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Solar Tracker Demonstration for High School and Undergraduate Students: Energy, Arduino, Coding, 3D Printing and Automation

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Abstract

As global energy demands grow, solar energy plays an increasingly vital role in achieving a sustainable future. The efficiency of solar energy harvesting can be improved with solar tracking systems. Developing solar tracking systems is an excellent project for students to develop, expand, and deepen their engineering skills while working on a project with real-world significance. This study demonstrates a low-cost, dual-axis solar tracker using an Arduino, 3D printed components, mathematical modeling, coding, and readily available electrical parts, including light-dependent resistors, a servo motor, and a stepper motor.

We report on a 15-month-long learning journey: participation in the Engineering Summer Academy at Penn (ESAP) Nanotechnology course for 3 weeks, followed by 14 months of subsequent abstract conceptualization, design, building, and testing the solar tracking systems, and reflections. Students led this project as part of a Project-based Learning framework grounded in Kolb's Experiential Learning Theory. Students gained foundational knowledge about principles of the solar cell, semiconductors and pn junction in lectures, then learned characterization method of the solar cell efficiency with Arduino, current sensor, potentiometer, and multimeter in a lab session of ESAP Nanotechnology course. After the course, students were further motivated to make a prototype solar tracking system for renewable energy technology. Through the iterative process of building, testing, and troubleshooting, the solar tracker demonstrated a 16.5% improvement in energy generation compared to the fixed solar panel.

Reflection highlights substantial learning outcomes, including interdisciplinary learning, automation, coding, problem-solving skills, self-efficacy, and collaborative experiences. This project allows high school and undergraduate students to replicate their experiences in an affordable, efficient, and educational manner.

Keywords

Solar energy, solar tracker, solar power, education, Arduino, Coding, automation, high school, undergraduate

1. Introduction

According to the International Energy Agency, global energy-related CO_2 emissions reached a new high of 36.8 billion tons in 2022, and the value will continue to grow as global electricity demand keeps increasing [1], [2]. There is an urgent demand for utilizing renewable energy rather than burning conventional fossil fuels to restrain the growth of the greenhouse effect. Solar energy, one of the cleanest and most abundant renewable energy sources, holds immense potential to address this challenge. The average solar energy that arrives at Earth is 44 quadrillion (4.4×10^{16}) watts of power, which is equivalent to 44 million large electric power plants with a capability of 1 billion watts of power [3]. In 2022, solar power capacity increased by 45% compared to the previous year, and to keep up with this fast growth pace, it is necessary to optimize the efficiency of solar energy harvesting systems [4]. One major issue with using solar energy, however, is the dilute nature of the power [4]. Even at the equator, the average solar energy density is barely 1.1 kW/m^2 [5]. One effective way to improve solar energy efficiency is through solar tracking systems, which align solar panels with the sun's movement, enhancing efficiency by up to 40% compared to fixed panels [6].

Various Project-based Learning (PBL) on solar cells, which include Arduino and sensors, have been demonstrated [7], [8]. The design and construction of a solar tracking system involve interdisciplinary engineering fields, including mathematical modeling, electrical engineering, coding, and automation. Building solar trackers is a good project for high school and undergraduate students to practice their engineering skills in real-world applications. In this study, a prototype of a low-cost and easy-to-make active two-axis solar tracking system was developed. This project adopts a PBL approach to engage students in designing, constructing, and analyzing a solar tracker. Also, grounded in Kolb's Experiential Learning Theory, the project follows a process of concrete experience, reflective observation, abstract conceptualization, and active experimentation [9]. The students first participated in lectures and a lab session introducing semiconductors, current-voltage (IV) characteristics, solar energy principles, and the efficiency characterization of a calibrated solar cell using Arduino, a multimeter, and a potentiometer. In addition to submitting the lab report, they engaged in reflective observation by thinking about applying their knowledge toward addressing the energy crisis. They subsequently conceptualized, prototyped, and iteratively refined a solar tracker using Arduino, 3D-printed components, light-dependent resistors (LDR), a servo motor, and a stepper motor.

This project allowed students to move from theory to practice. By working collaboratively to develop a functional solar tracker, students enhanced their understanding of renewable energy technologies and their application in engineering. We report on the 15-month-long learning experiences of the solar tracker development: learning about the principle of semiconductors and experiencing Arduino and solar cell efficiency characterization in ESAP Nanotechnology for three weeks, followed by subsequent solar tracker development with an iterative engineering process for fourteen months. The student's active role in the project and their reflections highlight the educational and technical impact of a project-based approach to solar tracking technology. By designing, testing, and optimizing a dual-axis solar tracker, students engaged in an interdisciplinary engineering project that integrated automation, mathematical modeling, coding, and solar energy research. These reflections are analyzed to assess the alignment of the project with the intended learning objectives.

