



RESEARCH PAPER

Design and functional verification of an Arduino-based single-axis solar tracking prototype with environmental monitoring

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Abstract

This study presents the design, fabrication, and functional verification of an Arduino-controlled single-axis photovoltaic (PV) tracking prototype that monitors ambient temperature, relative humidity, and rain status. Two light-dependent resistors (LDRs), separated by an optical divider, generate a differential light signal for closed-loop orientation control. An Arduino Uno commands incremental single-axis movement through a microstep driver and stepper motor until the LDR difference falls within a prescribed deadband. A DHT11 sensor, a rain-detection module, and a 16×2 P°C liquid-crystal display provide environmental information. Outdoor functional trials at SLIET, Longowal, confirmed differential-light response, incremental sun-following motion, cessation of commanded movement near balanced illumination, sensor and display operation, and the detection and display of a controlled-wetting condition. Visually observable mechanical play and reduced LDR discrimination under diffuse light were noted. The study establishes functional integration rather than an improvement in energy performance because simultaneous measurements of irradiance, PV output, angular error, and actuator energy consumption against an identical fixed panel were unavailable. The ideal relation $L(\%) = 100[1 - \cos(i)]$ is consequently used only to explain direct-beam geometric loss. The resulting platform provides a compact experimental basis for the comparative evaluation of fixed and tracked PV modules and for the refinement of sensing and control strategies.

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1. Introduction

Solar photovoltaic generation is central to the transition towards low-carbon energy systems. In a fixed PV installation, the incidence angle between the direct solar beam and the module normal varies during the day. Under clear-sky conditions, this geometric misalignment reduces the direct-beam component received by the module. The total plane-of-array irradiance and electrical output, however, also depend on diffuse and ground-reflected radiation, module temperature, spectral and reflection effects, wiring, load, and power-conversion losses.

Solar trackers reduce incidence-angle error by reorienting a PV module as the apparent solar position changes. Compared with

dual-axis arrangements, a single-axis tracker offers a simpler mechanical structure and control system. However, its attainable benefit depends on axis orientation, climate, season, control accuracy, parasitic energy use, and mechanical reliability. Published studies report improvements for particular configurations and test conditions, but those values cannot be transferred directly to a new prototype without a controlled comparison.

Although many LDR-based trackers have been reported, educational prototypes are often described without adequately distinguishing functional operation from measured energy performance. A compact experimental platform remains valuable for integrating differential-light tracking with environmental monitoring while clearly defining the evidence

required for subsequent energy validation. The present work addresses this need by focusing on prototype development and functional verification rather than on a new tracking principle. The specific objectives were to:

- Design and fabricate a mechanically simple single-axis PV-tracking prototype;
- Implement closed-loop differential-LDR control using an Arduino Uno;
- Integrate the monitoring of ambient temperature, relative humidity, and rain status;
- Verify tracking, display, and controlled-wetting responses through functional trials; and
- Establish a measurement framework for subsequent comparison with an identical fixed PV module.

2. Related work and research gap

Solar-tracking systems may be classified by degree of freedom, actuation mode, and control strategy. Single-axis systems generally offer lower mechanical and control complexity than dual-axis trackers, whereas dual-axis systems can compensate for both daily and seasonal changes in solar position [1–3]. Sensor-based closed-loop systems use LDRs, photodiodes, or imaging devices to minimize illumination errors; astronomical systems calculate the solar position from time and location; hybrid systems combine both approaches to improve operation under variable illumination [2,3].

