ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jul053

Design and Development of a Compact Active Deployable Solar Panel System for Enhanced Energy Harvesting

O. B. Goodtalk[1]; N. B. Nebo[2]; I. Mafiana[3]; O. E. Haruna[4]; D. Z. Zakut[5]

[1,2,3,4,5]National Space Research and Development Agency (NASRDA), Abuja, Nigeria

Publication Date: 2026/07/18

Abstract: Conventional fixed photovoltaic (PV) panels experience reduced energy harvesting efficiency because they cannot continuously align with the sun, while many portable solar systems require manual deployment. This paper presents the design and development of a compact active deployable solar panel system for enhanced energy harvesting. The proposed system employs an Arduino Nano-based embedded controller to automate panel deployment, solar tracking, and real-time system monitoring. A servo motor is used for deployment, while LDR sensors and a motor driver enable automatic sun tracking. Additional sensors monitor panel temperature, output current, orientation, and deployment status to ensure reliable and safe operation. A prototype incorporating a 3.84 W photovoltaic panel was developed and experimentally evaluated under varying solar conditions. The results demonstrate reliable deployment, accurate solar tracking, and improved energy harvesting compared with a conventional fixed-panel system. The proposed design provides a compact, low-cost, and intelligent solution suitable for portable photovoltaic applications and off-grid renewable energy systems.

Keywords: *Photovoltaic System, Active Deployment, Solar Tracking, Arduino Nano, Energy Harvesting, Embedded Control.*

How to Cite: O. B. Goodtalk; N. B. Nebo; I. Mafiana; O. E. Haruna; D. Z. Zakut (2026) Design and Development of a Compact Active Deployable Solar Panel System for Enhanced Energy Harvesting. *International Journal of Innovative Science and Research Technology*, 11(7), 234-241. https://doi.org/10.38124/ijisrt/26jul053

I. INTRODUCTION

Solar photovoltaic (PV) technology has become one of the most promising renewable energy sources due to its environmental benefits, low operating cost, and suitability for both grid-connected and off-grid applications [1], [2]. However, the energy output of conventional fixed PV panels is limited by changes in the sun's position throughout the day, resulting in reduced energy conversion efficiency [3]. Solar tracking systems have been developed to maintain optimal panel orientation and increase energy harvesting, but many existing designs are bulky, expensive, or unsuitable for portable applications [4].

Portable photovoltaic systems are increasingly used in remote monitoring, emergency power supply, and mobile energy applications where compactness and rapid deployment are essential. Most commercially available portable solar panels require manual deployment and positioning, which can reduce operational efficiency and lead to inconsistent solar alignment [5]. In addition, many low-cost solar trackers focus solely on panel orientation without integrating system monitoring or deployment feedback.

Recent advances in embedded systems have enabled the development of intelligent photovoltaic controllers capable of integrating sensing, actuation, and real-time monitoring into a single platform [6]. By combining environmental sensors with embedded control, photovoltaic systems can automatically deploy, track the sun, and monitor operating conditions while maintaining reliable and safe operation.

This paper presents the design and development of a compact active deployable solar panel system using an Arduino Nano microcontroller. The proposed system integrates a servo motor for automatic deployment, an L298N motor driver for solar tracking, LDR sensors for sunlight detection, a DS18B20 temperature sensor, an ACS712 current sensor, an MPU6050 orientation sensor, Hall effect sensors, and limit switches for feedback and safety. Unlike conventional portable photovoltaic systems, the proposed design combines automatic deployment, intelligent solar tracking, and real-time performance monitoring within a compact embedded architecture.

Experimental evaluation demonstrates that the developed system provides reliable deployment, accurate solar tracking, and improved energy harvesting compared with a fixed-panel configuration. The proposed design offers

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jul053

a low-cost and portable solution suitable for remote monitoring stations, agricultural systems, emergency power applications, and other off-grid renewable energy systems.