2. Experimental Methods

2.1 Preliminary Lecture and Laboratory Session

The School of Engineering at the University of Pennsylvania hosts highly motivated high school students to ESAP. ESAP runs for three weeks in July and grants students one course unit with the completion of the program. ESAP Nanotechnology mainly comprises introductory lectures and hands-on laboratory modules [10]. In 2024, the ESAP Nanotechnology course consisted of 15.5 hours of introductory lectures, 10.5 hours of invited talks, approximately 50 hours of laboratory modules, and other activities such as presentations, challenge projects, and group work. One of the laboratory modules is solar cell characterization, which includes a calibrated silicon solar cell, Arduino, coding, potentiometer, INA 219 current sensor, and multimeter [8]. Students learn how to wire various devices and measure the IV characteristic of the solar cell under dark condition in which the solar cell acts as a diode and illuminated condition in which the solar cell acts as a power generator as shown in Figure 1. The students submit the lab report after the lab session. Prior to the lab, students also learn the principle of the pn junction, semiconductors, and solar cells in the lectures.

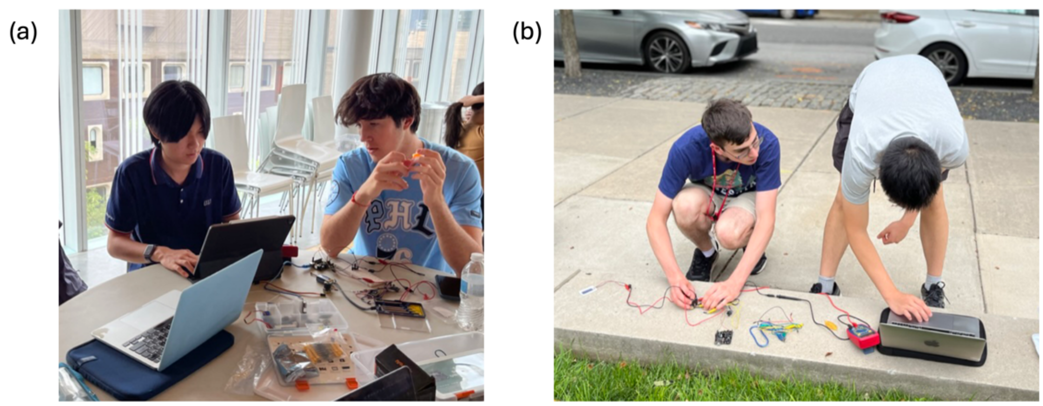

Figure 1. Engineering Summer Academy at Penn (ESAP) Nanotechnology students are learning how to characterize (a) IV characteristics under dark condition and (b) the efficiency of the solar cell under the sunlight

2.2 Angles for Solar Tracking System

Solar panels utilizing solar tracking mechanisms automatically keep their light-receiving face perpendicular to the sun's rays. Various types of solar-tracking devices have been reported to increase the harvesting efficiency of solar energy [6]. To track the sun, an active mechanism can be used, in which microprocessors use data from sensors to orientate the solar panels using motors. While this method does require an additional energy source to run, this type of solar tracker can provide an overall increased efficiency in energy production compared to fixed solar panels.

In this project, a dual-axis solar tracker was designed based on the motion of the sun, which consists of two parameters. The first parameter is the sun's altitude angle, the complementary angle of the Zenith angle, as drawn in Figure 2(a). This angle is associated with the sun's daily motion and determines a solar tracker’s movement in the East-West plane. The second important parameter is the Azimuth angle, the angle between the projection of sun rays and the North-South axis. This angle is associated with the sun's yearly motion. Due to the Earth’s 23.4° axial tilt, the sun moves through the year in the North-South direction as demonstrated in Figure 2 (b).

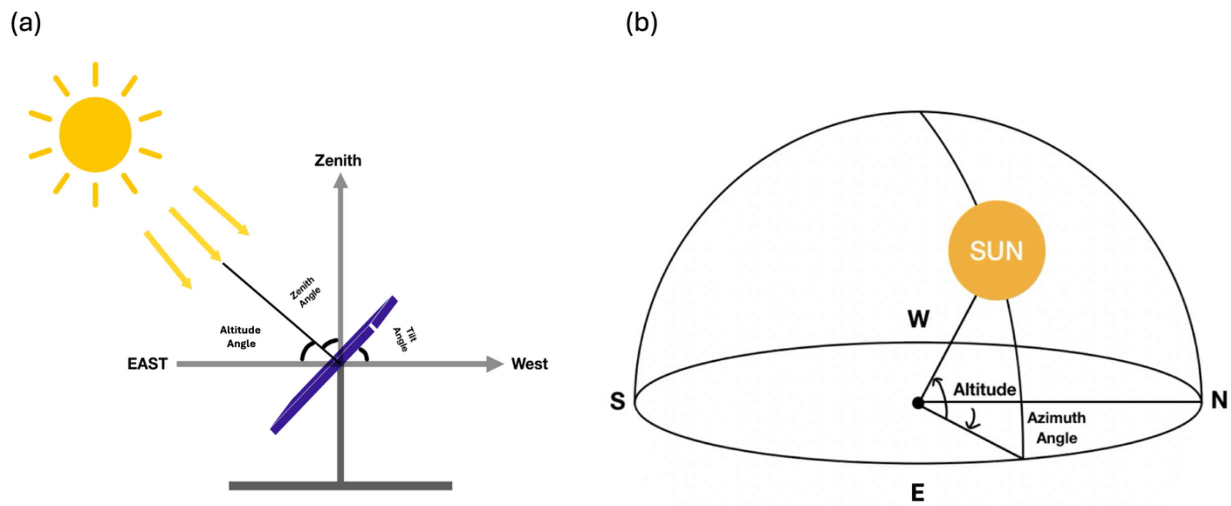

Figure 2. Two important angles to consider when making solar tracking systems (a) altitude angle for daily solar motion and (b) azimuth angle for yearly solar motion

