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Influence of a Dual Axis IoT- Based Off-Grid Solar Tracking System and Wheatstone Bridge on Efficient Energy Harvesting and Management

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Addressing the increasing need for sustainable energy solutions, this study presents an advanced dual-axis solar tracking system tailored for Mirpur, Dhaka, Bangladesh (23.8123° N, 90.3740° E). By integrating Internet of Things (IoT) based intelligent power management and automated panel cleaning, we aim to optimize the efficiency of solar photovoltaic (PV) systems. Our design significantly outperforms traditional fixed PV setups, achieving an average voltage improvement of

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about 18.59% throughout the day. Real-time data monitoring showcases the system's adaptability, with Solar Voltage (SV) and Solar Current (SC) standard deviations recorded at 1.059 and 0.058, respectively. This system not only captures sunlight more efficiently but also ensures self-maintenance, reducing manual intervention. The integration of IoT capabilities provides real-time feedback and adaptability. With a small household size of 4-6 members and a basic electricity demand as a prototype version, the study reveals promising results for sustainable energy solutions. In future integrating a Microgrid system for improved energy distribution and storage, alongside implementing a smart fuzzy logic-based tracking system to optimize solar panel orientation for maximum power generation.

Keywords: Dual axis; solar tracking; panel cleaning; smart power management.

1. INTRODUCTION

The rising carbon footprint and global warming are direct consequences of the increased reliance on fossil fuels for power generation [1]. To mitigate these negative impacts, renewable energy has emerged as a pivotal long-term solution [2]. Among renewable sources, solar energy stands out due to its affordability, off-grid functionality, and minimal maintenance costs [3]. However, to maximize the output of solar photovoltaic (PV) systems, efficient utilization of solar energy is imperative [4]. This necessitates the implementation of intelligent solar systems capable of optimizing electricity utilization and maintaining system efficiency through preventive measures against heat and grime accumulation on PV panels [5].

In recent years, there has been a notable surge in research efforts aimed at enhancing solar tracking systems, particularly through the integration of Internet of Things (IoT) technologies [6]. These advancements are designed to bolster the productivity and efficiency of solar panels by dynamically adjusting their orientation based on prevailing environmental conditions [7]. Such systems, equipped with IoT technology and intelligent features, leverage sensors, actuators, and IoT capabilities to enhance the energy efficiency of solar power systems [8]. Notably, extensive testing has demonstrated significant energy production improvements, up to 28.3%, compared to traditional fixed-mount systems, underscoring their potential to advance renewable energy utilization significantly [9].

Further advancements include the incorporation of analog controllers and maximum power point tracking (MPPT) devices, both integrated with IoT technology, to facilitate immediate monitoring and control of solar power generation and battery charging [10]. Additionally, emerging solar tracking systems powered by IoT, and machine learning algorithms offer dynamic angle adjustments based on real-time data analysis, coupled with remote monitoring and control capabilities for enhanced flexibility and ease of use [11]. Moreover, the integration of IoT and Raspberry Pi technology has yielded cost-effective and adaptable solar tracking systems suitable for various applications, including residential and small-scale business environments [12].

Eventually, dual-axis solar tracking systems, bolstered by IoT technology, represent a promising avenue for optimizing solar energy harvesting [13]. Through remote monitoring and feedback control mechanisms, these systems effectively position solar panels relative to sunlight, resulting in substantial improvements in energy collection efficiency compared to fixed-tilt panels [14]. By implementing power management strategies, energy consumption can be further minimized, highlighting the potential of these systems to enhance sustainability and efficiency in solar energy utilization [15].

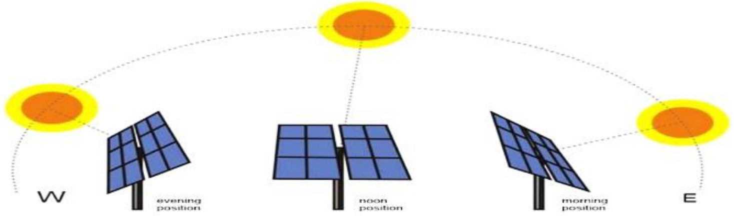


Fig. 1. Dual-axis solar tracking system [16]