II. RELATED WORK

Solar tracking has been widely investigated as an effective approach to improving the energy conversion efficiency of photovoltaic (PV) systems. Unlike fixed solar panels, tracking systems continuously adjust the panel orientation to maximize incident solar radiation, thereby increasing energy output. Single-axis trackers are commonly preferred because of their simpler mechanical structure and lower power consumption, whereas dual-axis trackers provide higher energy yield at the expense of increased system complexity and cost [7], [8].

Recent studies have implemented solar tracking systems using low-cost embedded platforms such as Arduino, ESP32, and PIC microcontrollers. Most of these systems employ Light Dependent Resistor (LDR) sensors or photodiodes to detect sunlight direction and control servo or DC motors for panel positioning [9], [10]. Although these approaches improve energy harvesting, many are limited to solar tracking and do not include automated deployment or comprehensive system monitoring.

The integration of sensing technologies has further enhanced photovoltaic system performance by enabling real-time monitoring of electrical and environmental parameters. Temperature sensors, current sensors, and inertial measurement units have been employed to monitor panel temperature, output current, and orientation, thereby improving operational reliability and facilitating performance evaluation [11]–[13]. Similarly, Hall effect sensors and limit switches have been incorporated into automated mechanisms to provide accurate position feedback and prevent excessive mechanical movement [14].

Despite these developments, existing portable photovoltaic systems generally require manual deployment and often lack an integrated control framework that combines deployment, solar tracking, and condition monitoring. Consequently, their operational efficiency and level of automation remain limited.

To address these limitations, this study presents a compact active deployable solar panel system that integrates automatic deployment, LDR-based solar tracking, real-time monitoring of temperature, current, and orientation, as well as safety feedback using Hall effect sensors and limit switches. The proposed embedded control architecture enhances energy harvesting while improving portability, operational reliability, and autonomous system performance.

III. MATERIALS AND METHODS

This research adopted an experimental design and implementation methodology involving the design, fabrication, programming, integration, and performance evaluation of a compact active deployable solar panel system. The methodology consisted of hardware selection, mechanical design, embedded software development, system integration, prototype fabrication, and experimental testing under varying environmental conditions. Figure 1 presents the overall methodology adopted in this study.

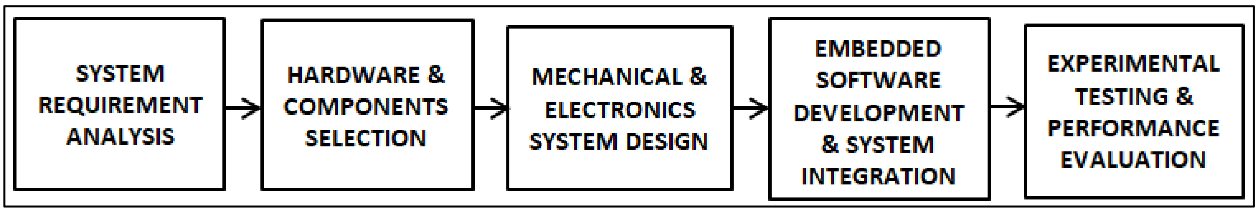

Fig 1 Block Diagram Illustrating the Engineering Design and Implementation Workflow.

The developed prototype was designed to automatically deploy the photovoltaic panel, track the direction of maximum solar irradiance, monitor environmental and electrical parameters, and ensure safe operation through closed-loop feedback.

- *System Architecture*

The proposed compact active deployable solar panel system consists of four major subsystems such as mechanical deployment subsystem, solar tracking subsystem, monitoring and sensing subsystem**, e**mbedded control subsystem as shown in Figure 2**.** The Arduino Nano serves as the central controller responsible for acquiring sensor data, executing the control algorithm, and generating control signals for the deployment and tracking actuators. The deployment subsystem employs a servo motor to automatically unfold or retract the photovoltaic panel. Position feedback is provided by Hall Effect sensors and limit switches to prevent excessive movement and improve deployment accuracy. The solar tracking subsystem utilizes four LDR sensors arranged in a quadrant configuration. Differences in illumination intensity between the sensors are processed by the Arduino Nano to determine the required tracking direction. The monitoring subsystem continuously measures panel temperature, output current, deployment position, and panel orientation using the DS18B20 temperature sensor, ACS712 current sensor, Hall effect sensor, limit switches, and MPU6050 inertial measurement unit. The interaction among these subsystems enables autonomous operation while maximizing solar energy harvesting.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jul053