2.3 Electrical Configuration and Data Collection

Two CC-2x4 calibrated solar cells (Solar Made®) were purchased. To accurately measure solar cells' efficiency, the characterization test must be performed under the standard testing conditions: 25°C of solar cell temperature, 1.5 air mass, one sun (1 kW/m^2) of illumination, and 4-point probe testing. However, dedicated equipment for characterizing solar cells is not affordable in many research facilities or high schools. The calibrated solar cell can be an excellent alternative solution. After the fabrication of solar cells, the manufacturer measures the short circuit current and open circuit voltage of the solar cell under standard test conditions. When students use the calibrated solar cell, the input power can be calculated with the ratio of the short circuit current of the measurement day to that under standard testing conditions. The current generated from the solar cells was monitored by two separate INA 219 DC current sensors connected in series with two 9.1 Ohm resistors, then converted to power and energy. The 9.1 Ohm resistors were used because the solar cells showed the maximum power output with this resistance [8].

Figure 3 shows the electrical configuration of the solar tracker. The motion system of the solar tracker consists of a 28bjy-48 stepper motor, a SG90 servo motor, a ULN 2003 motor driver, and three GL55XX-X LDRs connected in series with three 4.7k Ohm resistors. The DHT11 temperature and humidity sensor and the BMP085 temperature and pressure sensor were mounted to monitor environmental factors. Note that DHT11 and BMP085 are optional and do not affect the operation of the solar tracker. Finally, an Arduino Uno R3 board, a cheap and easily accessible option for students, was employed to control the entire solar tracker system. This project uses two different applications for data collection: Arduino IDE and PuTTY. Arduino IDE is an integrated development environment that allows users to write, compile, and upload code to an Arduino simultaneously from the same application. PuTTY is a terminal emulator that can be used to see and log serial messages. Although Arduino IDE supports seeing these messages, we used PuTTY to log all data points easily without losing them after the application closed. Approximately 25 data points were recorded every minute.

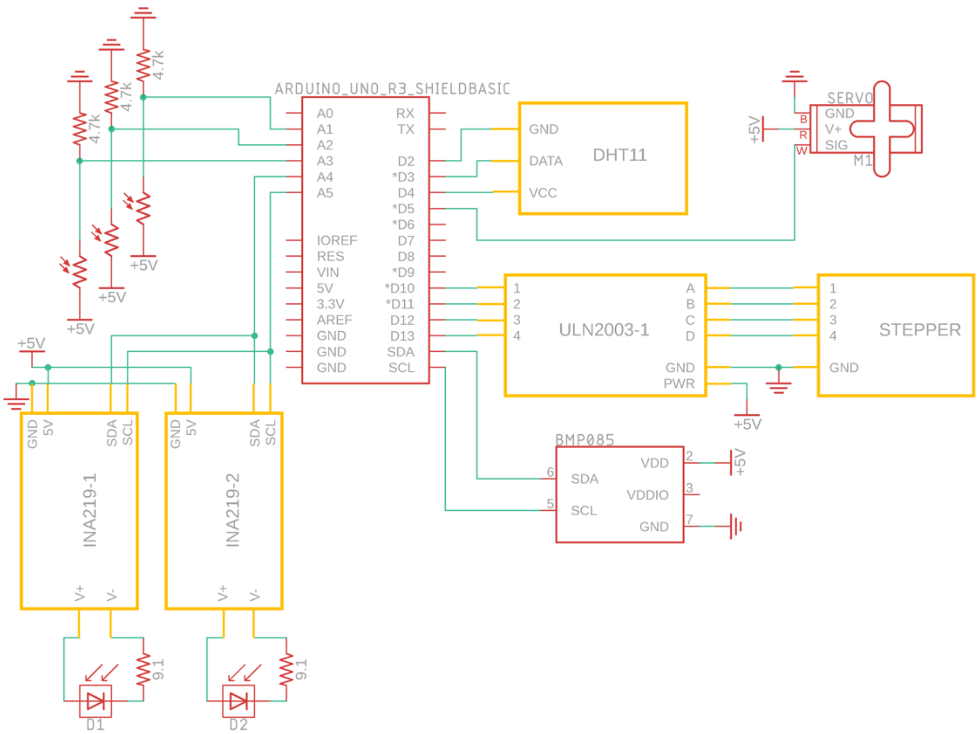

Figure 3. Electrical configuration of the solar tracker. The humidity and temperature sensor (DHT 11) and pressure and temperature sensor (BMP 085) are optional.

2.4 3D Printing and Automation

The solar cell, microcontroller, motors, sensors, resistors, and battery were integrated into a 3D-printed solar panel mounter and a base, as shown in Figure 4. One solar cell was attached to the solar panel mounter and the other solar cell was laid on the ground near the base. The LDRs were positioned in the center of an extruded Y shape on the solar panel mounter with a 120ºC separation between each branch. This shape was designed so that the light intensity cast on the LDRs would change when the sun moved, letting the Arduino update the tilt angle of the solar panel mounter.