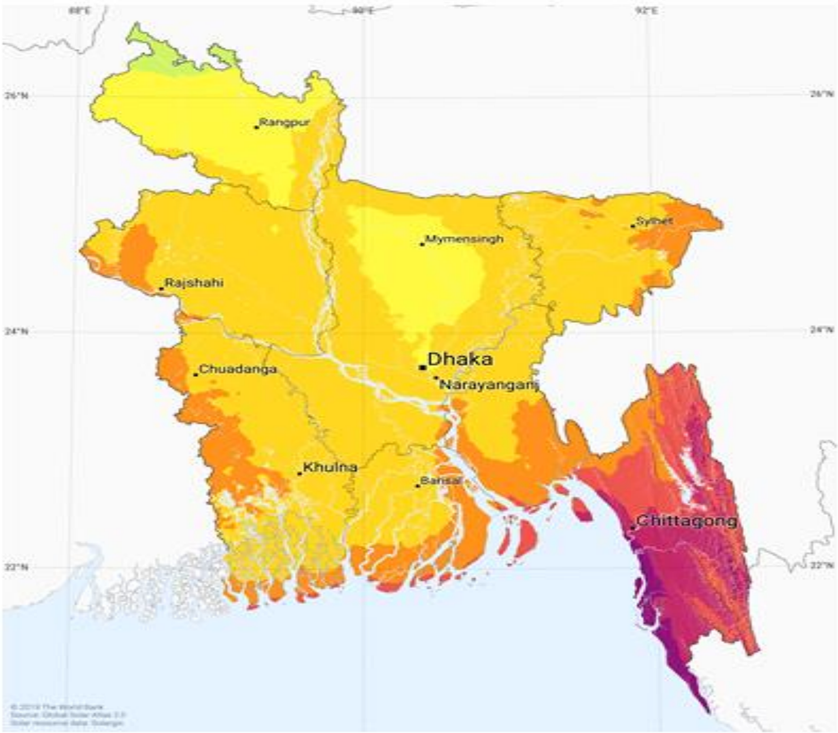


Fig. 2. Solar irradiance area of Bangladesh and Project test location [17]

We propose a system with automatic panel cleaning and solar tracking to maximize energy harvesting potential. We also use Internet of Things (IoT) gadgets to track and report data like solar energy output, battery life, and ambient temperature from a central location. The electricity demand is expected to continue rising globally, particularly in the post-COVID era, as reported by the International Energy Agency (IEA) [18].