Kacira et al. [4] examined PV orientation and tracking under site-specific conditions, demonstrating that reported gains depend on climate, geometry, and test protocol. Wang and Lu [5] integrated optical sensing with a single-motor mechanism, highlighting the interaction between sensor placement and mechanical design. Shang and Shen [6] experimentally evaluated a dual-axis system, whereas Hemza [7] presented a small-module fixed-versus-tracked comparison. These studies show that energy improvement cannot be inferred from motion alone and must be evaluated against a simultaneous fixed baseline. Recent work has shifted towards improved sensor geometry, reduced parasitic consumption, and hybrid control. Alshaabani [8] used four photodiodes in a single-axis configuration and combined experimental and simulation results. Hammas et al. [9] combined LDR feedback with time- and location-based control to reduce errors under shaded or diffuse conditions. Masoumi et al. [10] investigated online optimization and data-driven modeling for two-axis tracking. Sadeghi et al. [3] identify LDR saturation, cloudy-weather sensitivity, actuator consumption, and maintenance as persistent challenges. Nahim et al. [11] further demonstrated the continued use of Arduino-based single-axis prototypes with solar position algorithms. The literature, therefore, establishes tracking as a mature concept; novelty cannot be claimed from the use of an Arduino, LDRs, or a stepper motor alone. Instead, the present work presents a compact educational prototype that combines differential-light tracking with environmental monitoring and transparently reports evidence from functional verification, along with its associated limitations. This approach also provides a systematic basis for a subsequent instrumented energy study.

3. Materials and methods

3.1 System architecture and hardware

The prototype contains three interacting layers: (i) sensing, consisting of two LDR channels, a DHT11 temperature/relative-humidity sensor, and a rain-detection module; (ii) control and display, consisting of an Arduino Uno (ATmega328P) and a 16×2 I²C LCD; and (iii) actuation, consisting of a stepper motor, microstep driver, and bearing-supported panel mount. The LDR pair provides the tracking error, whereas the environmental sensors operate independently of the motion-control loop.

The available build record identifies a microstep driver with a rated input range of 9–42 V, a 24 V/5 A AC–DC supply, and a 12 V lithium battery. The final power-supply connections, regulator ratings, and operating voltage were not preserved in the project record. Consequently, the available information is insufficient to reproduce the complete electrical design. The prototype used separate logic-level sensing and control functions, as well as a motor-drive function, with the Arduino Uno serving as the central controller. The assembled prototype used for functional verification is shown in Fig. 1.

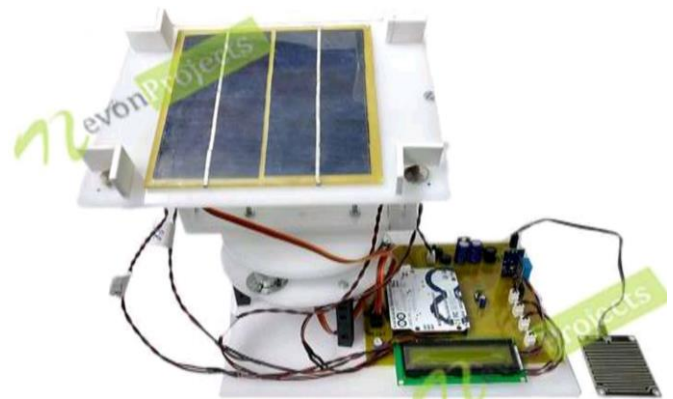


Figure 1: Fabricated single-axis solar-tracking prototype used for functional verification.

Table 1 presents the component information that can be recovered from the build record. Parameters unavailable in the project record are identified explicitly to prevent unsupported specifications from being inferred.

Table 1 provides a consolidated overview of the principal components incorporated into the developed solar tracking prototype, together with the technical information that was available from the prototype documentation and the parameters that could not be verified or were not archived. The system comprised a small photovoltaic (PV) module mounted on an iron structural body and actuated through a stepper motor with a microstep driver, while an Arduino Uno based on the ATmega328P served as the primary control unit. The electrical subsystem included a 24 V, 5 A AC–DC power supply and a 12 V lithium battery, whereas the sensing and user-interface subsystem consisted of two LDRs, a DHT11 temperature–humidity sensor, a rain-detection module, and a 16 × 2 I²C LCD. For mechanical support and motion, four 14 mm steel balls were incorporated into the structure, with the available

records also documenting the associated component costs.