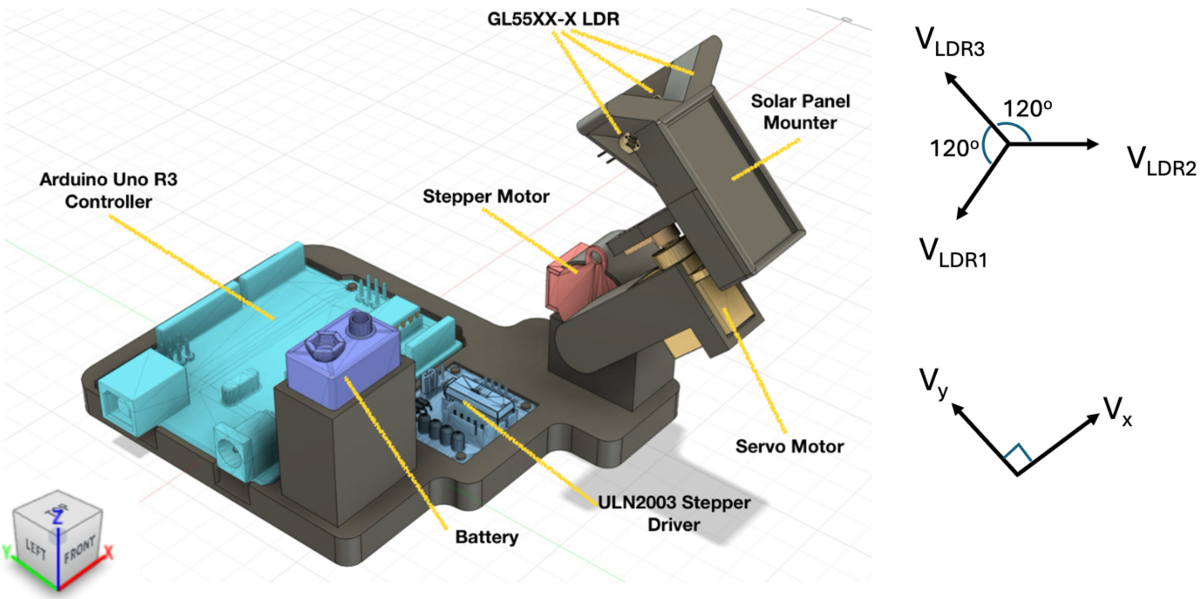

Figure 4. 3D model of the solar tracker and embedded electronic components.

To calculate the tilt angle of the solar mounter, the code treats each LDR value (V_{LDR1}, V_{LDR2}, V_{LDR3}) as a vector magnitude starting at the center and pointing towards each sensor, as shown in Figure 4. Two resultant vectors, V_x and V_y, were calculated as expressed in equations (1) and (2).

$$V_x = -cos\left(\frac{\pi}{6}\right) \times V_{LDR1} + cos\left(\frac{\pi}{6}\right) \times V_{LDR2} \quad (1)$$

$$V_y = V_{LDR3} - \left(sin\left(\frac{\pi}{6}\right) \times V_{LDR1} + sin\left(\frac{\pi}{6}\right) \times V_{LDR2}\right) \quad (2)$$

Whereas V_x controls the movement of the servo motor, which tracks the azimuth angle for yearly solar motion, V_y controls the movement of the stepper motor, which tracks the altitude angle for daily solar motion. The solar cell mounter adjusted its position until all three sensors were measuring values that were very close to one another. As the sun moves throughout the day, the solar cell moves with it and stays pointed at the sun. After updating the location, the program polled the sensors to get weather data such as humidity, temperature, and pressure, as well as the solar panel's power data. This data was all logged to the computer, and the cycle repeated forever. Figure 5 shows the range of motion of the solar tracker. Whereas Figures (a), (b) and (c) show the operation of the servo motor, and Figures (d), (e), and (f) show the operation of the stepper motor.

The solar tracker system was tested outdoors in Minnesota, US, for about 14 hours for two days, from early morning to the evening. The weather conditions were sunny and clear, and the test site had unobstructed access to sunlight throughout the daytime. A control group which does not track the sun was set directly upwards, about 150 mm away from the solar cell with the tracker.