2. METHODOLOGY

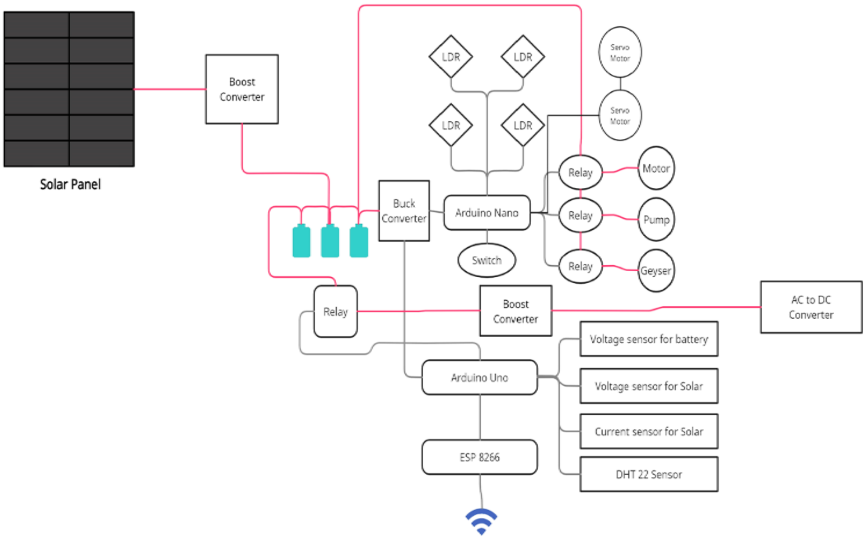


Fig. 3. System structure block diagram

The block diagram of the system structure (Fig. 3) depicts the system's overall operation. The system includes a solar panel that generates the essential energy for the system to function. The integration of a boost converter plays a pivotal role in enhancing the system's efficiency by transforming a lower voltage into a higher one. Complementing this, a 14.8-volt Lithium-ion battery is seamlessly integrated to store and supply energy to the system. This setup necessitates the incorporation of two boost converters within the design: one dedicated to elevating the solar panel's voltage to 16.8 volts and the other aimed at increasing the 12-volt AC to DC converter's voltage to the same level. This synchronization ensures optimal performance, particularly when the battery pack attains its maximum charge of 16.8 volts. Additionally, the initial utilization of the Wheatstone Bridge serves to measure shallow resistance values with precision, operating through voltage division. Its pivotal application lies in measuring variations in sensor resistance, providing a robust foundation for system calibration and optimization [19].

The implementation of the Dual Axis Solar Tracking control system represents a significant stride towards system robustness and efficiency. This closed-loop system seamlessly integrates the utilization of a Wheatstone bridge circuit and light-dependent resistors (LDRs), forming the backbone of the tracking mechanism. A compact and purpose-built control system is meticulously developed and assembled to validate the proposed approach, ensuring its effectiveness and efficiency. Within this framework, the reference input signal in the closed-loop dual-axis solar system is intricately tied to sunlight intensity, as depicted in Fig. 4. To enable seamless solar tracking, the integration of optical sensors becomes imperative to accurately discern the sun's position. Leveraging these optical sensors, the proposed tracking system dynamically adjusts the photovoltaic (PV) panel in alignment with the sun's angle, optimizing energy harvesting and system performance.

As light intensity increases, LDR sensors' electrical resistance decreases. A voltage differential emerges from an LDR sensor-generated voltage imbalance in the Wheatstone bridge branches. Fig. 2 shows the difference between solar radiation angle and PV panel position. The Wheatstone bridge output voltage is then boosted by the operational amplifiers (op-amps). Control circuits trigger the relay using operational amplifier output voltage. The relay starts engine rotation in the tracking system to move it in the right direction. Under ST control, the PV panel will rotate on its axis. This automatic mechanism positions the PV panel at the proper angle to the sun [20]. This process continues until the voltage disparity in the bridge branches decreases below a predetermined threshold value.

A Buck converter is used to supply 5 volts to the microcontroller and servo actuator. Two boost converters are required because the solar panel's voltage output is unstable and dependent on several variables, such as the intensity of sunlight, temperature, and shading effects. Three microcontrollers, Arduino NANO, Arduino Uno, and ESP 8266 are incorporated into the system's design. Arduino NANO controls dual-axis solar tracking systems, cleans solar panels, and operates geyser systems. The LDR sensor determines the movement of the servo motor, and the cleaning motor and pump are activated at predetermined intervals. In addition, the geyser system can be controlled via a valve. Arduino Uno is outfitted with two voltage sensors, a current sensor, and a DHT 22 sensor (consisting of a humidity sensor and a thermistor to measure air and generate digital data directly). The detected data is then transmitted via serial communication to ESP 8266. The data is sent to the web server by ESP 8266.

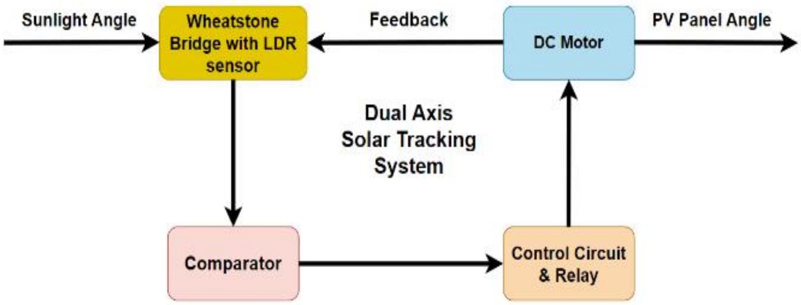


Fig. 4. Dual axis solar system block diagram

2.1 Dual Axis Solar Panel Movement Flowchart

Fig. 5 represents the Dual Axis Solar Panel Movement flowchart depicts the sequence of actions to be carried out by the command. The program begins with the power to commence and then directs the solar panel to its initial position. It accumulates and processes all the LDR sensor inputs. The program contrasts the values of the horizontal sensor data, namely whether LDR1 and LDR2 are equivalent. If the result is positive, Motor1 will be commanded to move towards the sensor above it. However, if the impact is negative, the program immediately compares the values of vertical LDR sensors. It determines whether LDR3 is equal to LDR4. If the result is positive, it instructs Motor2 to move towards the higher-up sensor.