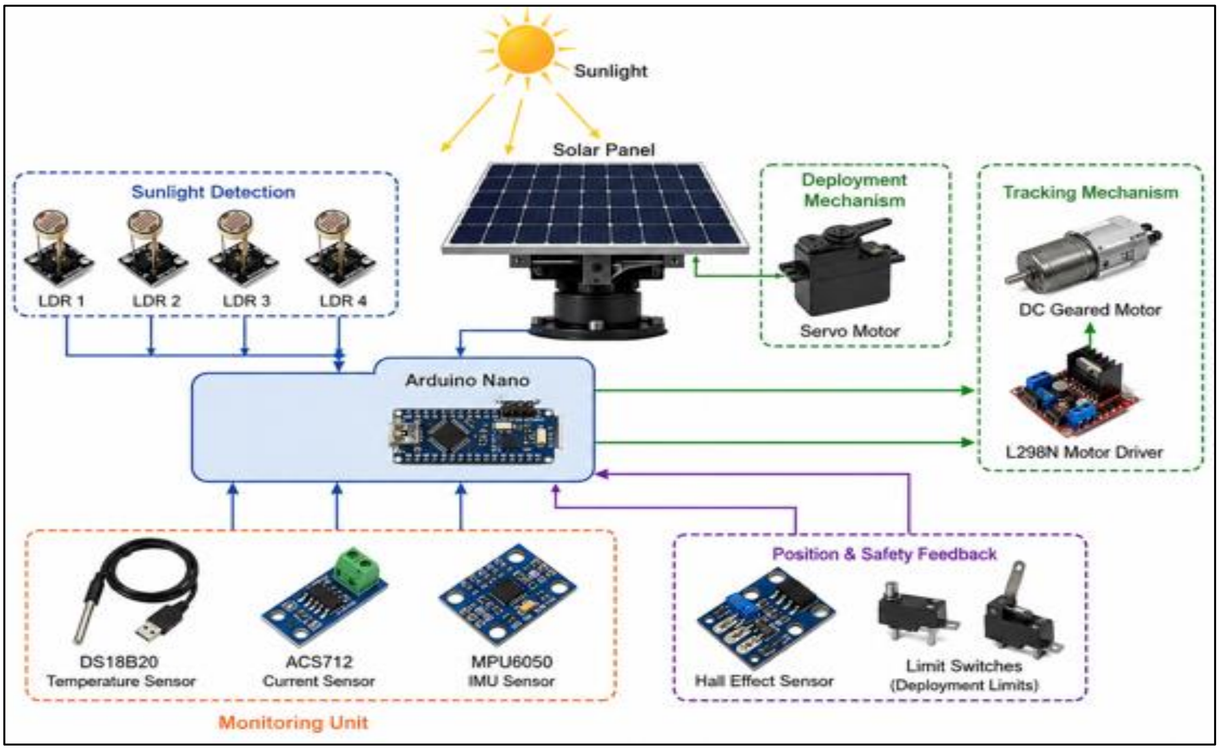

Fig 2 Functional Block Diagram of the Proposed Compact Active Deployable Solar Panel System.

➢ *System Components*

The hardware components employed in the prototype are summarized in Table 1.

