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Design and Fabrication of an Automatic Solar Tracking System

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***Abstract*—Rising demand for electrical energy and the environmental cost of fossil fuels have increased interest in solar photovoltaic (PV) power. A fixed-tilt panel, however, is optimally aligned with the Sun only briefly near solar noon, so a considerable fraction of the available solar energy is lost as the Sun's position changes through the day. This paper presents the design and fabrication of a low-cost automatic solar tracking system that continuously reorients a PV panel to remain favourably aligned with the Sun, using a photovoltaic panel, a sensor/control arrangement, an Arduino UNO microcontroller, a stepper motor and driver, and a gear-and-pinion mechanism. Solar-position equations, gear-ratio calculations, CAD modelling, fabrication and Arduino programming are covered, along with a comparative test between a fixed panel and the tracking panel under identical sunlight conditions. The tracking panel collected noticeably more energy over a working day than the fixed panel, confirming that a simple, inexpensive tracking mechanism of this kind suits educational and small-scale renewable-energy use.**

***Index Terms*—Automatic dual axis solar tracking mechanism, Photovoltaic panel, Arduino UNO, stepper motor.**

I. INTRODUCTION

Energy is one of the most essential requirements for industrial growth, transportation, agriculture and everyday domestic life, and global energy consumption has been increasing steadily as population and industrial activity expand. A large share of this demand is still met by conventional energy sources such as coal, petroleum and natural gas. These conventional sources are, however, available in limited quantity, and their continued extraction and combustion are closely associated with air pollution, greenhouse-gas emission and long-term environmental damage. Renewable energy sources provide a practical alternative that can reduce dependence on fossil fuels while supplying power in a cleaner and more sustainable manner. Among the various renewable options available - including wind, hydro, biomass and geothermal energy - solar energy is particularly attractive because sunlight is available over a very wide geographical area, requires no fuel transportation, produces no emissions during operation, and can be converted directly into electrical energy through photovoltaic cells.

The Sun emits radiant energy that reaches the Earth as solar radiation, and the radiation incident on a photovoltaic panel contains both a direct component and a diffuse component. The useful direct component depends strongly on the orientation of the panel relative to the incoming rays: when sunlight is close to normal (perpendicular) to the panel surface, the effective intercepted radiation and therefore the electrical power generated is at its highest. As the angle between the incident ray and the panel normal increases, the effective area presented to the Sun decreases and the collected energy falls accordingly. This sensitivity of output to orientation is the central physical reason why the way a panel is mounted and oriented has such a large influence on the overall energy yield of a photovoltaic installation.

A fixed solar panel is installed at a single, unchanging tilt and azimuth angle and is therefore optimally oriented towards the Sun only for a limited period of the day, generally close to solar noon. As the Sun appears to move continuously from east to west during the day - and its elevation also changes with the season - the angle of incidence on a fixed panel steadily increases away from this optimum point, and the available electrical output decreases correspondingly during the morning and afternoon hours. A solar tracking mechanism overcomes this limitation by continuously or periodically changing the orientation of the panel so that it remains more favorably aligned with the Sun for a longer period of the day, thereby improving the total energy captured without increasing the physical size or cost of the photovoltaic panel itself. This forms the central motivation for the present work: to design and fabricate a tracking arrangement that is simple, inexpensive and reliable enough to be built and tested with commonly available components.

Based on this motivation, the present work is guided by the following objectives:

- To design a low-cost automatic solar tracking mechanism suitable for a small photovoltaic panel.
- To fabricate the frame, shaft and gear arrangement required for smooth and stable panel movement.
- To control the tracking mechanism using an Arduino-based sensing and control system.
- To improve the orientation of the panel with respect to the incident sunlight throughout the day.
- To compare the electrical performance of the tracking arrangement with that of a fixed-panel installation under identical conditions.