Table 1. Principal components documented for the prototype.

Component	Recorded information	Information unavailable
PV module	Small prototype PV module	Nameplate rating and dimensions were not recorded
Stepper motor	One motor; recorded cost ₹1,800	Model, holding torque, rated current, and step angle were not recorded
Microstep driver	9–42 V input; ₹250	Model, current limit, and microstepping ratio were not recorded
Arduino Uno	ATmega328P; ₹300	Firmware version and complete pin map were not archived
AC–DC supply	24 V, 5 A; ₹700	The final supply connection was not documented
Battery	12 V lithium; cost not itemized	Capacity, BMS, and circuit role were not documented
Sensors/display	Two LDRs, DHT11, rain module and 16×2 I ² C LCD	Calibration data and individual costs were not recorded
Structure/bearings	Iron body; four 14 mm steel balls; recorded cost ₹1,356	Axis orientation, panel/frame dimensions, bearing layout, rotating mass, and angular travel were not archived
LDR/divider geometry	Two LDRs separated by an optical divider	LDR spacing, divider height/thickness, inclination, and alignment were not archived
Transmission geometry	Stepper-motor-driven single-axis motion	Coupling arrangement, transmission ratio, and angular resolution were not archived.
Travel and cable management	Supervised incremental movement was observed	Home position, end stops, cable loop/strain relief, and permissible overtravel were not archived.

3.2 Tracking and monitoring logic

The tracker uses a closed-loop null-seeking strategy. Let S_1 and S_2 denote the two digitized LDR signals. The signed tracking error is

$$e = S_1 - S_2 \quad (1)$$

When $|e| > \delta$, where δ is the control deadband, the controller sends a short burst of step pulses in the direction that reduces e . The LDRs are then sampled again. When $|e| \leq \delta$, no motor movement is commanded. This intermittent logic differs fundamentally from continuous rotation at the sun's nominal hour-angle rate. The controller also reads the DHT11 and rain-detection module at fixed intervals and updates the LCD. Controlled wetting was used to verify detection and display of wet conditions; behavior under natural rainfall and wind was

not evaluated.

The archived project record did not retain the LDR resistor values, ADC signal averaging, deadband, sampling interval, steps per correction, microstepping ratio, or angular increment. These omissions restrict independent replication and are included among the study limitations.

3.3 Mechanical, electrical and geometric configuration

The PV module was mounted on a bearing-supported single-axis structure and driven through the stepper-motor assembly. Supervised orientation changes were observed; however, the archived record does not establish whether the physical rotation axis was horizontal, vertical, or inclined. The direction of panel motion is therefore not used to infer the axis orientation. Complete panel and frame dimensions, support spacing, shaft geometry, transmission ratio, angular travel, rotating mass, and center-of-gravity offset were also unavailable. Figure 2 consequently presents a reporting convention rather than an as-built engineering drawing.

A right-handed site coordinate system is adopted for subsequent geometric reporting: x points east, y points north, and z points vertically upwards. The unit vectors s and n represent the solar direction and panel normal, respectively; a represents the physical rotation-axis direction; θ is the mechanical tracker angle; e_θ is the tracker-position error; and i is the three-dimensional solar incidence angle. The actual direction of a must be measured on the prototype before quantitative kinematic analysis.

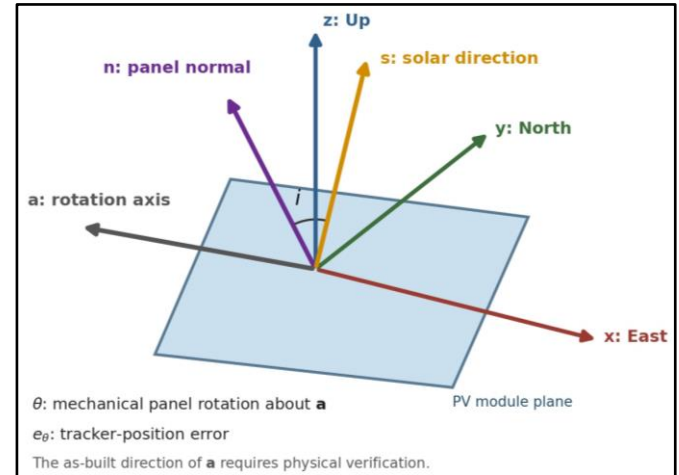


Figure 2: Geometric reporting convention; the as-built rotation-axis direction, a , requires physical verification.