Table 1 Hardware Components of the Proposed System

Component	Quantity	Function
Arduino Nano	1	Main embedded controller
3.84 W Solar Panel	1	Photovoltaic energy generation
Servo Motor	1	Active deployment and retraction
L298N Motor Driver	1	Controls the tracking motor
DC Geared Motor	1	Rotates the panel for solar tracking
LDR Sensors	4	Detect sunlight direction
DS18B20 Sensor	1	Measures panel temperature
ACS712 Current Sensor	1	Measures photovoltaic output current
MPU6050	1	Measures tilt angle and orientation
Hall Effect Sensor	1	Position feedback
Limit Switches	2	Detect deployment limits
Rechargeable Battery	1	Auxiliary power supply
Structural Frame	1	Mechanical support

➢ *Mechanical Design*

The mechanical structure was designed to satisfy three primary objectives such as compactness, reliable deployment, and stable solar tracking. The photovoltaic panel was mounted on a hinged support frame driven by a servo motor. During storage, the panel remains folded to minimize occupied space. Upon activation, the servo rotates through a predefined angular displacement, deploying the panel into its operating position. A geared DC motor connected through a rotating platform provides horizontal solar tracking. The motor rotates the deployed panel according to commands generated from the embedded tracking algorithm. Hall effect sensors and limit switches provide closed-loop feedback by confirming deployment completion and preventing excessive angular movement. The compact frame was fabricated using lightweight materials to reduce total system weight while maintaining structural rigidity.

➢ *Embedded Control Hardware*

The Arduino Nano functions as the system controller because of its compact dimensions, low power consumption, and sufficient digital and analog input/output resources. Its primary responsibilities include reading sensor measurements, computing solar tracking direction, controlling deployment, driving tracking motors, monitoring safety conditions, and recording system parameters. The Arduino executes the control algorithm continuously throughout system operation.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jul053

➢ *Sensor Integration*

- *Light Dependent Resistor (LDR) Sensors*

Four LDR sensors were positioned at the four quadrants surrounding a small vertical divider. The divider creates illumination differences whenever sunlight is not perpendicular to the panel. The Arduino continuously compares the sensor voltages.

If

$$LDR_{Left} > LDR_{Right}$$

The tracking motor rotates toward the left.

Similarly,

$$LDR_{Top} > LDR_{Bottom}$$

Indicates upward adjustment where applicable.

When all sensor readings become approximately equal,

$$LDR_1 \approx LDR_2 \approx LDR_3 \approx LDR_4$$

The solar panel is considered properly aligned with the sun.

- *DS18B20 Temperature Sensor*

The DS18B20 continuously measures photovoltaic panel temperature. Temperature affects photovoltaic efficiency according to:

$$\eta = \eta_{ref}\left[1 - \beta\left(T - T_{ref}\right)\right] \quad (1)$$

Where: η = solar panel efficiency, η_{ref} = reference efficiency, β = temperature coefficient, T = measured panel temperature, and T_{ref} = reference temperature (25°C). The measured temperature is displayed and stored for performance analysis.

- *ACS712 Current Sensor*

The ACS712 measures the generated output current. The output current is calculated from:

$$I = \frac{V_{out} - V_{offset}}{S} \quad (2)$$

Where I = output current (A), V_{out} = sensor output voltage, V_{offset} = zero-current voltage, and S = sensor sensitivity.

Generated electrical power is determined by:

$$P = VI \quad (3)$$

Where P = output power (W), V = output voltage (V), and I = output current (A).

- *MPU6050 Orientation Sensor*

The MPU6050 provides acceleration and angular velocity measurements. The solar panel inclination angle is calculated as:

$$\theta = \tan^{-1}\left(\frac{A_y}{A_z}\right) \quad (4)$$

Where A_y = acceleration along Y-axis and A_z = acceleration along Z-axis.

The orientation information is used to verify correct deployment and monitor tracking performance.

- *Hall Effect Sensor*

The Hall Effect sensor detects the magnetic position of the deployment mechanism. Whenever the attached magnet reaches the sensing location,

$$B \geq B_{threshold} \quad (5)$$

The sensor outputs a digital HIGH signal indicating successful deployment.

- *Limit Switches*

Two normally closed limit switches define fully deployed position and fully retracted position. Whenever either switch is activated,

$$Motor = OFF$$

Preventing mechanical over travel.

The embedded tracking algorithm continuously compares LDR readings. The tracking error (e) is computed as:

$$e = L - R \quad (6)$$

Where L = average left LDR intensity and R = average right LDR intensity

If

$$e > \delta$$

The motor rotates clockwise.