The remainder of this paper is organized as follows: Section II reviews previous work on solar-tracking systems; Section III describes the working principle and underlying solar geometry of the proposed system; Section IV lists the components and the governing solar-position and gear-ratio equations; Sections V and VI describe the CAD modelling, fabrication and control program; Section VII presents the results and discussion, then finally the conclusion, and cost estimation.

II. LITERATURE SURVEY

The increasing demand for renewable energy has encouraged researchers to improve the efficiency of photovoltaic (PV) systems by maximizing the solar radiation received by PV modules. Solar tracking systems are an important approach for increasing solar energy capture by continuously or periodically adjusting the orientation of the solar collector or PV panel toward the sun. Hafez et al. [1] presented a comprehensive review of solar tracking technologies, covering different tracker configurations, drive mechanisms, tracking strategies, and control approaches. The review established that tracking can significantly improve solar energy collection compared with fixed systems, while also highlighting the importance of tracker complexity, energy consumption, reliability, and cost. Similarly, Al-Rousan et al. [2] reviewed advances in PV tracking systems and discussed the relationship between tracking accuracy, energy gain, mechanical complexity, and economic feasibility.

Several researchers have subsequently focused on developing low-cost and practical tracking mechanisms. Jamroen et al. [3] developed a low-cost dual-axis solar tracking system based on digital logic design. Their work demonstrated the feasibility of implementing dual-axis tracking while reducing system complexity and power consumption. Wang and Lu [4] proposed a dual-axis single-motor sun tracker using an optical sensor-based approach. Their design attempted to reduce the number of actuators while maintaining effective solar alignment, demonstrating that mechanical simplification can contribute to improved system practicality.

Single-axis tracking has also received considerable attention because of its relatively simple construction and lower energy consumption. Huang et al. [5] conducted a long-term field test of a one-axis, three-position sun tracker for PV power generation. The study emphasized the importance of evaluating tracker performance under actual outdoor operating conditions rather than relying solely on short-term experimental results. A study on the feasibility of a low-power-consumption solar tracker [6] further emphasized that the electrical energy consumed by the tracking mechanism must be considered when evaluating net energy benefit of a tracking system. Thus, an effective tracker should not only increase PV output but should also minimize its own energy requirements. Modelling and simulation have been used to optimize tracker design before hardware implementation. The study on a standalone single-axis active solar tracker using MATLAB/Simulink [7] investigated the design and performance of an active tracking system through modelling, simulation, and experimental testing. Such approaches are useful for predicting tracking behaviour, evaluating control strategies, and reducing development time and cost. Haq [8] developed a solar tracking system with the objective of improving solar energy collection and addressing energy challenges. The study demonstrated the applicability of tracking technology in regions with significant solar energy potential.

The development of microcontroller- and Arduino-based solar trackers has further improved the accessibility of tracking technology. Gaeid et al. [9] designed and implemented a dual-axis solar tracker using an Arduino platform, demonstrating the use of low-cost digital control for automatic solar positioning. Naif [10] similarly investigated an Arduino-based dual-axis solar tracking system, highlighting the suitability of microcontrollers for implementing tracking algorithms and sensor-based control. Swami et al. [11] also demonstrated a dual-axis solar tracking system using Arduino, indicating the potential of inexpensive embedded controllers for educational, experimental, and small-scale PV applications. Fadhil et al. [12] developed a smart electronic solar tracker based on Arduino, extending the use of embedded control and electronic sensing for automatic solar tracking. More recent research has explored hardware implementation and intelligent control. Khalaf et al. [13] presented a hardware-implemented dual-axis solar tracking system aimed at enhancing energy efficiency. The study illustrates the continued movement from conceptual and simulation-based designs toward practical hardware implementation. Pardosi et al. [14] developed a dual-axis tracking system using an Arduino Uno microcontroller, further demonstrating the applicability of low-cost embedded platforms for automatic tracking. These studies collectively indicate that Arduino and similar microcontroller platforms provide a practical solution for implementing sensor-based solar tracking systems with relatively low hardware cost. A recent comprehensive review by Kazem et al. [15] examined advancements in PV tracking systems, including tracking technologies, performance metrics, and future research directions. The review highlights the continuing development of tracking systems toward improved energy yield, reliability, reduced parasitic consumption, and better economic performance. It also indicates that the evaluation of a solar tracker should not be limited to tracking accuracy alone; parameters such as energy gain, auxiliary power consumption, system cost, reliability, environmental conditions, and long-term performance are equally important.