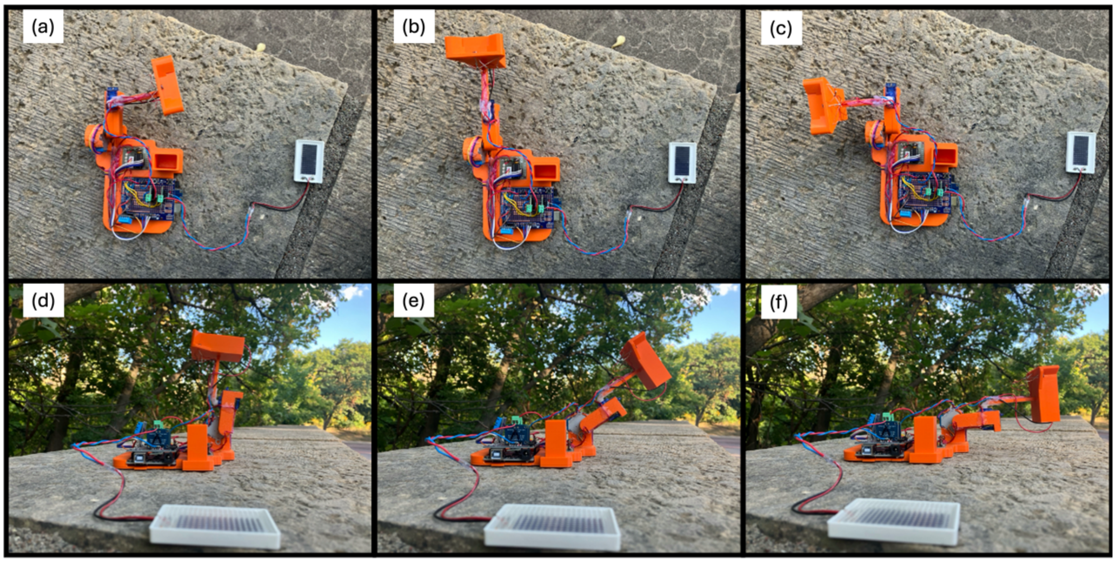

Figure 5. The movement test of the assembled solar tracker. Whereas (a), (b) and (c) show the operation of the servo motor, (d), (e), and (f) show the operation of the stepper motor.

3. Results

The performance of the solar tracker was examined by comparing the power and energy produced by a solar panel with the solar tracker to those of a solar panel without a solar tracker, with both running simultaneously at the same location.

The power generated at each data point was calculated using the equation (3):

$$P = VI \tag{3}$$

where P is the power generated by the solar panel, V is the voltage produced, and I is the current measured.

Moreover, the total energy produced was calculated by cumulating the energy produced at each data point using the equation (4):

$$E = VIt \tag{4}$$

where E is the energy the solar panel produces, and t is the time interval between two measurements.

The generated power and energy on day 1 are presented in Figure 6 (a) and (b), respectively. The same test was performed on day 2 to check the reproducibility, with the results shown in Figure 6 (c) and (d). Since the measured data at each data point is affected by the temporary weather conditions, especially clouds, smoothing is applied with the adjacent averaging method. This data processing averages the data points within the window to make the trend of curves more observable.

Figures 6 (a) and (c) show that the solar cell on the tracker generates significantly more power during the early mornings and the evenings. This indicates the effect of the solar tracker comes mainly from its ability to provide the solar cells with large tilt angles when the sun is at low altitudes.

The cumulative energy plotted in Figures 6 (b) and (d) indicates the solar tracker is able to improve the energy produced by the solar cell. The total energy produced by the solar cell with the solar tracker achieved 1423 J and 1536 J over a single day, whereas that without a tracker only harvested 1249 J and 1289 J of energy. A 16.5% improvement due to the solar tracker aligns with reported improvements in other solar trackers, which typically range between 15% to 40%, depending on system design [6]. This shows the effectiveness of the solar tracking system developed at a low cost and in an educational context.

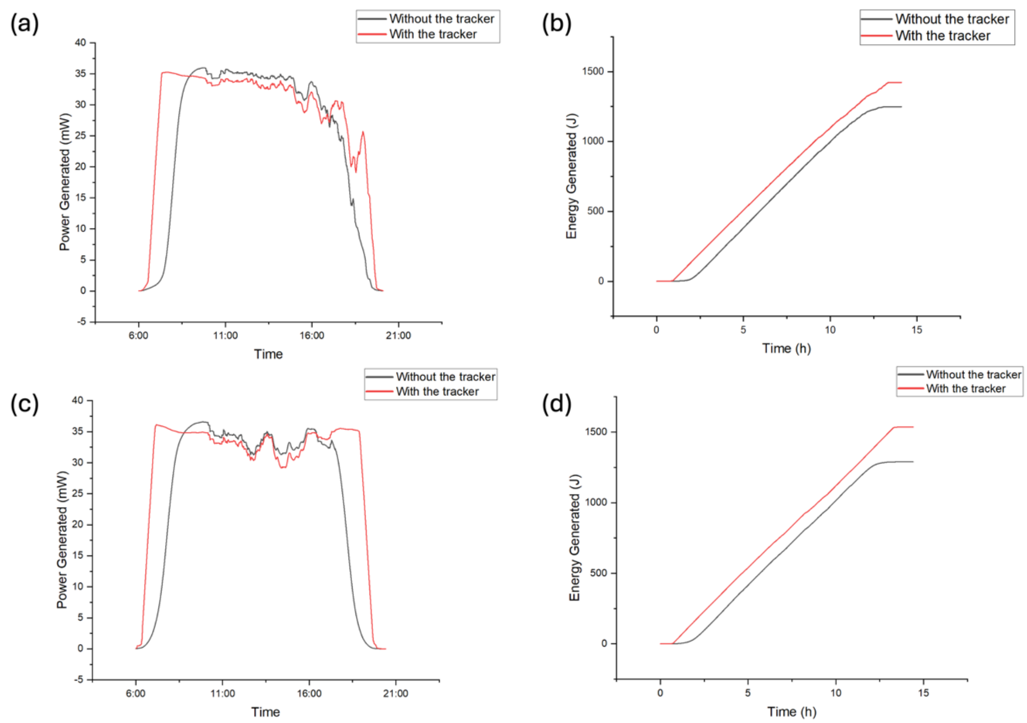

Figure 6. Generated (a) power and (b) energy on day 1. Generated (c) power and (d) energy on day 2