If

$$e < -\delta$$

The motor rotates counterclockwise.

If

$$|e| < \delta$$

The motor remains stationary.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jul053

The dead-band threshold δ prevents unnecessary oscillation due to small illumination differences.

IV. SYSTEM IMPLEMENTATION

The proposed compact active deployable solar panel system comprises four functional units: the sensing unit, embedded control unit, actuation unit, and photovoltaic power generation unit, as shown in Figure 1. The Arduino Nano serves as the central controller, processing sensor data and coordinating the deployment and solar tracking operations.

The sensing unit consists of four LDR sensors for sunlight detection, a DS18B20 sensor for panel temperature measurement, an ACS712 sensor for output current monitoring, an MPU6050 sensor for panel orientation measurement, and Hall Effect sensors and limit switches for deployment position feedback. These sensors provide real-time information required for closed-loop control.

The actuation unit includes a servo motor for automatic deployment and retraction of the solar panel, and a DC geared motor driven by an L298N motor driver for single-axis solar tracking. During operation, the servo deploys the panel to its operating position, after which the tracking motor continuously adjusts the panel orientation based on the illumination difference detected by the LDR sensors.

The control algorithm, implemented in the Arduino IDE using C/C++, initializes all sensors and actuators before verifying the deployment status. If the panel is folded, the servo motor deploys it until the Hall effect sensor and limit switch confirm the deployed position. The controller then executes the solar tracking algorithm by continuously comparing the LDR outputs and rotating the tracking motor until balanced illumination is achieved. Simultaneously, the system monitors panel temperature, output current, and orientation to evaluate operating performance. The Hall Effect sensor and limit switches provide safety feedback by preventing excessive mechanical movement during deployment and retraction.

The developed prototype integrates all hardware and software modules into a compact embedded platform capable of autonomous deployment, real-time solar tracking, and continuous performance monitoring, making it suitable for portable and off-grid photovoltaic applications. The operational sequence of the proposed system is summarized in Figure 3.