Vijayan et al. [16] experimentally tested Parabolic trough solar collectors using Al_2O_3–DI water nanofluids (0–3.5% v/v) at mass flow rates of 0.02–0.06 kg/s, followed by an analytical study of a 5% increase in ambient temperature. The study demonstrates that nanofluids combined with ambient-temperature management can provide a potential approach for optimizing PTSC performance. Author [17] experimentally investigated Al_2O_3/DI water nanofluids at different concentrations and mass flow rates in a parabolic trough solar collector. The results confirmed that nanofluid concentration and flow rate significantly influence heat transfer and overall PTSC performance, demonstrating its potential for solar thermal applications. Vijayan et al. [18] investigates the thermal performance of an unshielded parabolic trough solar collector using low-volume-fraction Al_2O_3 / deionized water nanofluids (0.2–1.0% v/v). The nanofluids were prepared using a surfactant-free ultrasonic technique and evaluated as heat-transfer fluids to improve the collector's thermal performance.

III. SOLAR TRACKING SYSTEM

A. Types of Solar Trackers

Solar trackers can be broadly classified by their axis of movement and method of actuation, as summarized in Table I. Single-axis trackers are mechanically simpler and less power-hungry, while dual-axis trackers follow both azimuth and elevation components of solar movement at the cost of added complexity. Passive trackers use thermal expansion of a working fluid, while active trackers use an electronic-controller-driven actuator, as adopted in the present work. Trackers may further be classified by control strategy as open-loop (programmed or chronological), moving on calculated data or a fixed schedule, or closed-loop, relying on real-time sensor feedback; the prototype described in this paper is an active, sensor-based single-axis tracker.

B. Working Principle

The solar tracking system works by changing the orientation of the photovoltaic panel during the day so that the panel surface stays more closely aligned with the incoming solar rays. The control section receives input from the sensing arrangement, compares it against the required reference condition, and provides output signals to the motor-driving circuit whenever a correction in orientation is needed. The motor rotates the mechanical drive, and the gear arrangement transfers the required angular movement to the panel through the supporting shaft, forming a simple sensing-decision-actuation control loop.

C. Photovoltaic Effect

The photovoltaic effect is the direct conversion of light energy into electrical energy in a semiconductor material. When photons of sufficient energy strike the photovoltaic material, electron-hole charge-carrier pairs are generated within the semiconductor. These charge carriers are separated by the internal electric field present at the p-n junction of the solar cell, creating a potential difference across the cell terminals that drives current through an external load. The magnitude of the current generated is directly proportional to the intensity of incident light and the effective area of the panel exposed normally to that light, which is why a favourable angle of incidence has a direct, measurable effect on output.

D. Sun's Path

The apparent position of the Sun in the sky depends on the time of day, the day of the year (season) and the geographical latitude of the observation point. Over a single day the Sun appears to trace a path from east to west across the sky, and over a year this path shifts higher or lower with the season, owing to the tilt of the Earth's rotational axis relative to its orbital plane. The main angles used in solar-position analysis are the solar altitude, azimuth, declination, hour angle, zenith angle and angle of incidence, discussed in the upcoming chapter.

Table I. Classification of Solar Tracker Types

Type	Movement	Description
Single-axis	One axis	Tracks the Sun mainly in one direction.
Dual-axis	Two axes	Follows both major components of solar movement.
Passive	Thermal movement	Uses solar heating effects to produce motion.
Active	Motor-driven	Uses an actuator controlled by an electronic controller.
Open-loop	Calculated / time based	Uses programmed solar-position information.
Chronological	Time based	Moves according to a predetermined time schedule.