Note that the amount of power consumed by the solar tracker was not considered in Figure 6. While net power, which accounts for both generated and consumed, is a fairer comparison, the solar tracking system in this project is not designed to be the most power-efficient. Students used the materials mostly provided in the kits during ESAP Nanotechnology rather than purchasing new optimized materials. The motors used on the solar tracker are stronger than they need to be for small solar panels and therefore use more power than they would if we were aiming for creating a commercial system. At the same time, the motors are not strong enough to support commercial solar panels that people have in their homes today. The amount of power motors use does not represent what a system like this would use if put into production. Thus, using net power as a performance metric would be a misleading statistic, as it would be negative due to the overpowered motors. The value of the solar tracker is both in the educational use, and in the change in efficiency measured. While net power is a great way to compare commercial systems, this tracking system was not made to compete as a standalone solution.

4. Assessment

After a 15-month journey in which two students completed the ESAP Nanotechnology course and subsequently designed and developed the solar tracker, a reflection survey of students as learners was conducted to assess the learning procedure. Note that these learners are also the developers of the solar tracker and, thus, are participants in this research.

4.1 General reflections

<u>*What motivated you to participate in this project?*</u>

- First, I'm excited to have the opportunity to apply our knowledge toward addressing the energy crisis. Additionally, because this project involves key skills like coding, modeling, and researching, I believe it will greatly contribute to my personal development.
- When I started this project, I wanted more experience in designing and running my own experiment. I hoped to be able to stay in touch with my roommates from ESAP, and do something I enjoyed (engineering)

<u>*What were your initial expectations, and how did they compare to your actual experience?*</u>

- My initial goal was to manufacture a solar tracker that would greatly boost solar cell efficiency. In reality, we did succeed in building the tracker, but the resulting efficiency increase was not as significant as we had initially assumed.
- I initially expected this project to last a single summer, but it has since lasted far longer. I also expected the project to be simpler than it turned out to be. Planning meetings, organizing good dates for testing, and managing unexpected results all made it more complex than I initially assumed.

4.2 Learning Experience

<u>*What technical skills (e.g., coding, working with Arduino, automation, 3D printing, circuit design, etc) did you gain or improve during this project?*</u>

- I got better at turning digital designs into real ones. It is easy to create a circuit diagram, or to 3D model a project, but taking those digital blueprints and joining them together neatly is no easy task. Designing my wiring to complement the physical design, and the 3D model to complement the wiring was a new challenge for me.
- I have improved my Arduino, coding, circuit design, and independent research skills.

<u>*What concepts or knowledge about energy and automation technologies, and their applications were most surprising or valuable to you?*</u>

- I was amazed by the large amount of solar energy our planet receives and the enormous potential for harnessing it. Based on my knowledge of automation and general engineering—

particularly coding, 3D printing, and sensor technology—I've gained valuable insights into practical, cost-effective methods of improving current solar energy harvesting processes.
- I learned about a lot of different types of renewable energy, such as heliostats or solar power towers, which use mirrors to concentrate heat for a boiler rather than convert it directly into electricity like solar panels.

How did this project help you understand engineering principles in a hands-on way?
- This experience taught me to take into account real-world considerations—such as the surrounding environment, cost, and manufacturability—that aren't always detailed in textbooks. Additionally, it highlighted the significant potential of coding in engineering, motivating me to study it more extensively.
- By testing my design for an extended amount of time outside, and using it afterwards, I was required to face and improve upon my earlier mistakes. Keeping my design simple and thinking ahead helped a lot. For example, the Arduino logs data in csv formatting, making it easy to analyze as a spreadsheet later.

What challenges did you face during the development process, and how did you overcome them?
- One of our first challenges was dealing with the misleading effects of tree and cloud shadows on the tracker. We addressed this by installing the system in different locations to achieve more accurate results and by smoothing the data curve for better analysis. Additionally, the inaccuracies inherent in 3D printing highlighted the gap between design concepts and real-world manufacturing, showing us the importance of incorporating uncertainty into our modeling process.
- While developing the system, there were a couple of times that poor wiring caused inexplicable problems. At first, it seemed like these were caused by the programming, but after probing around with a multimeter for a while, I found the problematic wires.

4.3 Teamwork and Collaboration

How did working as a team contribute to the success of the project?
- First, working as a team significantly boosts efficiency because each member can focus on their areas of expertise. Furthermore, our diverse perspectives and creative thinking enable us to develop innovative, effective solutions in a relatively short timeframe.
- I am incredibly grateful for my partner's contributions. The amount of research and insight he brought was amazing, and he helped point out pitfalls that I hadn't considered.