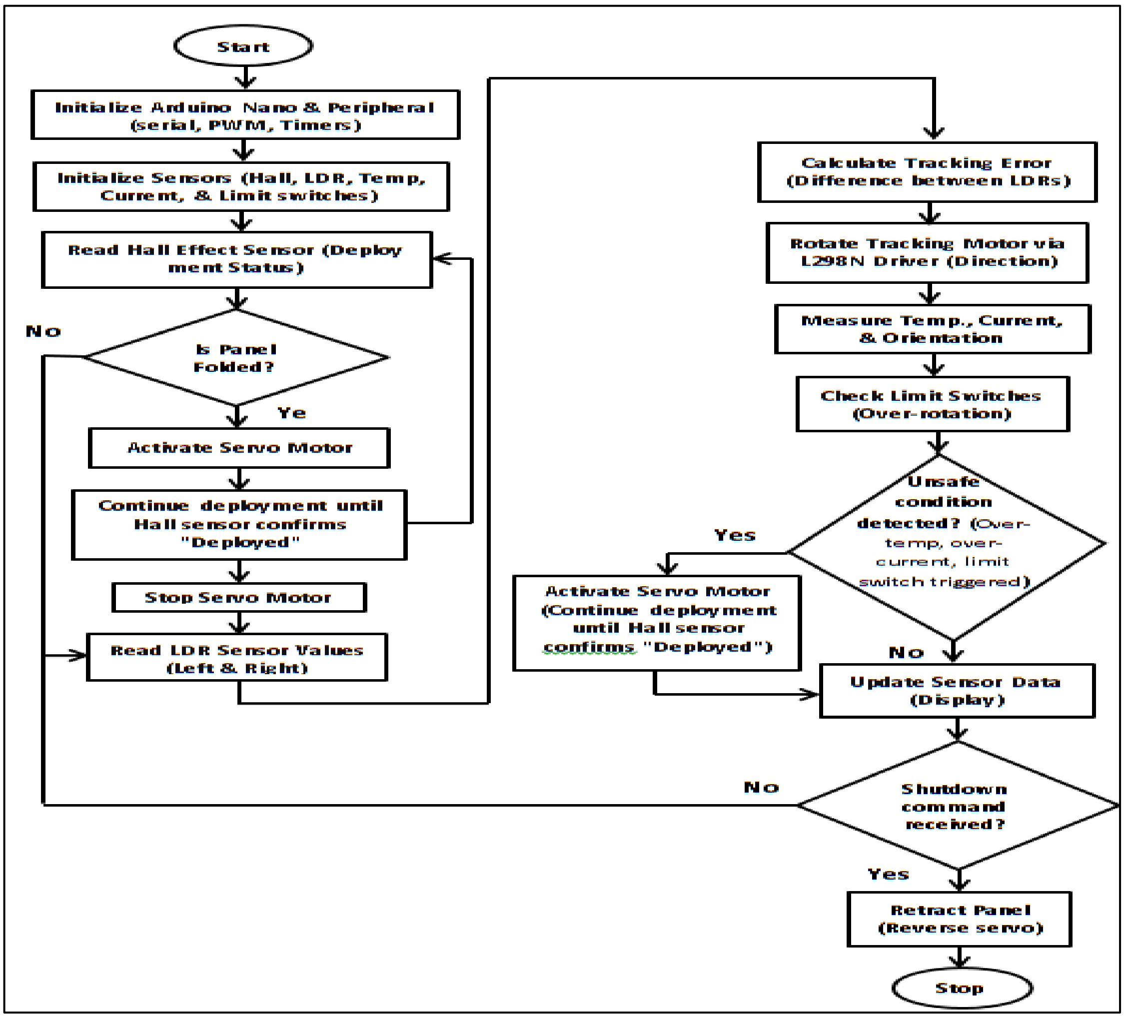

Fig 3 Operational Sequence of the Proposed System

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jul053

This control strategy ensures autonomous deployment, continuous solar tracking, and reliable monitoring throughout system operation.

A laboratory-scale prototype of the compact active deployable solar panel system was successfully constructed using the selected hardware components. The prototype incorporates a 3.84 W photovoltaic panel mounted on a hinged support structure driven by a servo motor for automatic deployment. A DC geared motor controlled through an L298N motor driver provides horizontal solar tracking based on feedback from four LDR sensors. The Arduino Nano serves as the central controller, coordinating sensor acquisition, deployment, tracking, and safety monitoring.

The completed prototype demonstrates the feasibility of integrating active deployment, intelligent solar tracking, environmental sensing, and embedded control into a compact photovoltaic platform. The implementation provides a practical foundation for evaluating system performance under different environmental conditions.

V. RESULTS AND DISCUSSION

This section presents the performance evaluation of the developed compact active deployable solar panel system. The prototype was experimentally evaluated to assess the effectiveness of the active deployment mechanism, solar tracking capability, electrical performance, and overall energy harvesting efficiency. The evaluation focused on deployment reliability, tracking accuracy, output current, output power, panel temperature, and comparison with a conventional fixed photovoltaic panel.

➢ *Electrical Performance Analysis*

The results indicate that the electrical output of the photovoltaic panel closely followed the variation in solar irradiance throughout the day. Table 2 presents the measured electrical performance of the developed prototype during different periods of the day.

Table 2 Experimental Performance of the Prototype Solar Panel System

Time	Solar Irradiance (W/m²)	Voltage (V)	Current (A)	Output Power (W)	Panel Temp. (°C)	Tracking Acc. (%)
08:00	420	5.10	0.31	1.58	27.3	96.5
09:00	580	5.42	0.45	2.44	29.1	97.3
10:00	720	5.71	0.55	3.14	31.8	98.1
11:00	850	5.89	0.61	3.59	34.6	98.6
12:00	930	6.02	0.64	3.85	37.5	99.2
13:00	910	5.98	0.63	3.77	39.4	99.0
14:00	820	5.84	0.58	3.39	40.6	98.5
15:00	690	5.63	0.51	2.87	39.1	97.9
16:00	520	5.32	0.40	2.13	36.2	97.1
17:00	360	4.91	0.27	1.33	32.8	96.4

Output power increased steadily from 1.58 W in the early morning to a maximum of 3.85 W at approximately 12:00 h, corresponding to the highest measured solar irradiance of 930 W/m². Beyond midday, the gradual reduction in solar irradiance resulted in a corresponding decrease in both current and output power.