E. Solar Angle Relations

- Hour angle: changes approximately 15° per hour and is zero at solar noon.
- Declination angle: the Sun's position north or south of the equatorial plane, varying between about +23.45° and −23.45° through the year.
- Solar azimuth: the horizontal direction of the Sun measured from true north or south.
- Solar altitude: the angle of the Sun above the horizontal plane at the observation point.
- Zenith angle: the angle between the overhead vertical and the direction of the Sun; complement of the solar altitude.
- Angle of incidence: the angle between the incident solar beam and the panel normal; tracking keeps this close to zero.

F. Advantages of Tracking

- Improved alignment with incident sunlight throughout the day, not only near solar noon.
- Better utilization of available solar radiation and higher effective collection area.
- Potential increase in energy generation during morning and afternoon hours.
- Improves system efficiency without a larger or more expensive photovoltaic panel.
- Suitable for demonstration, teaching and small-scale renewable-energy applications.

IV. COMPONENTS AND GOVERNING EQUATIONS

The prototype combines electrical, electronic and mechanical components selected to meet the torque, control and structural requirements calculated below, while remaining low in cost and easy to procure. The photovoltaic side uses a polycrystalline panel (model SRPV-P3P); two panels are used, each with 18 cells, dimensions of 180 × 155 × 15 mm, maximum power of 3 W, maximum power voltage of 9 V, maximum power current of 0.33 A and a stated efficiency above 15.8% - these values should be verified against the actual panel label before final submission. Angular movement is provided by a stepper motor measuring 42.3 mm square × 40 mm excluding shaft, weighing 350 g, with a 5 mm shaft diameter, 200 steps per revolution and a step angle of 1.8°; it is rated at 12 V with a current of 1.5 A per phase, a resistance of 21.65 Ω and inductance of 23.2 mH per phase, and is a 6-wire unipolar type with a holding torque of 23.6 kg·cm. The mechanical structure consists of an aluminium hollow shaft 38 cm long with a 9 mm internal diameter and 12.5 mm outer diameter, a PVC frame of approximately 3 m of pipe joined with elbow and T fittings, and an acrylic gear and pinion for speed reduction and angular positioning. Control is handled by an Arduino UNO as the main microcontroller, an L293D motor driver interfacing the controller signals with the motor circuit, and a sensor/control arrangement that provides the input used for tracking. Together, the stepper motor and L293D driver supply sufficient holding torque and controlled step resolution to rotate the panel assembly smoothly, while the Arduino UNO offers enough digital input/output pins and processing capability for the control logic described in Section VI, keeping the overall electronic cost of the prototype low.

The mechanical and control design of the tracker is based on the following solar-position and gear-ratio calculations, which determine the required angular range of movement and the gear dimensions needed to achieve it with the selected stepper motor.

A. Solar-Position Calculation

The declination angle is calculated as:

$$\delta = 23.45^\circ \sin[(360/365)(284 + d)]$$

For the selected date, the calculation gives a declination angle of approximately 1.21°. The elevation angle is calculated as:

$$\alpha = 90^\circ - \varphi + \delta$$

Using a latitude of approximately 13°03′08″ (Kodambakkam, Chennai), the elevation angle is obtained as approximately 78°09′28″. The hour angle changes at 15° per hour, and for a tracking period from 7:00 a.m. to 5:00 p.m. the working angular range is approximately 150°. This angular range defines the total rotation that the mechanical drive must be capable of providing over the course of a tracking day.

B. Gear Ratio

The stepper motor step angle is 1.8°. For 15° movement per hour and four movements per hour, the required movement per actuation is 3.75°, giving a required gear ratio:

$$\text{Gear ratio} = 3.75^\circ / 1.8^\circ = 2.0833$$

A 50-tooth gear and a 24-tooth pinion were selected, giving a gear ratio of 50/24 = 2.0833, matching the calculated requirement exactly and avoiding the need for a non-standard tooth count.

