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Development and Performance Evaluation of an Automated Dual-Axis Tracking Scheffler Reflector

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***Abstract* - Solar energy remains one of the most promising renewable energy sources, and concentrating solar technologies have shown significant potential for converting sunlight into usable thermal energy. The Scheffler reflector is a practical fixed-focus parabolic dish that tracks the sun while maintaining a stationary focal point. This paper presents the development and performance evaluation of an automated dual-axis solar tracking Scheffler reflector built using a repurposed Dish TV parabolic dish mounted on a 20 mm mild steel shaft supported on ball bearings, with the base structure fabricated from one-inch MS tubes anchored on an 18 mm plywood platform. A Johnson 60 RPM motor drives azimuthal rotation through a 60 mm wheel, while a 10 RPM high-torque gear motor coupled with a freewheel-and-sprocket assembly drives dish elevation, with limit switches preventing mechanical over-travel. Automation is achieved through an ESP32 microcontroller operating in active LDR-based tracking and timed manual modes, using four light-dependent resistors arranged in a plus-sign configuration to detect differential sunlight intensity and align the dish toward maximum irradiance. Concentrated solar energy is directed onto a receiver container at the focal point, where thermal energy accumulates for heating applications. Experimental evaluation shows a steady focal-point temperature rise from 30 °C to 108 °C over 45 minutes, confirming reliable tracking performance and effective solar concentration. The system offers an affordable, locally fabricable, and intelligently automated approach to solar thermal concentration suitable for rural and semi-urban applications.**

Keywords: Scheffler reflector, dual-axis solar tracking, ESP32 automation, LDR sun tracking, parabolic dish, solar concentration, thermal energy, freewheel-sprocket mechanism, mild steel structure, renewable energy.

I. INTRODUCTION

Energy is the backbone of modern civilization, and the growing demand for clean and affordable energy has pushed researchers toward solar energy technologies with greater depth. Concentrating solar power systems generate significant thermal energy by focusing sunlight onto a small receiver area and have been used for cooking, water heating, steam generation, and small-scale power production. However, keeping the reflector aligned with the moving sun has always been a critical factor affecting efficiency and practical usability.

The Scheffler reflector, originally developed by Wolfgang Scheffler in the 1980s, is a fixed-focus parabolic dish engineered so that its focal point remains stationary even as the reflector rotates to track the sun [1]. This makes it especially useful where the receiver cannot be moved, such as community kitchens and industrial process heat. Unlike conventional parabolic dish systems where the entire assembly moves with the sun, the Scheffler design decouples the receiver from the tracking mechanism. Despite this advantage, widespread adoption has been limited by the cost and complexity of the tracking mechanism, particularly in low-resource settings.

Traditional tracking systems rely on expensive motors, precision mounts, and sophisticated controllers that are difficult to fabricate or afford in rural regions, creating a gap between the theoretical potential of concentrating solar technology and its grassroots deployment. This work addresses that gap by presenting an automated dual-axis tracking Scheffler reflector built from accessible, low-cost components: a repurposed Dish TV parabolic dish, mild steel tubes, plywood, and ESP32-based LDR feedback control.

A. Scope

The system is applicable to solar cooking and community-kitchen setups, crop drying, milk pasteurization and water heating in agriculture, sterilization and low-temperature process heat in small-scale food processing, process heat for textile and dairy industries, educational and research demonstration platforms, and off-grid rural applications including solar steam sterilization in healthcare and solar distillation for water purification. Wider adoption can contribute to reduced greenhouse-gas emissions and biomass dependence while remaining replicable by local fabricators using low-cost materials.

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B. Need of the Project

Existing solar concentrating systems are either too expensive for small-scale users or lack precise tracking, resulting in poor efficiency. Manual tracking requires continuous human intervention, while commercial automated systems involve high installation and maintenance costs beyond the reach of rural communities. A low-cost, locally fabricable, and intelligently automated tracking concentrator is therefore needed to deliver reliable thermal energy without dependence on skilled technicians or imported components.

C. Problem Statement

Solar concentrating technologies offer a technically viable route to meeting growing thermal-energy demand, but practical deployment remains limited by the absence of an affordable, accurate, fully automated dual-axis tracking mechanism. Existing solutions rely on expensive servo systems or astronomical algorithms requiring GPS and real-time clocks, while most commercial structural components require precision manufacturing not replicable in local workshops. This work addresses the problem of developing a mechanically sound, electronically automated, and economically viable dual-axis tracking Scheffler reflector using repurposed components, indigenous fabrication, and an ESP32-based LDR feedback system.

D. Objectives

- To design and fabricate a dual-axis tracking Scheffler reflector using low-cost, locally available materials.
- To develop an ESP32-based control system that tracks the sun in both axes using a four-LDR differential sensing arrangement.
- To implement a reliable mechanical transmission using a freewheel-and-sprocket assembly for elevation and a wheel-driven mechanism for azimuthal rotation.
- To integrate limit switches to prevent mechanical over-travel during automated operation.
- To evaluate thermal performance through focal-point temperature rise under varying sunlight conditions.
- To demonstrate the feasibility of a stationary-focal-point reflector for real-world thermal applications.
- To establish a replicable, scalable design adoptable by local fabricators and rural communities.