For a motor full-step angle θ_s , microstepping ratio N_μ , and motor-to-panel transmission ratio G , the nominal panel increment is

$$\Delta\theta_p = \theta_s / (N_\mu G) \quad (2)$$

Because θ_s , N_μ , and G were not archived, the prototype's angular resolution is not reported. Similarly, the gravitational moment depends on the perpendicular center-of-gravity offset e_c :

$$T_g = m g e_c \sin(\theta) \quad (3)$$

A preliminary wind-load model may be written as:

$$F_w = 0.5 \rho C_d A_p v^2 \quad (4)$$

$$T_w = F_w r_w \quad (5)$$

where ρ is air density, C_d is the drag coefficient, A_p is the projected area, v is wind speed, and r_w is the perpendicular distance from the aerodynamic center to the rotation axis. No numerical torque or structural-safety claim is made because the required geometry and wind data were unavailable.

The control architecture consisted of two analog LDR channels, digital and serial sensor interfaces, Arduino logic, and step/direction signals to the motor driver. The 24 V supply, 12 V battery, and logic supply were present in the build documentation, but their final interconnections were not fully documented. The records also did not establish the home position, end-stop locations, cable loop, strain relief, or overtravel allowance. Accordingly, the electrical and geometric results are limited to confirming functional integration under supervised operation.

3.4 Direct-beam incidence-angle model

For an ideal receiving surface exposed only to direct-beam irradiance, the ratio of the irradiance component normal to the module surface is $\cos(i)$. In vector form, $\cos(i) = s \cdot n$, where s and n are unit vectors. The incidence angle i is distinct from the mechanical tracker angle θ and the tracker-position error e_θ . A single-axis mechanism can correct only the component of solar-position error that lies within its permitted rotation plane; therefore, it cannot generally be equated with θ or e_θ . The corresponding fractional and percentage geometric losses are

$$L_{fraction} = 1 - \cos(i) \quad (6)$$

$$L(\%) = 100[1 - \cos(i)] \quad (7)$$

This relation is used only as a simplified geometric model. It does not predict total PV energy because it excludes diffuse and reflected irradiance, optical losses, temperature, and electrical operating conditions. The selected angles are illustrative rather than measured tracking errors. The calculated values are summarized in Table 2 and illustrated in Fig. 3.

Table 2: Ideal direct-beam geometric loss at selected incidence-angle errors

Incidence-angle error, i	$100[1 - \cos(i)]$
0°	0.0%
5°	0.4%
15°	3.4%
30°	13.4%
45°	29.3%
60°	50.0%
75°	74.1%

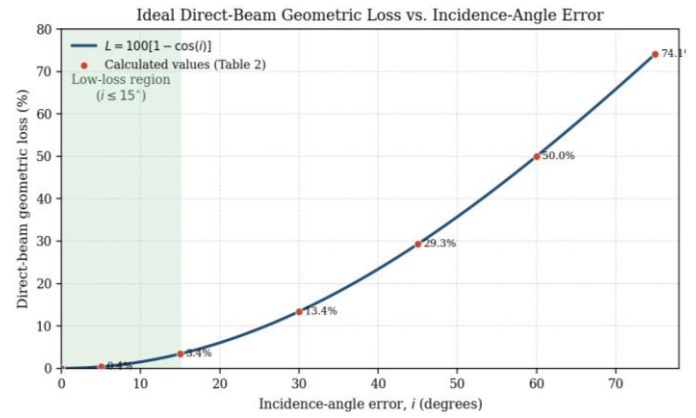


Figure 3: Ideal direct-beam geometric loss as a function of incidence-angle error.