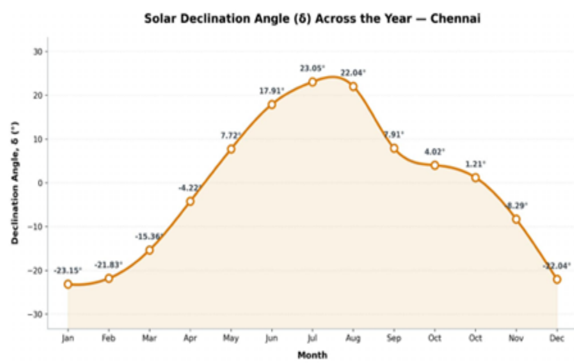

Fig. 1. Solar declination angle (δ) across the year - Chennai.

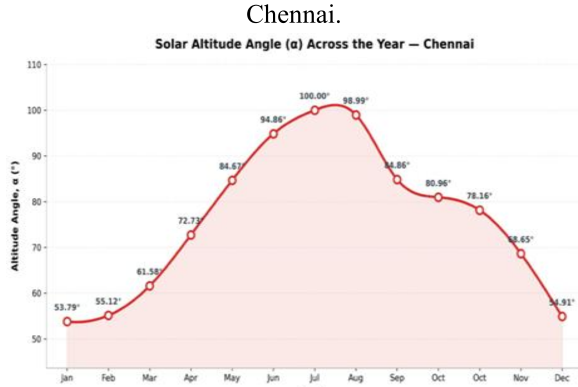

Fig. 2. Solar altitude angle (α) across the year - Chennai.

C. Gear Dimensions
- Module selected = 2.00 mm.
- 50-tooth gear: pitch diameter 100 mm, tip diameter 104 mm, root diameter ≈ 95.372 mm, base diameter ≈ 96.814 mm.
- 24-tooth pinion: pitch diameter 48 mm, tip diameter 52 mm, root diameter ≈ 43.372 mm, base diameter ≈ 46.471 mm.

V. CAD MODELLING AND FABRICATION

A. CAD Modelling
The solar-tracker assembly was modelled using Creo Parametric. The CAD model represents the support frame, shaft, panel mounting arrangement and gear mechanism. Modelling the parts before fabrication helps establish dimensions and component relationships, and allows interferences or clearance problems to be identified and corrected before any material is cut or machined.

B. Gear and Pinion Model
The gear and pinion were modelled using the selected tooth numbers, module and pitch dimensions calculated in Section IV. The final geometry was used for fabrication of the mechanical drive components, ensuring that the physically manufactured gear train matches the gear ratio required to achieve the 3.75° actuation step calculated earlier.

C. Fabrication Procedure
- Prepare the frame and support members according to the design dimensions.
- Prepare the aluminium shaft and provide the required mounting arrangement.
- Fabricate the gear and pinion according to the calculated dimensions.
- Mount the solar panel securely on the rotating support.
- Install the motor and connect it to the gear mechanism.
- Mount the Arduino and motor-driver circuit in a protected position.
- Connect the sensing/control inputs and motor supply.
- Check alignment, free rotation, wiring and mechanical clearances.
- Upload the control program and test the tracking movement.

VI. CONTROL SYSTEM AND PROGRAM

A. Arduino Control
The Arduino UNO is used as the control unit. The control program reads two digital inputs and activates the corresponding digital outputs, which are used by the motor-driving arrangement to control panel movement. The core logic is given below:

```
void setup()
{
pinMode(2, INPUT);
pinMode(3, INPUT);
pinMode(4, OUTPUT);
pinMode(5, OUTPUT);
}
void loop()
{
if (digitalRead(2) == HIGH)
{
digitalWrite(4, HIGH);
}
else if (digitalRead(3) == HIGH)
{
digitalWrite(5, HIGH);
}
else
{
digitalWrite(4, LOW);
digitalWrite(5, LOW);
}
}
```

B. Control Sequence
- Read the sensor/control inputs.
- Determine the required direction of panel movement.
- Activate the corresponding motor-drive output.
- Rotate the panel through the required angular displacement.
- Stop the motor when the desired position is reached.
- Repeat the process during the tracking period.