If the result is negative, the program then determines whether all sensor values are below the threshold value. If the result is negative, the program delays ten minutes before rereading the LDR sensor values. If the result is positive, the program sleeps for six hours and restarts the procedure by repositioning the solar panel.

2.2 Power System Flow Diagram

Fig. 6 depicts a comprehensive overview of the sequential steps the power management system follows in response to user commands. The flowchart begins with the "start" command and continues with the battery's charge percentage calculation. If it is determined that the battery charge is 40%, the system will command the relay to power on. An alarm will sound if the battery charge declines below 40%. The system will also control the relay to pull on when the battery charge reaches 60%. When the battery reaches its maximum capacity, the system will command the excess generating current to be supplied to the grid.

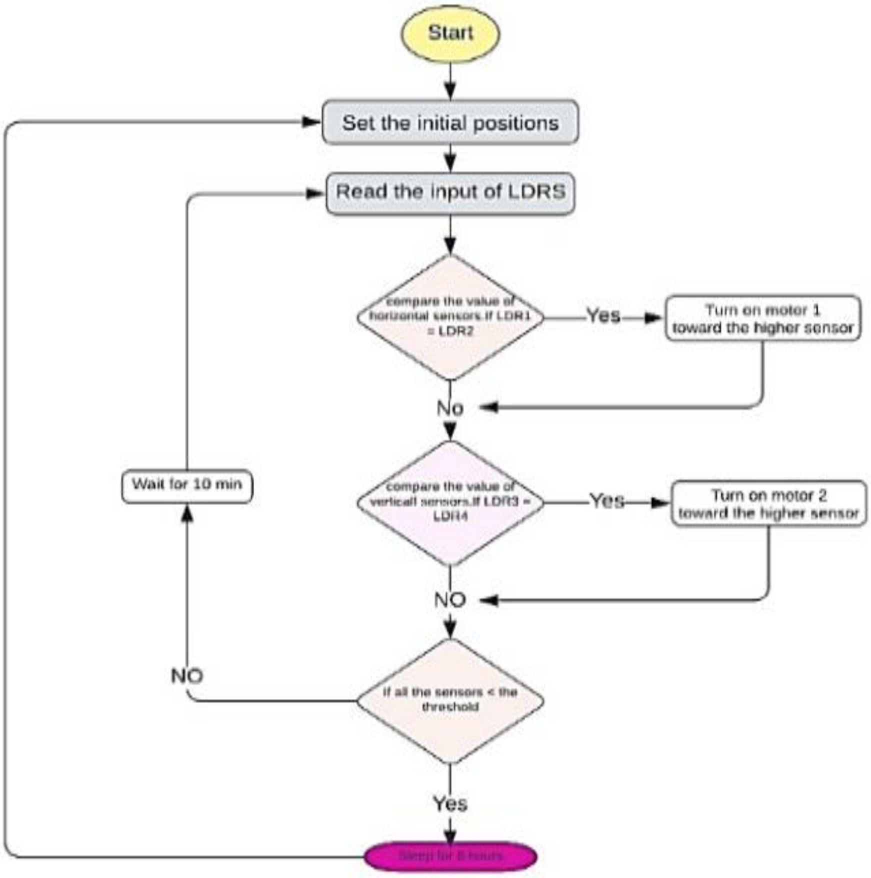


Fig. 5. Dual-axis solar panel movement flowchart

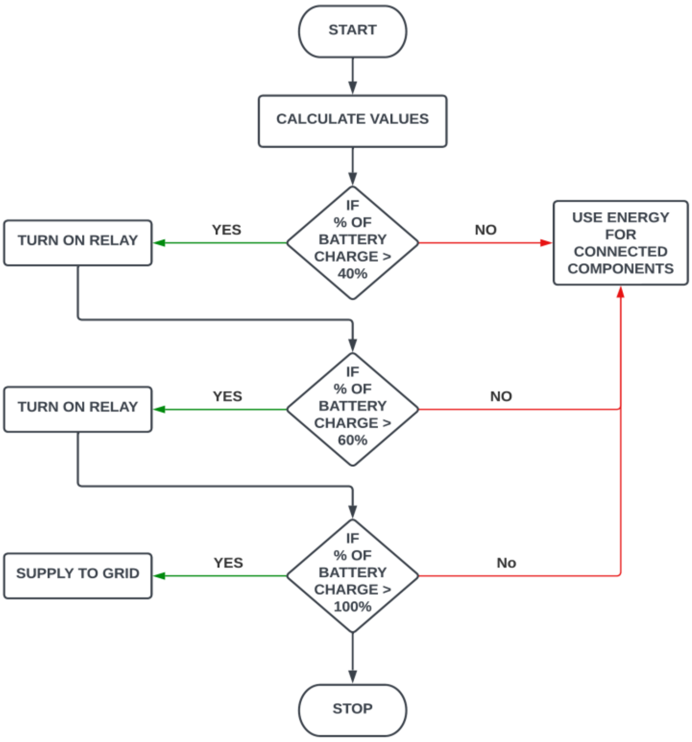


Fig. 6. Power management system flowchart

3. DESIGN AND SIMULATION

SolidWorks, a popular CAD software, was used to construct an elaborate 3D model of the project in Fig. 7. The 3D model correctly depicts the project concept and demonstrates the anticipated conclusion. System-critical solar panels are on top of the model. LDR (light-dependent resistor) sensors on the top and a gear motor on the left ensure precise solar panel cleaner control. Two strategically placed servo motors for horizontal and vertical axis movements enable dual-axial rotation for better tracking. For precise and smooth motor positioning, a well-designed frame is needed. A hardware component box holds vital system components and is delicately attached to the frame. The model's bottom battery ensures power supply, maximizing space utilization and system performance.

Fig. 7. Prototype 3D model of the project

3.1 Simulation of Robotic System and Operation

Fig. 8. displays the Simulation models assessing the IoT-based intelligent photovoltaic solar power system's performance before construction. It lets you test multiple design configurations and operating parameters and predict system performance. Simulation models can estimate a solar power system's energy output, battery charge, and efficiency in varied weather conditions.

The simulation of the robotic system and its operations was carried out with the help of the Proteus program. Fig. 9 shows that an Arduino Uno R3 microcontroller served as the simulation's primary processing unit, and its use was facilitated by incorporating this component into its design. Within the simulation, there were a total of four LDR sensors used. In addition, the simulation was equipped with three servo motors, which stood in for the cleaning brush motor, the horizontal axis motor, and the vertical axis motor, respectively. Additionally, to raise the voltage of both the solar panels and the 12-volt AC to DC converter, the system was equipped with two boost converters. The objective of these converters was to enhance the voltage. In addition, a buck converter was developed to supply energy to the microcontroller and the servo motor at a voltage of 5 volts. In the final step of the simulation, an energy storage device comprised of a solar panel and a battery was used.