The average output voltage remained relatively stable because of the inherent voltage characteristics of the photovoltaic module, while the output current exhibited a stronger dependence on solar irradiance. This observation confirms that the active tracking mechanism effectively maintained favorable solar incidence angles, thereby maximizing electrical power generation during peak sunlight periods.

➢ *Deployment Performance*

The effectiveness of the active deployment mechanism was evaluated through repeated deployment and retraction tests. The measured performance parameters are summarized in Table 3.

Table 3 Deployment Performance

Parameter	Measured Value
Deployment Time	3.4 s
Retraction Time	3.1 s
Servo Position Accuracy	±1°
Successful Deployment Cycles	50/50
Deployment Success Rate	100%
Hall Sensor Detection Accuracy	100%
Limit Switch Response Time	0.05 s

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jul053

The experimental results demonstrate that the servo-driven deployment mechanism provided rapid and reliable operation. The average deployment time was 3.4s, while panel retraction required 3.1s. Throughout fifty repeated operating cycles, no deployment failures were observed, resulting in a deployment success rate of 100%. The Hall Effect sensor consistently verified the deployed position, and the limit switches effectively prevented mechanical over travel. The use of closed-loop feedback significantly improved deployment reliability compared with open-loop positioning systems.

- *Solar Tracking Performance*

The tracking subsystem was evaluated by measuring its ability to maintain panel alignment with the direction of maximum solar irradiance as presented in Table 4.

Table 4 Tracking Performance

Parameter	Value
Average Tracking Error	1.7°
Maximum Tracking Error	3.5°
Average Tracking Accuracy	98.1%
Average Motor Response Time	1.2 s
Daily Tracking Adjustments	42

The developed tracking algorithm successfully maintained panel orientation throughout the experimental period. The average tracking accuracy of 98.1% indicates that the LDR-based tracking system effectively followed the apparent movement of the sun while minimizing unnecessary motor operation through the implemented dead-band threshold. The average tracking error of 1.7° demonstrates the effectiveness of the feedback control strategy, while the average motor response time of 1.2s ensured timely correction of panel orientation.

- *Comparison with a Fixed Photovoltaic System*

The performance of the proposed compact active deployable solar panel system was compared with a conventional fixed photovoltaic panel under similar environmental conditions. The result is presented in Table 5.

Table 5 Performance Comparison

Parameter	Fixed Panel	Proposed System	Improvement
Peak Output Power	3.20 W	3.85 W	20.3%
Daily Energy Harvested	20.4 Wh	24.9 Wh	22.1%
Average Output Current	0.46 A	0.55 A	19.6%
Automatic Deployment	No	Yes	Available
Solar Tracking	No	Yes	Available
Temperature Monitoring	No	Yes	Available
Orientation Monitoring	No	Yes	Available
Deployment Feedback	No	Yes	Available

The comparison indicates that the proposed system significantly outperformed the conventional fixed photovoltaic panel. The active tracking mechanism enabled continuous alignment with the sun, resulting in a 20.3% increase in peak output power and a 22.1% improvement in daily energy harvested. In addition to enhanced electrical performance, the proposed design introduced automated deployment and integrated monitoring capabilities that are absent in conventional fixed-panel systems.

The experimental evaluation demonstrates that integrating active deployment with intelligent solar tracking and real-time monitoring substantially improves the operational performance of compact photovoltaic systems. The automated deployment mechanism eliminated the need for manual panel positioning and consistently achieved successful deployment within a short period. The incorporation of Hall effect sensors and limit switches provided reliable feedback, ensuring safe operation and preventing mechanical over travel.