C. Factors Affecting PV Performance
- Solar radiation and weather conditions.
- Panel orientation and angle of incidence.

- Shading from nearby objects.
- Operating temperature.
- Panel pitch and installation geometry.
- Dust and other surface contamination.

VII. RESULTS AND DISCUSSION

The automatic solar tracking prototype was designed and fabricated by integrating the photovoltaic panel, mechanical support, shaft, gear arrangement, Arduino controller, sensing/control section and motor drive. The design calculations were used to determine the required solar-angle range and the gear ratio needed to move the panel through that range with the selected stepper motor. Both panels produced their lowest output in the early morning and late afternoon and their highest output around midday, following the expected rise and fall of solar irradiance over the day. The tracking panel recorded a higher voltage and current than the fixed panel at every measured time step, with the difference smallest near solar noon - when the fixed panel is already close to its most favorable orientation - and largest during the morning and afternoon hours, when the Sun's position has moved well away from the fixed panel's tilt angle. Summing the instantaneous power readings over the observation period, the tracking panel achieved an approximately 17% increase in total energy output compared with the fixed panel under the tested conditions. This is broadly consistent with the range reported in the literature reviewed in Section II, where the improvement from single-axis tracking is typically reported between about 10% and 25% depending on location, season and sensor arrangement, and somewhat lower than the gains reported for dual-axis systems, which track both the azimuth and elevation components of solar movement rather than one axis alone.

The measured results confirm the basic principle discussed in Section III: tracking improves the orientation of the panel relative to the incident solar beam, which increases the effective irradiance reaching the cell and therefore the electrical output, particularly during the morning and afternoon when a fixed panel has moved furthest from its favorable angle.

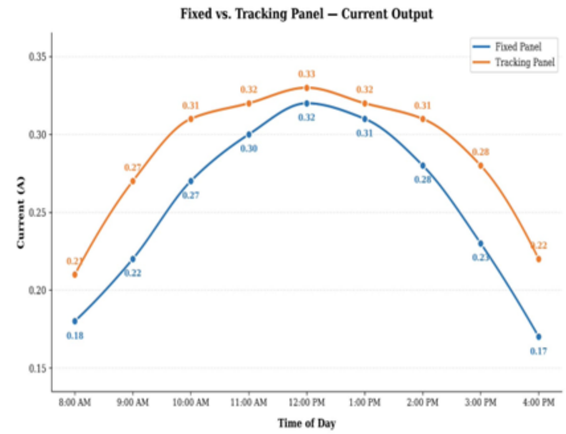

Fig. 3. Fixed vs. tracking panel - current output.

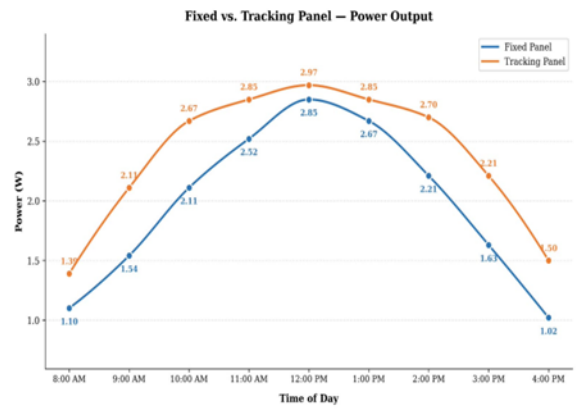

Fig. 4. Fixed vs. tracking panel - voltage output.