3.5 Functional-test procedure

The assembled unit was operated outdoors at SLIET, Longowal, under daylight conditions. Functional checks covered: (i) differential-LDR response; (ii) incremental single-axis panel motion; (iii) cessation of commanded motion near balanced illumination; (iv) display of temperature and relative humidity; and (v) rain-detection-module response to controlled wetting. The original test log did not include the exact date, start and end times, axis orientation, angular limits, irradiance, wind conditions, cloud cover, sensor readings, angular error, PV output, or actuator energy consumption. The test is therefore classified as functional verification rather than as a quantitative performance experiment.

4. Results and Discussion

The LDR control loop produced incremental sun-following movement, and the controller, driver, motor, and display operated together during the supervised outdoor trial. The DHT11 values were displayed, and the rain-detection module identified the controlled-wetting condition and displayed the corresponding rain status. Visually observable mechanical play was noted during direction reversal, and the LDR pair provided less distinct directional discrimination under diffuse illumination. These observations demonstrate subsystem integration, but they do not quantify tracking accuracy, backlash, reliability, or improvements in energy performance. Table 3 consolidates the functional observations retained in the project record. “Passed” denotes that the expected qualitative response was observed; it does not represent calibrated performance or long-term reliability.

Table 3 summarizes the functional testing and experimental validation of the proposed solar tracking and environmental monitoring system under different operating conditions. The differential-light sensing test confirmed that the controller could successfully distinguish between unequal illumination levels received by the paired LDR sensors and determine the direction of the stronger light signal. Under outdoor daylight conditions, the incremental tracking test demonstrated that the solar panel responded progressively to the LDR imbalance by making small directional adjustments towards a position of

balanced illumination, indicating appropriate closed-loop tracking behavior. Once the illumination levels of the two LDRs approached equilibrium, no further movement was commanded, demonstrating that the control algorithm could recognize the approximate optimum tracking position and avoid unnecessary actuator operation. In addition to tracking functionality, the environmental monitoring subsystem was validated using the DHT11 sensor, which successfully measured and displayed temperature and relative humidity during system operation. The rain-detection functionality was also verified through controlled wetting of the rain sensor, with the system correctly identifying and displaying the wet condition. However, two practical limitations were observed during testing. Under diffuse or weakly directional illumination, the difference between the LDR signals became less pronounced, thereby reducing the system's ability to reliably discriminate the direction of incident light. Furthermore, mechanical testing involving direction reversal and small corrective movements revealed observable mechanical play, which may introduce minor positioning errors and affect tracking precision.

Table 3: Functional Testing Results of the Proposed Solar Tracking System

Functional check	Applied condition	Observed response	Status
Differential-light sensing	Unequal illumination of the LDR pair	The controller identified the direction of the stronger signal	Passed
Incremental tracking	Outdoor daylight with LDR imbalance	The panel moved incrementally towards balanced illumination	Passed
Balanced-light condition	LDR signals approached balance	No further movement was commanded	Passed
Environmental display	DHT11 connected during operation	Temperature and relative humidity values were displayed	Passed
Rain detection	Controlled wetting of the rain module	A wet condition was detected and displayed	Passed
Diffuse-light behavior	Reduced directional illumination	Directional discrimination between the LDR signals decreased	Limitation observed
Mechanical response	Direction reversal and small corrections	Visually observable mechanical play was noted	Limitation observed

No simultaneous comparison was conducted using an identically rated fixed module, and no calibrated irradiance or energy measurements were logged. Consequently, the improvements of 24.6–43.7% reported for other trackers [6,7] are retained only as literature context and are not attributed to this prototype. Likewise, the ideal cosine model explains why direct-beam alignment matters but cannot quantify daily PV

energy gain.

