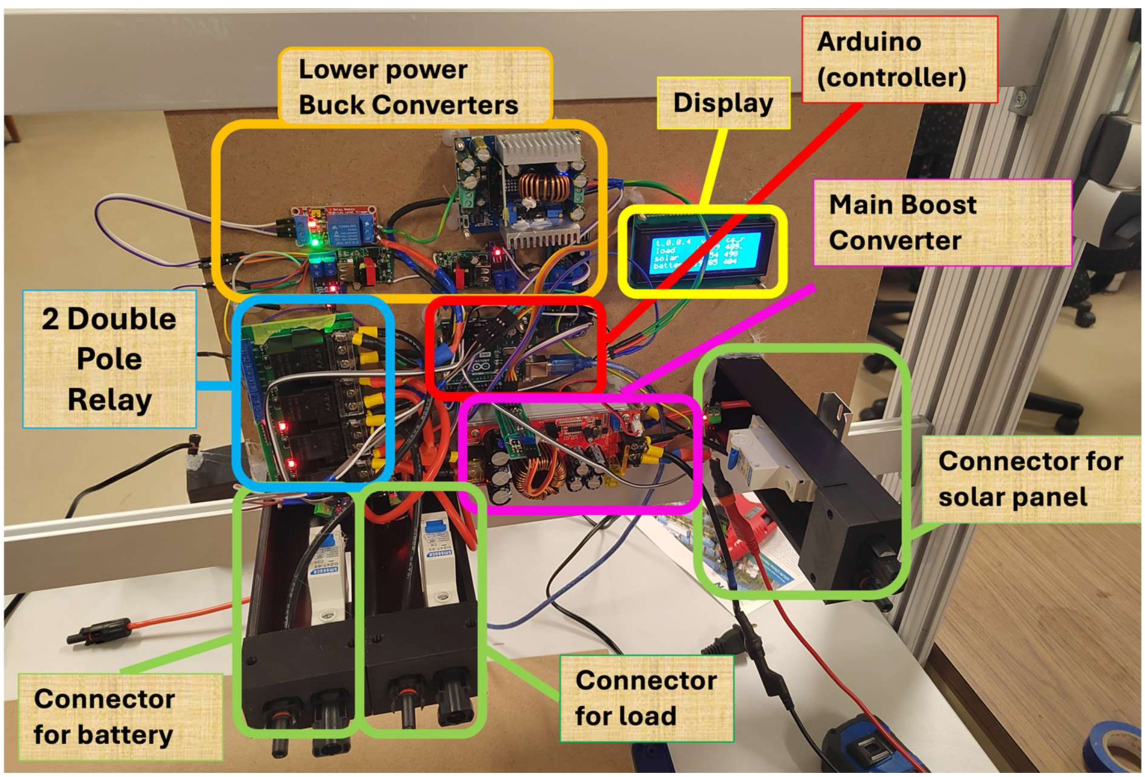

Figure 3. Power module with controller

2.3 Tracker

The dual-axis tracker is guided by two servos—one that controls rotation and another that adjusts the tilt (see Figure 4). These servos change their angles based on the duty cycle of a PWM signal. To determine the direction of incoming light, the Arduino continuously reads data from four light sensors (light_00, light_01, light_10, and light_11) over I2C at address 0x49 (as mentioned in Section 2.1). These sensors are mounted on the solar panel and move along with it (Figure 5), allowing the system to stay aware of light direction as the panel shifts.

When all four sensors detect roughly the same light intensity, it means the panel is properly aligned—the shadow cast by the central cross-structure falls evenly across the sensors, pointing directly at the light source. But if the readings differ, the system knows it's time to make some adjustments. It does so by gently changing the angles of the servos, following a simple pattern:

- If **light_00** and **light_01** see less light than **light_10** and **light_11**, it means the shadow is leaning toward the left side. So, the system **increases the rotation angle** to bring it back to center.
- If **light_00** and **light_01** see more light than **light_10** and **light_11**, the shadow has shifted to the right. In this case, it **decreases the rotation angle**.
- If **light_00** and **light_10** detect less light than **light_01** and **light_11**, the shadow is tilted down toward the bottom. The system responds by **increasing the tilt angle**.
- If **light_00** and **light_10** see more light than **light_01** and **light_11**, the shadow is higher up, so it **decreases the tilt angle**.