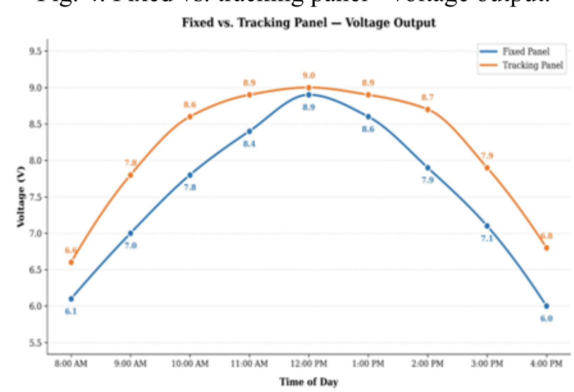

Fig. 5. Fixed vs. tracking panel - power output.

Because the improvement is largest away from solar noon, the total daily energy gain depends strongly on how many tracking corrections are made through the day and how promptly the sensing arrangement responds to changing light conditions. Several factors limit the energy benefit actually realized by the prototype. The stepper motor and driver draw electrical power whenever a correction is made, and this tracker power consumption must be subtracted from the additional energy captured to obtain the true net benefit; for a small demonstration panel of this rating, the motor draw is a non-trivial fraction of the panel's own output, so the net gain is smaller than the raw energy-yield figure suggests. Mechanical losses in the gear-and-pinion drive, small errors in the gear ratio calculated in Section IV, and backlash between the acrylic gear and pinion can all introduce a small positioning error between the commanded angle and the actual panel angle. Sensor-related effects, including shading of one LDR by a neighboring sensor or its mounting bracket, can also cause the controller to under- or over-correct the orientation.

Environmental conditions during testing further affect the comparison between the two panels. Cloud cover reduces the direct-beam component of sunlight, which is exactly the component that tracking is most effective at capturing, so the percentage improvement from tracking is expected to be smaller on a partly cloudy day than on a clear day. Ambient temperature also affects the panel's output characteristics, since PV cell efficiency generally falls as cell temperature rises; because the tracking panel intercepts more direct sunlight, it may also run marginally warmer than the fixed panel, partially offsetting the benefit of improved alignment. Given these dependencies, the reported literature range of roughly 10-25% for single-axis tracking should be read as an indicative range rather than a fixed figure, and the same design can be expected to perform somewhat differently at other locations, seasons, weather conditions and times of year.

VIII. CONCLUSION

This work presents the design, fabrication and testing of a low-cost automatic solar tracking system built from an Arduino UNO, a stepper motor and driver, and a gear-and-pinion mechanism. Solar-position and gear-ratio calculations were used to size the mechanical drive, and a working prototype was fabricated and tested against a fixed panel of the same rating. The tracking panel collected noticeably more energy than the fixed panel over the test period, broadly matching gains reported in the literature, though the net benefit depends on tracker power consumption, mechanical losses, sensor accuracy and weather conditions. The results indicate that the gap between fixed and tracking output is largest away from solar noon, when a fixed panel is furthest from its favourable angle, and smallest near midday. The prototype demonstrates that a simple, inexpensive and easily reproducible tracking mechanism of this kind is well suited to educational demonstrations and small-scale renewable-energy applications.

Table II. Approximate Material Cost

Component	Cost (₹)
Arduino UNO	380
10 RPM motor	240
Motor driver	150
Sensor module	120
Battery	20
Sensor	15
Battery cap	10
Shaft	75
Total	1,010

Based on this work, the following directions are suggested for future development:

- Develop a two-axis tracker for improved solar alignment.
- Use calibrated multiple LDR sensors or a solar-position algorithm.
- Add voltage, current and power sensors for automatic data logging.
- Optimize motor operation to reduce tracker energy consumption.
- Improve weather protection and mechanical rigidity.
- Add automatic end-of-day return positioning.

The total component cost for the prototype is approximately ₹1,010. Fabrication labour, wiring, fasteners and incidental expenses may be added separately as required. Because the components used are all commonly available, the design can be reproduced at similar cost by other students or hobbyists wishing to build or extend the prototype.