What role did you play in the project, and how did you feel about your contribution?
- I did all of the programming, building, and testing of the device. I also did the majority of the 3D modeling, and the entirety of the electrical design. A minority of the data analysis and writing was done by me. I feel proud of this project and am satisfied with the amount that I was able to contribute.
- My primary role is researching scholarly papers for practical solutions and brainstorming the initial design. In addition, I serve as the project's main writer, gathering and summarizing all relevant information and progress. While I'm glad I can focus on areas where I excel, I also hope to gain more direct experience with the engineering and hands-on components of the project.

What did you learn about collaboration or communication in an engineering context?

- I believe collaboration is essential in engineering because most projects require multiple, specialized skill sets that different team members bring to the table. Working together ensures tasks are completed quickly and accurately. Effective communication is equally important and can sometimes be challenging, particularly when explaining technical concepts to those with different backgrounds. Hence, the ability to convey technical progress in a clear, accessible way is crucial for productive collaboration in an engineering context.
- Planning is difficult! I had to learn how to manage three different time zones, as well as handle rescheduling and conflicting plans when trying to organize meetings. Dividing up work was also a new skill I had to work on, made more difficult by the fact that Dash didn't do the work that was assigned to him.

4.4 Broader Impact

How could this project benefit others, such as individuals living in areas with higher demand for renewable energy or students learning engineering?

- For individuals looking to maximize solar energy production, using a solar tracker can be extremely advantageous. In larger systems, such as extensive solar panel arrays, tracking the sun can substantially boost energy output. This is particularly helpful when space is limited—like on certain rooftops—where every bit of additional efficiency matters. For students, a hands-on solar tracker project offers valuable personal development opportunities. It requires practical skills in coding, modeling, and independent research—all of which are essential in real-world engineering. By integrating these diverse skills, the project allows students to experience a true engineering endeavor that addresses a real need.
- This project provides a baseline design for how a solar tracker works. It can be adapted for use in urban applications where space is limited, and energy demand is high. For students, this project is a great way to learn about the intersection of many engineering disciplines. Electrical engineering, mechanical engineering, and software engineering must be used together for this project to work well.

Did this project change your perspective on how technology can solve real-world problems? If so, how?

- Yes, I've realized that using technology to solve real-world problems requires taking into account numerous practical factors, such as cost and the operating environment. Recognizing this has allowed me to further realize the importance of teamwork, where engineers and other experts must collaborate to effectively address these real-world considerations.
- Yes. Previously, I had a much more monotonic view of technology and believed that scientists or engineers of a single field could make a single advancement that would have great changes. I now believe that these great discoveries must involve cooperation and collaboration across disciplines.

4.5 Future Aspirations

Has participating in this project influenced your interest in engineering, technology, or related fields?

- Yes, I’ve learned how crucial it is to integrate coding, modeling, and other hands-on activities in real-world engineering applications. This realization has sparked a greater interest in coding. Additionally, by recognizing the importance of practical considerations, I’ve begun exploring other facets of engineering, such as cost management.
- Yes, this project has increased my interest in engineering as a whole.

What would you like to explore further as a result of this experience?

- I would like to focus in more on the movable arm I designed for this project. While it works perfect for this application, I would be interested in creating a larger, more mobile/flexible version.
- I plan to delve deeper into coding and computational modeling, as they offer a cost-efficient and convenient approach to designing and testing engineered products. Additionally, I want to broaden my horizons beyond pure engineering by exploring project management, as well as cost and risk management.

4.6 Feedback on the Project

What aspects of this project were most engaging or rewarding for you?

- The feeling after I was finally able to record a full day’s worth of data with full sun the entire time was incredible. The knowledge that all of our work had come together to that success was the most rewarding moment. As for most engaging, I had a great time working on the code.
- For me, the most engaging part was performing the data analysis. It was exciting to identify mistakes we made and uncover ways to enhance our product by examining the real-world data we collected.

What improvements or changes would you suggest for similar projects in the future?

- I would suggest that the walls around the LDR's be raised. For this design, while the walls are tall enough for it to track the sun, they are short enough that there was some small error while tracking.
- It’s necessary to minimize the false movements caused by shadows, especially those from clouds. Reducing the motor’s energy consumption is also a priority. Moreover, incorporating a mathematical model to predict the sun’s position would greatly improve tracking accuracy.

4.7 Final Reflection

If you could summarize your experience in one or two sentences, what would you say?

- This project had a lot of pitfalls, but instead of treating them as failures, I learned from them and changed. Iteration, communication, and responsibility allowed my partner and I to create something we are both proud of.
- A meaningful journey that connects our academic pursuits with solving an urgent, real-world challenge.

5. Discussion

This project demonstrates a framework for high school and undergraduate students to foster engineering competencies grounded in Kolb's Experiential Learning Model and PBL. By analyzing student reflections, we can recap their learning experiences as a continuous cycle of four stages: concrete experience, reflective observation, abstract conceptualization, and active experimentation [9]. We can also highlight the PBL components of collaborative, real-world problem-solving with a hands-on approach.