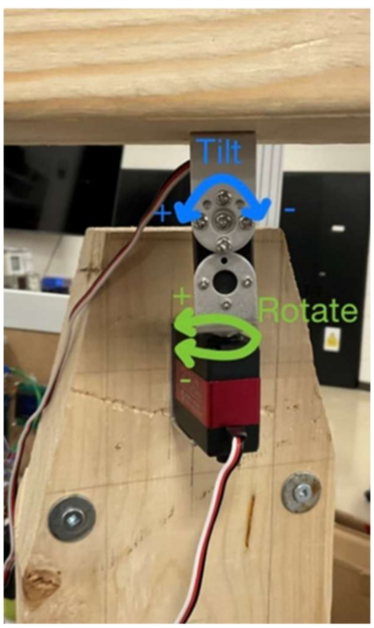

Figure 4. Servos on the Tracker

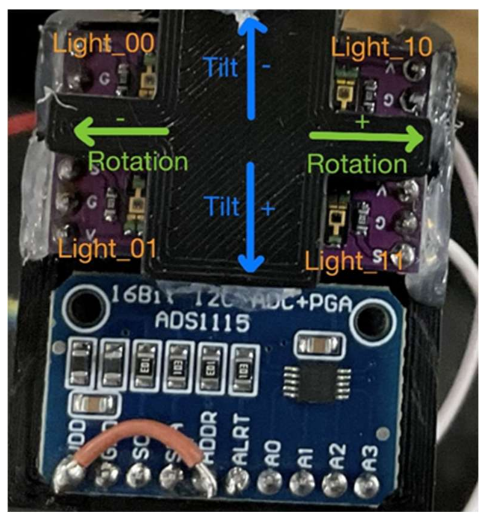

Figure 5. Light Sensors with ADC

2.4 Interactive UI

To enable real-time data tracking and command execution during testing, a Python-based user interface was developed, as illustrated in Figure 6. The left panel of the interface allows users to select the operating mode—fixed, single-axis, or dual-axis—and to input specific tilt and rotation angles for the solar panel. On the right panel, real-time plots display the recorded voltage, current, and power data, providing a clear and efficient means to monitor changes and evaluate system performance.

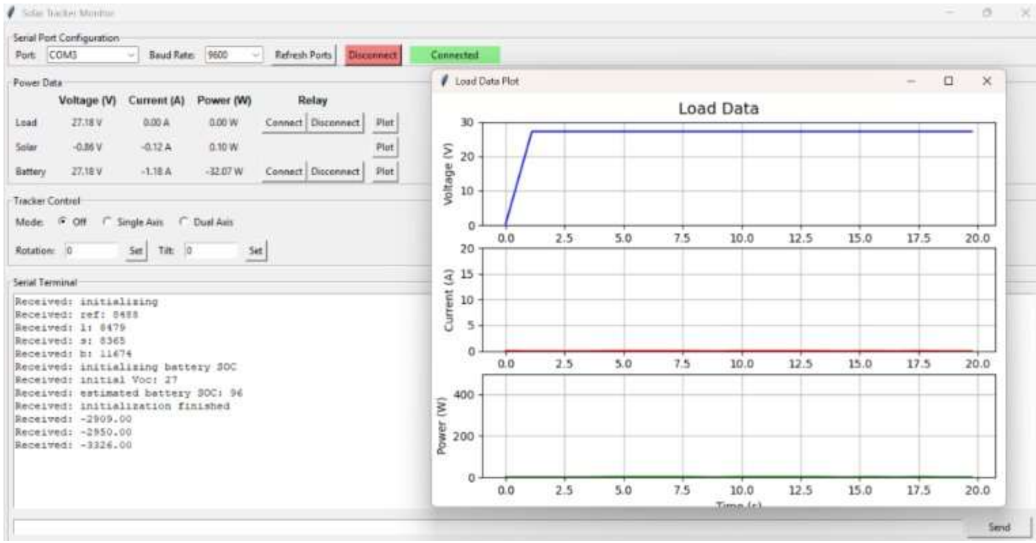

Figure 6. User Interface

The complete dual-axis interactive educational platform is shown in Figure 7.

Figure 7. Complete design of dual-axis solar tracker system

3.0 Educational Value

The interactive educational model of the dual-axis solar panel tracker originated from a student capstone project aimed at exploring sustainable energy solutions. Recognizing the challenge of intuitively understanding solar power systems without hands-on experience, students took the initiative to develop a functional prototype. This project not only enhanced their own comprehension, practical integration, and programming skills but also established a valuable learning platform for future students.

Throughout the development process, students gained firsthand experience in solar power system design, component selection, and custom module fabrication. Integrating these modules helped them intuitively grasp system inputs and outputs, particularly through the three power rails. The implementation of dual-axis tracking required them to develop custom control algorithms, enabling the solar panel to rotate and tilt in response to the Sun's position, thus improving energy capture efficiency. Additionally, assembling the system on a mobile cart and testing its overall functionality provided essential hands-on engineering experience.

Beyond immediate project goals, the dual-axis tracker offers opportunities for future enhancements, such as integrating a battery management system or implementing advanced functions like automated snow removal. While the capstone project had time and resource constraints, students gained invaluable experience in electrical, firmware, and mechanical design. More importantly, they developed problem-solving skills critical for professional engineers, learning to tackle real-world challenges through iterative design and implementation.

This system has significant educational potential beyond the capstone course. It can be incorporated into power electronics labs as a hands-on study module or serve as a research platform for students studying sustainable energy systems. By bridging the gap between theory and practice, the dual-axis solar tracker provides students with an immersive learning experience—allowing them to connect theoretical concepts with real-world applications, refine their coding skills, and critically assess existing solar technologies. Ultimately, it fosters a deeper understanding of solar power systems and inspires continuous innovation in renewable energy solutions.