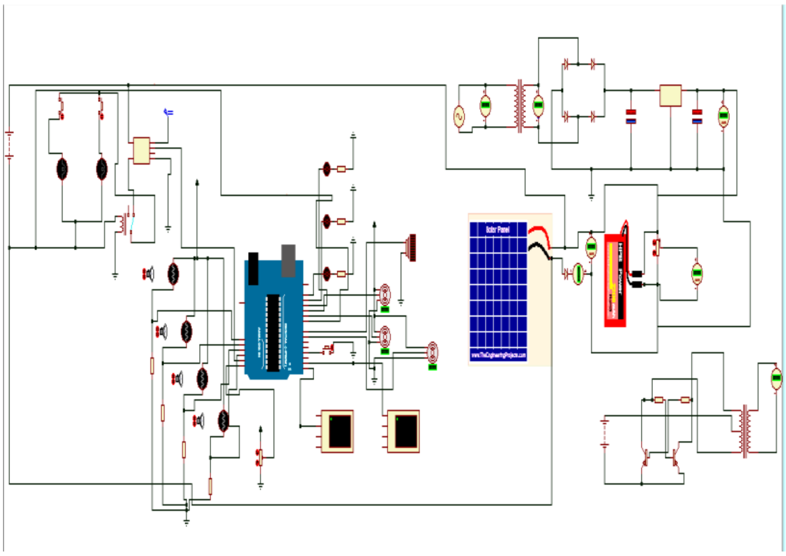
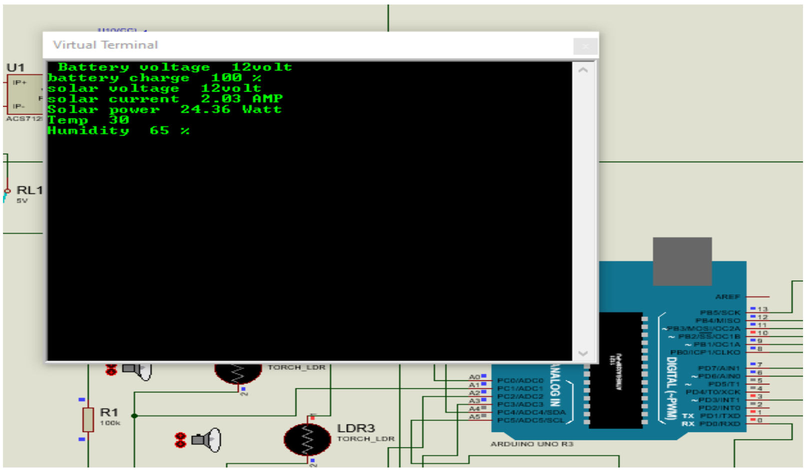