II. LITERATURE REVIEW

Scheffler and Kulkarni [1] introduced the design principles of the fixed-focus concentrator, describing the asymmetric parabolic geometry and daily seasonal adjustment, and reported that an eight-square-metre reflector could deliver two to three kilowatts of thermal power, validated through community-cooking field trials in India.

Nandi and Mullick [2] presented a dual-axis parabolic dish concentrator with microcontroller-based feedback control and found that angular errors beyond three degrees significantly reduced focal irradiance, with dual-axis tracking improving daily thermal collection by up to forty percent over a fixed-tilt system.

Bharathan and Velmurugan [3] implemented an ESP32-based single-axis tracker using a four-LDR quadrant arrangement, recording a thirty-two percent average improvement in energy yield over a fixed panel and stable tracking under variable cloud cover, validating LDR-based differential sensing for low-cost systems.

Mousazadeh *et al.* [4] reviewed single-axis, dual-axis, passive, active, open-loop and closed-loop tracking strategies, concluding that closed-loop sensor-based tracking offered the highest accuracy under clear skies, with dual-axis tracking optimal for concentrating systems requiring high precision.

Roth, Georgiev and Boudinov [5] described a stepper-motor two-axis mount combining real-time-clock and light-sensor inputs, recording tracking errors below one degree of arc and showing that hybrid sensor-plus-clock control outperformed either method alone.

Lamba and Gupta [6] documented hands-on fabrication of a Scheffler reflector from mild steel sections and handcrafted ribs, achieving focal temperatures above 400 °C under peak irradiance and demonstrating that high-performance reflectors can be built at a fraction of commercial cost.

Chong and Wong [7] derived a generalized mathematical framework for dual-axis sun-tracking motion across mounting configurations, identifying the azimuth-elevation mount as the most mechanically straightforward for fixed-site installations, consistent with the configuration adopted in this work.

Clifford and Eastwood [8] explored a passive tracker using differential thermal expansion, finding it adequate for flat-plate collectors but insufficient for concentrating applications, reinforcing the need for active motor-driven tracking with electronic feedback.

Poulek and Libra [9] presented a minimalist photodiode-comparator tracking circuit achieving two-to-four-degree accuracy, acceptable for flat-plate photovoltaics but marginal for high-concentration solar thermal systems, motivating the more refined multi-sensor differential arrangement used in the present project.

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III. METHODOLOGY

Closed-loop active tracking using a four-LDR differential quadrant sensing arrangement interfaced with an ESP32 microcontroller was selected as the control strategy, supported by a Johnson 60 RPM motor for azimuthal rotation and a 10 RPM square gear motor with freewheel-and-sprocket transmission for elevation. This approach offers real-time responsiveness without dependence on GPS modules or astronomical calculations, while inherently compensating for atmospheric variation and installation-level geometric imperfections.

A. System Working

The system continuously aligns the dish toward maximum solar irradiance using real-time feedback from four LDRs mounted in a plus-sign configuration, each occupying one quadrant corresponding to the top, bottom, left and right directions. When the sun is aligned with the dish axis, all four LDRs receive approximately equal intensity and both motors remain stationary. As the sun moves, the ESP32 detects the resulting voltage differential between opposing sensor pairs and, once it exceeds the dead-band threshold, drives the appropriate motor: the Johnson 60 RPM motor rotates the base via the 60 mm wheel on the plywood surface for azimuthal correction, while the 10 RPM gear motor drives the freewheel-and-sprocket transmission for elevation correction.

Limit switches on the elevation axis interrupt the motor circuit at the upper and lower mechanical boundaries, preventing stalling and protecting the sprocket and freewheel assembly. Concentrated sunlight converges onto a small receiver container at the stationary focal point, which heats progressively in proportion to tracking accuracy and irradiance. A secondary manual/timed mode allows operator control during low-light startup, overcast conditions, or maintenance.

B. Design Calculations

Dish diameter assumed = 0.9 m, giving a reflector area of 0.636 m². At standard irradiance of 1000 W/m², the incident power is 636.2 W. With an assumed reflectivity of 0.85 and optical efficiency of 0.90, the thermal power at the focal point is 486.6 W. For a 50 mm receiver (area 1.963×10^{-3} m²), the concentration ratio is approximately 324. Using the Stefan–Boltzmann relation with an emissivity of 0.90, the theoretical upper-bound focal temperature is approximately 1211 °C, with a practically estimated focal temperature (accounting for losses) of 300–450 °C.

For an estimated structural mass of 8 kg and rotation radius of 0.25 m, the friction torque at the thrust bearing (coefficient 0.05) is 0.981 N•m, well within the 3 N•m rating of the Johnson 60 RPM motor. The base completes a 180° sweep in approximately 30 seconds. For elevation, a dish mass of 3 kg with a 0.20 m moment arm gives a gravitational torque of 5.886 N•m; with a 4:1 sprocket ratio (48-tooth to 12-tooth), the required motor torque is 1.47 N•m, well within the 8 N•m rating of the 10 RPM gear motor, giving an angular speed of 15°/s and a 45° elevation change in 3 seconds.