3.1 Understanding solar power system

Reaching the goal of Net Zero Emissions starts with understanding one of the most promising sources of sustainable energy: solar power. However, most solar power systems used in homes and businesses are too large and complex for students to easily explore and learn from. To bridge this gap, we developed a compact, interactive dual-axis solar panel tracker system specifically designed for educational use. All the components are mounted on a mobile display cart that fits easily in a lab setting. The solar power module and Arduino-based controller are securely attached to a vertical display board using a glue gun, making the circuitry easy to see and understand. The tracking module is mounted on an adjustable arm, while other key parts—like batteries and computers—are neatly placed on the cart's table. With this scaled-down, accessible setup, students can gain hands-on experience with how a solar power system works, learn how to control it, and see firsthand how a dual-axis tracker can improve energy efficiency.

3.2 Hands-on Experience in Circuit Assembling

The interactive design of the dual-axis solar tracker model also gives students the chance to physically build and modify the circuits themselves—a hands-on experience that's key to truly understanding how the electronics behind a solar power system work. To support this, three connection boxes are placed near the solar module, allowing students to connect and disconnect the solar panel, batteries, and load. This lets them see how each component functions within the system. For example, if the lighting in the lab isn't strong enough, students can swap the solar panel with a lab power supply to keep the circuit running. Instructors can also design lab questions around these setups—for instance, asking students what would happen if the battery were removed from the circuit. These kinds of practical exercises not only help students understand what makes a solar power system work effectively but also encourage them to think critically about how the electronics could be improved.

3.3 Coding Practices Based on Interactive Serial Control

Because the controller module in the dual-axis solar panel tracker uses an Arduino that connects directly to a computer via a serial port, students can easily write and upload their own code to the system. This setup leaves plenty of room for further software improvements and customization. For instance, the current display shows voltage and current readings from the solar panel, battery, and load. Students could take it a step further by adding a column to display power, simply by writing code to calculate it and adjusting the screen's layout to show the extra data. This flexibility encourages creativity, giving students the chance to improve the system and see the impact of their ideas in real time.

3.4 Protection mechanism of power electronics

Safety is always the top priority in any student lab, and the dual-axis solar panel system is designed with that firmly in mind. Since this is a power electronics lab, all students are required to complete safety training and strictly follow lab safety protocols. Special attention is given to the risks associated with high-voltage circuits—providing a valuable opportunity for students to learn how to protect themselves when working with such systems in real-world situations. In addition, the solar tracker system includes built-in protections against overcharging, over-discharging, and over-current conditions. These features not only help keep the system safe to use but also teach students to recognize potential hazards and design their own circuits with safety in mind.

3.5 Testing Results of the System

Once the dual-axis solar tracker system was fully integrated, it underwent a series of interactive tests. Students used power supplies, multimeters, and oscilloscopes to check whether the system met its voltage and power requirements. They also used the Arduino IDE terminal to send commands, ensuring the solar panel could tilt and rotate accurately—and reset itself when needed. To support these actions, light intensity readings and the corresponding tilt and rotation angles were displayed in the terminal, helping students better understand how the system was responding.

During testing, however, students found it challenging to keep track of system parameters while manually entering commands in the serial terminal. To improve usability, an interactive

Python-based interface was developed. This interface includes intuitive control buttons and real-time plots showing voltage, current, and power. With this upgrade, students could monitor the system's performance more easily, making the platform much more user-friendly and effective for learning.

Although the platform hasn't yet been tested on a large scale, the three students involved in the project found it to be an excellent hands-on learning tool. Through this experience, they deepened their understanding of solar power systems while gaining essential engineering skills like soldering, wiring, programming, system integration, and troubleshooting. Just as importantly, they learned how to recognize design flaws and implement practical solutions—a key part of the engineering process.

Without this kind of practical engagement, students often rely solely on theoretical learning or online resources. But working with a functioning prototype gives them a unique opportunity to confront real-world challenges and think critically about how to improve system performance. This kind of experiential learning not only reinforces technical knowledge but also nurtures creativity, problem-solving, and innovation—skills that are vital for any aspiring engineer.

In the end, the dual-axis solar tracker proves to be more than just a lab tool. It's a meaningful educational platform that helps students build confidence, develop practical competencies, and explore new possibilities in renewable energy. Future students can continue to use and improve upon this system, deepening their understanding of solar technologies and contributing to the advancement of sustainable energy solutions.

4.0 Conclusion

In short, the interactive dual-axis solar panel tracker offers a simple, accessible, and highly effective platform for learning about one of today's most promising sustainable energy technologies. It presents the core principles of solar power in a clear, hands-on way, helping students connect theoretical knowledge with real-world application. The system also leaves room for creativity, giving students the freedom to explore, experiment, and be inspired as they deepen their understanding and engagement with renewable energy.

5.0 Reference

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