Fig. 8. Micro-controller-based power controller system designed in proteus



```
 Battery voltage  12volt
battery charge  100 %
solar voltage  12volt
solar current  2.03 AMP
Solar power  24.36 Watt
Temp  30
Humidity  65 %
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Fig. 9. Simulation result of micro-controller-based power controller system

4. RESULTS AND DISCUSSION

Fig. 10 depicts the final prototype of a project that includes a dual-axis solar tracking system, a panel cleaning system, and a power management system. Previously, a 3D model of the project was presented, and now its completion has been accomplished. The final product is a solar panel that converts sunlight into electricity. On the upper portion of the meeting, there are LDR sensors, and on the right side, there is a cleaner gear motor to move the cleaning brush across the solar panel. A horizontal servo motor is located beneath the board and is responsible for horizontal panel movement. The buck converter and vertical servo motor, which move the panel along the vertical axis, are located beneath this. This results in a dual axis tracking system for the project, enabling the solar panel to be moved along both the horizontal and vertical dimensions.

Fig. 11 depicts a top view of the project, displaying the solar panel, LDR sensors, cleaner, and cleaner gear motor. The solar panel and LDR sensors work together as a tracking system component, whereas the cleaner and cleaner motor facilitate the solar panel cleaning system.

Fig. 11 depicts the sun monitoring and dual-axis movement systems incorporated into the project. The primary function of the dual-axis movement system is to allow the solar panel to move horizontally and vertically. This is accomplished by employing a horizontal servo motor to facilitate movement in the horizontal plane and a vertical servo motor to boost the solar panel about its vertical axis. In addition, a buck converter is integrated into the system to provide 5 volts of stable power to the microcontroller and servo actuator.

Fig. 12 depicts the project's primary terminal unit for power and control. This image represents all of the project's constituent parts. The Arduino Uno, Arduino Nano, and ESP 8266 are readily identifiable as the project's primary processing devices. Additionally, the image displays the Boost and Buck converters. The lithium-ion battery cell is positioned on the image's left side. In addition, the painting depicts one current sensor and one voltage sensor used for measuring purposes. The image's reverse side displays the motor control and single-channel relay modules. In addition, DHT11 and the switch are located adjacent to these modules.

Fig. 10. Implemented dual-axis solar tracking, panel cleaning, and power management system project

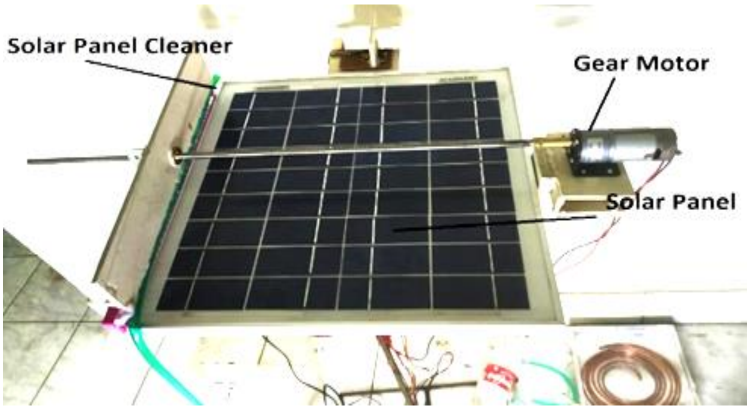


Fig. 11. Top view of solar sun tracking and cleaning system

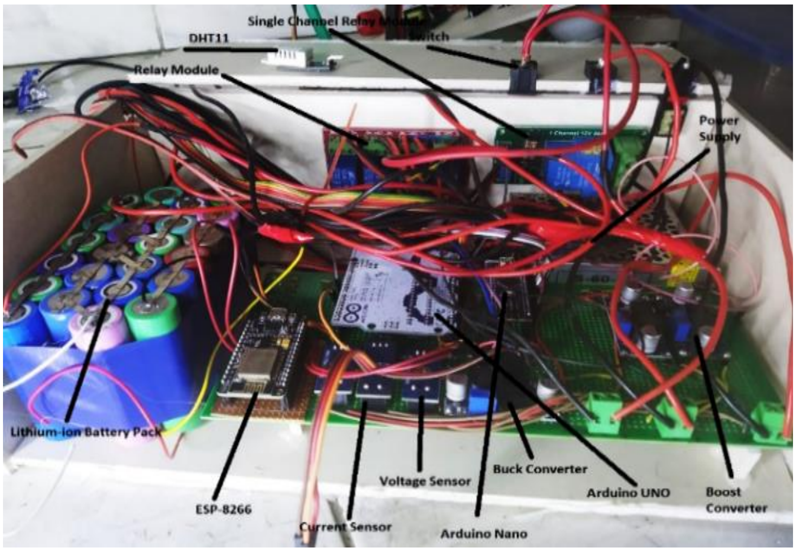
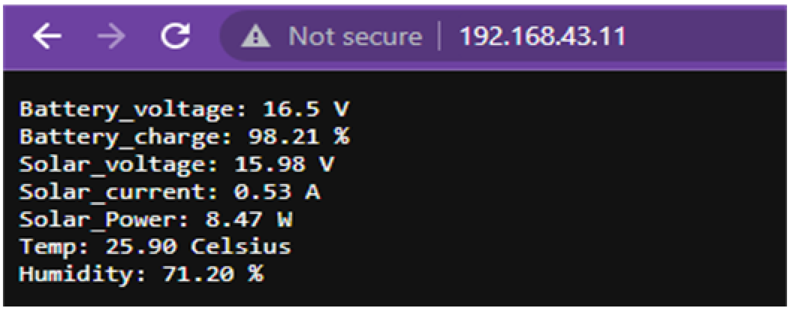


Fig. 12. Inside of hardware primary device

The simulation result is seen in this photo, which depicts the virtual terminal. It displays the voltage of the battery, as well as the battery's percentage of charge, and the voltage, current, and power of the solar panel. The system draws power from the grid if the battery charge is lower than 40 percent, equivalent to 4.2 volts. Let's say that the battery has 4 volts. The battery pack operates at 16.8 volts. The calculation is:

$$= ((4*100)/16.8)\ \% = 23.81\%$$

In this situation, this system takes power from the grid.