Actuator consumption was not estimated from the sun's angular rate because a stepper system operates intermittently and may draw holding current; driver loss, mechanical efficiency, friction, and wind loading also influence its electrical demand. Tracker consumption should therefore be measured at the electrical input:

$$E_{\text{tracker}} = \int_{t_0}^{t_f} V_{\text{tracker}}(t) I_{\text{tracker}}(t) dt \quad (8)$$

Here, t_0 and t_f denote the beginning and end of the test interval, respectively, while V_{tracker} and I_{tracker} are the tracker input voltage and current. Energy may be reported in joules when time is expressed in seconds or in watt-hours when power is integrated over hours. A valid comparison should operate identical tracked and fixed panels simultaneously under the same load or maximum-power-point control. Let E_{tracked} and E_{fixed} denote the electrical energies generated by the tracked and fixed PV modules, respectively, and let E_{tracker} denote the electrical energy consumed by the tracking mechanism. Electrical power, $P = VI$, should be integrated over the test interval to determine energy. The gross and net energy gains are then calculated as follows:

$$G_{\text{gross}}(\%) = 100(E_{\text{tracked}} - E_{\text{fixed}})/E_{\text{fixed}} \quad (9)$$

$$G_{\text{net}}(\%) = 100(E_{\text{tracked}} - E_{\text{fixed}} - E_{\text{tracker}})/E_{\text{fixed}} \quad (10)$$

The comparison should report the site coordinates, date, sampling interval, module specifications, fixed-panel tilt and azimuth, tracker-axis orientation, plane-of-array or reference irradiance, ambient and module temperatures, wind conditions, and sky state. Repeated full-day trials and uncertainty estimates are required before general conclusions can be drawn.

5. Conclusion

An Arduino-based single-axis solar-tracking prototype was fabricated by integrating differential LDR sensing, stepper-motor actuation, temperature and relative humidity sensing, rain detection, and an LCD. Functional trials confirmed directional light response, incremental panel movement, cessation of commanded motion near balanced illumination, environmental display operation, and detection and display of the controlled-wetting condition. The functional trials also revealed visually observable mechanical play and weaker LDR discrimination under diffuse light, thereby identifying practical targets for mechanical and control refinement.

The study contributes a compact experimental platform and a transparent functional-verification framework. Improvements in energy performance, tracking accuracy, and net energy balance were not established because measurements of the fixed-panel baseline, irradiance, angular error, and tracker energy consumption were unavailable. Future investigations should combine complete hardware and firmware documentation with simultaneous testing of tracked and fixed modules, measurement of parasitic energy consumption,

repeated full-day trials, and uncertainty analysis.

5.1 Limitations

The study was limited to qualitative functional verification of a single prototype at a single site. The archived record did not preserve the physical rotation-axis direction, panel and frame dimensions, angular range, transmission geometry, LDR/divider dimensions, center-of-gravity offset, motor and PV-module ratings, several firmware parameters, test timing, irradiance, angular error, PV output, or tracker energy consumption. Rain response was evaluated by controlled wetting, while natural precipitation, wind loading, durability, and long-term reliability were not investigated. The DHT11 and rain-detection module provided indicative environmental information rather than calibrated meteorological measurements.

5.2 Future work

Future experiments should archive dimensioned top, front, and side views; identify the physical rotation-axis direction; record the panel, frame, shaft, bearing, LDR/divider, and transmission geometries; measure angular limits, center-of-gravity offset, and backlash; and document the electrical schematic, firmware parameters, and component specifications. Homing, end stops, cable clearance, and strain relief should be incorporated before extended outdoor operation. Identical tracked and fixed modules should then be operated simultaneously, with irradiance, PV voltage and current, module temperature, and tracker supply power logged at a common sampling interval. Repeated full-day trials should report gross and net energy gains with measurement uncertainty. Adaptive deadband, PID, fuzzy logic, and hybrid astronomical-sensor control strategies may then be compared consistently using energy consumption and tracking accuracy.

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