5.1 Concrete Experience

Students first learned the principles of solar cells and semiconductors, then engaged in a hands-on lab session to characterize the efficiency of a calibrated solar cell using Arduino, current sensor, and coding. This initial exposure provided a foundational experience and motivation for further research associated with the real-world application. Their decision to design a solar tracker stemmed from the knowledge and curiosity sparked during ESAP Nanotechnology.

5.2 Reflective Observation

The reflective observation was not limited to the lab report submission during the ESAP Nanotechnology. The assessment reveals that students realized the gap between their initial expectations based on the literature review and the realities of project work. One student noted the poor wiring led to inexplicable problems, which required systematic troubleshooting with a multimeter to diagnose the issue. Another student pointed out the complexity of organizing meetings and managing unexpected experimental results. These reflections align with Kolb's reflective observation phase, where learners analyze experiences to gain new understanding and review the importance of teamwork and collaboration.

5.3 Abstract Conceptualization

One student stated the motivation for this project was to apply their knowledge toward addressing the energy crisis. Through the project, students formed broader and deeper insights into the technologies associated with this project. One student was amazed by the potential of solar energy technologies and gained valuable insights into practical, cost-effective methods to improve current technology. This realization indicates how experiential learning can foster abstracting engineering and technology concepts.

5.4 Active Experimentation

Throughout 15 months, the solar tracker’s design and its performance testing method have been updated with multiple iterations and reflections. The example includes data fluctuation due to shadow and data smoothing as troubleshooting. Another example is a systematic approach to problem-solving by revising code and checking wires with a multimeter. These problem-solving experiences show iterative design and adaptation, which are key experiential learning.

5.5 PBL

The solar tracker project demonstrated the principles of PBL by letting students perform hands-on experiments to address real-world problems. Students defined the energy crisis problem and then tried to solve the problem with creative and interdisciplinary engineering approaches such as circuit design, coding, mathematical modeling and 3D printing. The students pointed out the challenges of turning CAD designs into actual prototypes, managing environmental factors, and troubleshooting various technical issues. Students also stated they were mostly engaged when they were finally able to record a full day's worth of data, troubleshoot with code, and perform data analysis. Throughout the iterative process, the students collaborated to find the best answers to the open-ended question about how to enhance the efficiency of solar energy harvesting.

5.6 Institutional Adoption, Scalability and Structured Learning Assessment

The solar tracker we demonstrated has scalability potential. Most essential components for solar cell lab module in ESAP Nanotechnology are included in Elegoo Uno Project Super Starter kit. This kit contains an Arduino board, a breadboard, jumper cables, a stepper motor and driver, a servo motor, a DHT11 sensor, two LDRs, a 10k Ohm potentiometer, and resistors. It is necessary to purchase calibrated solar cells, INA 219 sensors, a 100 ohm potentiometer, and a multimeter. The total cost is approximately $90 in total, making it a cost-effective option for the institution to implement. After completing ESAP Nanotechnology, to make the solar tracker, one of the students fabricated 3D printing components using a personal 3D printer and purchased extra LDRs and a BMP 085 sensor. While the current tracker is developed for small-scale educational use, the design could be scaled for larger solar tracking systems by optimizing the size of solar panels.

As mentioned above, this interdisciplinary engineering project integrates 3D printing, automation, coding, electrical engineering, and solar energy. Educators can adapt and expand PBL experiences based on students' majors, interests, and academic levels by setting specific goals and content. For example, automation educators could focus on 3D printing, Arduino, coding, and motor controls, while energy educators could emphasize energy harvesting with pre-made 3D printing components. 3D printing designs and source codes are available for educators and students to download [11].

This study assessed two students' learning through thematic analysis of reflections. However, in the future, with a larger-scale lab setting, a structured learning assessment that includes pre- and post-lab competency surveys could be conducted to measure learning outcomes quantitatively.

5.7 Broader Applications of Solar Tracking Technology Beyond Education

Beyond solar tracker's educational benefits, this technology has broader real-world applications. For example, it can maximize the efficiency of small-scale solar energy systems, such as rooftop solar plant [12]. Another application is rural electrification [13], where solar trackers can enhance energy reliability for households, facilities, and schools in areas with limited access to grid power by maximizing energy output and integrating energy storage systems. Additionally, vegetable or poultry farms that require artificial lighting can benefit from solar trackers [14]. The use of solar tracking technology is aligned with sustainability initiatives. Harvesting more energy per solar panel reduces the need for additional panels, ultimately minimizing solar panel waste.

6. Summary

This study demonstrates a low-cost, two-axis solar tracker system for high school and undergraduate students. As a result of iterative process of building and testing, the solar tracker demonstrated a 16.5% improvement in energy generation compared to the fixed solar panel. The design and construction of a solar tracking system include various engineering-related fields, including mathematical modeling, electrical engineering, coding, 3D printing, and data processing. This project conducted Kolb's Experiential Learning Theory to analyze the educational process through the continuous cycle of four stages: concrete experience, reflective observation, abstract conceptualization, and active experimentation. The PBL approach allowed students to be engaged in an interdisciplinary, real-world project. The students gained confidence through critical thinking, problem-solving and collaboration experiences. This project will offer high school and undergraduate students to replicate their experiences in an affordable, efficient, and educational manner.

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