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REFERENCES

[1] Hafez, A. Z., Yousef, A. M., & Harag, N. M. (2018). Solar tracking systems: Technologies and trackers drive types – A review. Renewable and Sustainable Energy Reviews, 91, 754–782.

[2] Al-Rousan, N., Isa, N. A. M., & Desa, M. K. M. (2018). Advances in solar photovoltaic tracking systems: A review. Renewable and Sustainable Energy Reviews, 82, 2548–2569.

[3] Jamroen, C., Komkum, P., Kohsri, S., Himananto, W., Panupintu, S., & Unkat, S. (2020). A low-cost dual-axis solar tracking system based on digital logic design: Design and implementation. Sustainable Energy Technologies and Assessments, 37, 100618.

[4] Wang, J.-M., & Lu, C.-L. (2013). Design and implementation of a sun tracker with a dual-axis single motor for an optical sensor-based photovoltaic system. Sensors, 13(3), 3157–3168.

[5] Huang, B. J., Ding, W. L., & Huang, Y. C. (2011). Long-term field test of solar PV power generation using one-axis 3-position sun tracker. Solar Energy, 85(9), 1935–1944.

[6] Power feasibility of a low power consumption solar tracker. (2013). Procedia Environmental Sciences, 17, 494–502.

[7] Design, modeling and testing of a standalone single axis active solar tracker using MATLAB/Simulink. (2011). Renewable Energy, 36(11), 3075–3090.

[8] Haq, Q. A. U. (2019). Design and implementation of solar tracker to defeat energy crisis in Pakistan. International Journal of Engineering and Manufacturing, 9(2), 31–42.

[9] Gaeid, K. S., Uddin, M. N., Mohamed, M. K., & Mohmmoud, O. N. (2020). Design and implement of dual axis solar tracker system based Arduino. Tikrit Journal of Engineering Sciences, 27(2).

[10] Naif, Y. H. (2020). Design of Arduino-based dual axis solar tracking system. Journal on Advanced Research in Electrical Engineering, 4(2).

[11] Swami, S., Kumar, R., & Kumar, N. (2020). Dual axis solar tracking system using Arduino. Periodica Polytechnica Electrical Engineering and Computer Science, 4(1), 34–36.

[12] Fadhil et al. (2019). Design and implementation of smart electronic solar tracker based on Arduino. TELKOMNIKA (Telecommunication Computing Electronics and Control), 17(5).

[13] Khalaf et al. (2023). Design and implementation of hardware-implemented dual-axis solar tracking system for enhanced energy efficiency. Engineering Proceedings, 59(1), 122.

[14] Pardosi, C. H., Siregar, M., & Pandjaitan, L. W. (2024). Design and implementation of a dual-axis solar tracking system using Arduino Uno microcontroller. Jurnal ELTIKOM, 8(1).

[15] Kazem, H. A., Chaichan, M. T., Al-Waeli, A. H. A., & Sopian, K. (2024). Recent advancements in solar photovoltaic tracking systems: An in-depth review of technologies, performance metrics, and future trends. Solar Energy, 282, 112946.

[16] Vijayan Gopalsamy, Robert Baccoli, Karunakaran R. (2025). Experimental and analytical evaluation of nanofluid based parabolic trough solar collector under varying concentrations, flow rates, and ambient temperatures, Case Studies in Thermal Engineering, 75, 107219.

[17] Vijayan Gopalsamy, Shantharaman PP, Karunakaran R. (2025). Exploring performance variations of mono-nanofluid-based parabolic trough solar collectors at various concentrations and mass flow rates: an experimental analysis., Journal of Thermal Analysis and Calorimetry, 150(6), 4261-4277.

[18] Vijayan Gopalsamy, Shantharaman PP, Senthil R, Karunakaran R. (2021). Thermal performance analysis of a low volume fraction Al_2O_3 and deionized water nanofluid on solar parabolic trough collector, Journal of Thermal Analysis and Calorimetry, 147(1),753-762.