```
Battery_voltage: 16.5 V
Battery_charge: 98.21 %
Solar_voltage: 15.98 V
Solar_current: 0.53 A
Solar_Power: 8.47 W
Temp: 25.90 Celsius
Humidity: 71.20 %
```

Fig. 13. Hardware result of the Project in a Web-based interface

Table 1. The Percentage Improvement in Voltage for The Dual Axis Setup Over the Fixed PV Setup

Time (Hour)	Fixed PV Setup (V)	Dual Axis Setup (V)	Improvement Voltage (%)
06.00 AM	8.89	10.14	14.06
07.00 AM	10.25	12.57	22.63
08.00 AM	12.31	14.33	16.41
09.00 AM	13.36	14.69	9.96
10.00 AM	13.89	15.11	8.78
11.00 AM	14.02	15.34	9.42
12.01 PM (at Noon)	15.13	15.98	5.62
01.00 PM	14.46	15.66	8.30
02.00 PM	13.67	15.25	11.56
03.00 PM	12.49	14.82	18.65
04.00 PM	10.92	14.16	29.67
05.00 PM	9.14	13.63	49.12

Fig. 13 displays the outcome of the implemented gadget. https://192.168.43.11 is the Internet Protocol address of the data display website.

In Table 1, the average percentage improvement over the day is approximately 18.59%. This means, on average, the Dual Axis Setup provides an 18.59% improvement in voltage over the Fixed PV Setup throughout the day. This result shows that the Dual Axis Setup is significantly more efficient than the fixed PV Setup, as it consistently produces higher voltage outputs across all times of the day.

Table 2 shows the hardware findings from a monitoring day from 6:00 AM to 6:00 PM. Battery voltage, battery charge, solar voltage, solar current, solar power, temperature, and humidity are all included in the findings. Where, Temperature, humidity, light intensity, and electricity output from solar panels are all displayed. Short forms used in the table are Battery Voltage = BV, Battery charge = BC, Solar Voltage = SV, Solar Current = SC, Solar power = SP, Temperature = Temp, Humidity = Hum.

The solar voltage (SV) rises from 6 AM, peaks around midday, and then diminishes, aligning with anticipated solar intensity patterns. The consistent SV curve indicates the system's efficient adaptability to sunlight variations. Similarly, the solar current (SC) follows this trend but has a distinct surge at 2 PM, possibly due to unique environmental circumstances. Solar power (SP), being the result of voltage and current, mirrors these trends, with a marked spike at 2 PM, signaling a notable boost in energy production. In essence, the steady SV and SC trends highlight the system's effective response to daily solar changes, proving the Dual Axis Setup's capability in optimal solar tracking and energy harnessing. The standard deviations for rate changes in Solar Voltage (SV)

Table 2. Implemented hardware result

Time	BV	BC	SV	SC	SP	Temp	Hum
6 AM	15.3	90.54 %	10.14	0.13	0.91	23.2	70.88
7 AM	15.4	91.28 %	12.57	0.14	0.95	23.9	70.96
8 AM	15.5	92.26 %	14.33	0.14	0.98	24.8	71.07
9 AM	15.6	92.85 %	14.69	0.14	1.2	25.0	71.02
10 AM	15.7	93.45 %	15.11	0.16	1.45	25.0	71.30
11 AM	15.9	94.65 %	15.34	0.19	1.99	27.20	72.05
12 PM (at Noon)	16.0	95.23 %	15.87	0.19	2.08	27.46	72.43
1 PM	16.2	96.4 %	15.66	0.21	2.74	27.40	72.44
2 PM	16.5	98.21 %	15.25	0.35	6.25	28.05	71.03
3 PM	16.8	100 %	14.82	0.25	4.12	26.01	71.67
4 PM	16.8	100 %	14.16	0.27	4.18	24.47	70.04
5 PM	16.8	100 %	13.63	0.30	5.07	23.41	70.38
6 PM	16.8	100 %	11.91	0.21	3.42	23.19	70.18

and Solar Current (SC) are 1.059 and 0.058, respectively. The SC low value indicates a smoother and more consistent response to daily solar variations. Both values suggest the system effectively adapts to changing solar conditions [21].

5. CONCLUSION

In this study, we successfully engineered a dual-axis solar tracking system, realizing an average voltage improvement of approximately 18.59% over traditional fixed PV setups. Our system's incorporation of an automated cleaning mechanism and IoT capabilities ensured real-time monitoring and adaptability, as evidenced by the Solar Voltage (SV) and Solar Current (SC) standard deviations of 1.059 and 0.058, respectively. Future directions include integrating AI for optimal panel orientations, fortifying IoT security, exploring advanced battery storage solutions, enhancing system scalability, and merging with other renewable energy sources. This endeavor represents a significant leap in sustainable solar energy solutions, promising broader applications in the future.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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