VI. CONCLUSION

This paper presented the design and development of a compact active deployable solar panel system for enhanced energy harvesting. The proposed system integrates automatic panel deployment, LDR-based solar tracking, and real-time monitoring within an Arduino Nano-based embedded platform. Experimental evaluation demonstrated reliable deployment, accurate solar tracking, and improved energy harvesting compared with a conventional fixed photovoltaic panel. The integrated sensing and feedback mechanisms also enhanced operational safety and system reliability.

The developed prototype provides a compact, low-cost, and autonomous solution for portable photovoltaic applications. Its ability to combine deployment control, solar tracking, and performance monitoring in a single embedded system makes it suitable for remote monitoring stations, portable power systems, agricultural applications, and other off-grid renewable energy systems. Future work will focus on integrating maximum power point tracking (MPPT),

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jul053

wireless remote monitoring, and dual-axis solar tracking to further improve energy harvesting and system intelligence.

REFERENCES

- [1]. J. A. Duffie and W. A. Beckman, *Solar Engineering of Thermal Processes*, 5th ed. Hoboken, NJ, USA: John Wiley & Sons, 2020.
- [2]. A. Luque and S. Hegedus, *Handbook of Photovoltaic Science and Engineering*, 3rd ed. Hoboken, NJ, USA: John Wiley & Sons, 2022.
- [3]. T. Markvart and L. Castañer, *Practical Handbook of Photovoltaics: Fundamentals and Applications*, 3rd ed. Amsterdam, The Netherlands: Elsevier, 2021.
- [4]. M. A. Green, *Solar Cells: Operating Principles, Technology and System Applications*. Englewood Cliffs, NJ, USA: Prentice Hall.
- [5]. S. A. Kalogirou, *Solar Energy Engineering: Processes and Systems*, 3rd ed. London, U.K.: Academic Press, 2020.
- [6]. H. Mousazadeh, A. Keyhani, A. Javadi, H. Mobli, K. Abrinia, and A. Sharifi, "A review of principle and sun-tracking methods for maximizing solar systems output," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 8, pp. 1800–1818, 2009.
- [7]. S. Seme, B. Štumberger, M. Hadžiselimović, and K. Sredenšek, "Solar photovoltaic tracking systems for electricity generation: A review," *Energies*, vol. 13, no. 16, Art. no. 4224, 2020.
- [8]. R. Sadeghi, M. Parenti, S. Memme, M. Fossa, and S. Morchio, "A review and comparative analysis of solar tracking systems," *Energies*, vol. 18, no. 10, Art. no. 2553, 2025.
- [9]. R. F. Fuentes-Morales, A. Diaz-Ponce, M. I. Peña-Cruz, P. M. Rodrigo, L. M. Valentín-Coronado, F. Martell-Chavez, and C. A. Pineda-Arellano, "Control algorithms applied to active solar tracking systems: A review," *Solar Energy*, vol. 212, pp. 203–219, 2020.
- [10]. M. Abdallah and S. Nijmeh, "Two-axis sun tracking with PLC control," *Energy Conversion and Management*, vol. 45, no. 11–12, pp. 1931–1939, 2004.
- [11]. S. Racharla and K. Rajan, "Solar tracking system—A review," *International Journal of Sustainable Engineering*, vol. 10, no. 2, pp. 72–81, 2017.
- [12]. A. Mellit and S. A. Kalogirou, "Artificial intelligence techniques for photovoltaic applications: A review," *Progress in Energy and Combustion Science*, vol. 34, no. 5, pp. 574–632, 2008.
- [13]. A. H. El Khateb, N. A. Rahim, J. Selvaraj, and M. N. Uddin, "Fuzzy-logic-controller-based SEPIC converter for maximum power point tracking," *IEEE Transactions on Industry Applications*, vol. 50, no. 4, pp. 2349–2358, 2014.
- [14]. N. Femia, G. Petrone, G. Spagnuolo, and M. Vitelli, *Power Electronics and Control Techniques for Maximum Energy Harvesting in Photovoltaic Systems*. Boca Raton, FL, USA: CRC Press, 2013.