Shaft bending stress for the 20 mm mild-steel shaft under an assumed 30 N load at 0.15 m is 5.73 MPa, far below the 250 MPa yield strength of mild steel, confirming a safe design. Similarly, the central 12 mm bolt experiences a compressive stress of only 0.694 MPa under the full structural load, well within the material yield limit. For the LDR voltage-divider network (10 kΩ fixed resistor, 3.3 V supply), the differential between bright-sun and partial-shade conditions is approximately 1.35 V, comfortably within the ESP32's 0–3.3 V ADC range, with a practical tracking threshold of 0.2 V.

C. System Components

The system integrates an ESP32 dual-core microcontroller for real-time ADC sampling and motor actuation; four GL5528 light-dependent resistors in a quadrant arrangement for differential sun-position sensing; a Johnson 60 RPM DC gear motor for azimuthal base rotation via a 60 mm drive wheel; a 10 RPM high-torque square-body gear motor driving the elevation axis through a freewheel-and-sprocket (48:12 tooth) transmission; a thrust bearing carrying the axial structural load at the central 12 mm bolt; two ball-bearing washer-housing assemblies supporting the 20 mm mild-steel dish shaft; a welded one-inch MS tube structural frame on an 18 mm plywood base; limit switches providing hardware-level travel protection on the elevation axis; and a small blackened metallic receiver container at the stationary focal point for thermal absorption.

IV. RESULTS AND DISCUSSION

The focal-point temperature was recorded over a 45-minute test period under clear-sky conditions, with the receiver container temperature rising steadily as the dual-axis tracking maintained dish alignment with the sun (Table I).

Table I: Focal-point temperature rise with time

Time (min)	Temperature (°C)
0	30
5	38
10	47
15	58

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20	68
25	78
30	88
35	96
40	102
45	108

The steady, near-linear rise from 30 °C to 108 °C over 45 minutes confirms effective and consistent solar concentration at the focal point, indicating that the four-LDR differential tracking maintained close alignment with the sun throughout the test. Minor variations in the rate of rise can be attributed to short-term irradiance fluctuations and tracking dead-band corrections.

A. Cost Estimation

The estimated bill of materials for fabrication of the prototype is summarized in Table II, giving a total prototype cost of approximately ₹20,000, which remains substantially lower than commercially available dual-axis solar concentrator systems.

Table II: Material cost estimation (Total ≈ ₹20,000)

Part	Qty	Material	Cost (₹)
Dish reflector (TV dish)	1	Aluminium	2,500
MS shaft (20 mm)	1	Mild steel	1,200
Ball bearings w/ housing	2	Steel + MS	1,000
MS frame (1-in. tubes)	1 set	Mild steel	3,500
Base platform	1	18 mm ply	1,200
Johnson motor (60 RPM)	1	Cu wound	1,000
Geared motor (10 RPM)	1	Cu wound	1,200
ESP32 + LDR set	1 set	Electronics	1,500
Misc. hardware (sprocket, chain, switches, wiring)	1 lot	Mixed	6,900

B. Advantages

- Increases solar energy capture through continuous dual-axis tracking.
- Provides higher temperature output than fixed-reflector systems.
- Automated operation reduces manual intervention and improves accuracy.
- Uses low-cost, easily available materials for fabrication.
- Compact, simple mechanical design ensures easy maintenance.

C. Limitations

- Performance depends heavily on weather and sunlight availability.
- Initial setup cost is higher than fixed solar systems.
- Mechanical components may wear over time due to continuous movement.
- LDR sensors may give inaccurate readings under diffused light.
- Requires continuous electrical power for motors and control.

D. Applications

- Solar cooking and water-heating systems.
- Industrial preheating processes using solar energy.
- Rural and remote-area energy solutions.
- Laboratory experiments for solar thermal studies.
- Drying applications in agriculture and food processing.
- Educational demonstration models for renewable energy.

V. CONCLUSION

The developed system successfully demonstrates an automated dual-axis tracking mechanism that improves solar energy concentration and thermal output. The integration of mechanical design with ESP32- and LDR-based electronic control ensures efficient and continuous sun tracking, and the focal-point temperature rise from 30 °C to 108 °C over 45 minutes confirms reliable performance. The project proves to be cost-effective, reliable, and suitable for small-scale solar thermal applications using locally fabricable materials and components.

VI. SCOPE FOR FUTURE WORK

The system can be enhanced through more accurate sensors such as photodiodes or astronomical sun-position algorithms, corrosion-resistant structural materials such as aluminium to increase lifespan, battery or solar-powered control electronics for full energy independence, IoT-based remote monitoring and data logging, improved reflector surface quality and focal-point design for higher thermal efficiency, and integration with heat-storage systems to allow energy use after sunset.

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