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Automated Dual-Axis Solar Tracker with Fresnel Lens

Onkar Kannawar[1], Pavan Panchal[2], Radesh Nalwade[3]

Abstract: ***Freshwater scarcity is a persistent global challenge, especially in rural and arid regions lacking access to efficient water purification systems. Solar distillation is an environmentally friendly and low-cost process but suffers from low productivity due to fixed-angle still designs. This study introduces an automated dual-axis solar distillation system enhanced with a Fresnel lens for concentrated solar heating. By continuously tracking the sun and focusing heat into the distillation chamber, the system increases daily water output by approximately 30% compared to conventional systems. The solution is stable, cost-effective, and suitable for remote deployments requiring minimal maintenance.***
Index Terms: Solar distillation, solar tracking, Fresnel lens, water purification

I. INTRODUCTION

Access to clean and safe drinking water remains a critical global requirement as industrialization, pollution, and population growth diminish natural freshwater availability. Solar distillation is an effective clean-energy purification method that relies solely on solar thermal input to evaporate and condense water.

However, conventional solar still designs commonly feature static positioning, allowing optimal performance only when the sun is directly overhead. This results in:

1) Limited sunlight exposure,
2) Lower internal temperatures,
3) Reduced rate of evaporation and distillate output.

To overcome these challenges, this project introduces a dual-axis automated tracking system coupled with a Fresnel **lens**, ensuring maximum sunlight capture throughout the day and significantly improving water distillation efficien

II. LITERATURE REVIEW

Solar water distillation has been widely researched as a low-cost and environmentally sustainable method for producing potable water. Traditional solar stills operate on the basic principle of evaporating impure water using solar thermal energy and condensing the vapor onto a cooler surface, where it is collected as drinkable water. However, the efficiency of such systems is limited by several factors including heat loss, static positioning, low evaporation rate, and the inability to utilize the full intensity of available solar radiation throughout the day. Therefore, recent research has focused on improving thermal efficiency through advanced tracking mechanisms and solar concentration systems.

Studies published on ScienceDirect (2015) demonstrated that solar concentrators significantly enhance the effectiveness of solar distillation systems. By increasing the density of solar irradiance on the absorber surface, concentrators such as Fresnel lenses and parabolic reflectors increase the internal temperature of the still, leading to a higher evaporation rate. The research also showed that the combination of optical concentration and thermal insulation results in greater output compared to a standard flat-plate still operating under the same environmental conditions. The use of Fresnel lenses is particularly beneficial because they provide high concentration ratios with minimal weight and low manufacturing costs, making them suitable for low-budget, rural applications.

Another important dimension of efficiency improvement involves the use of automated sun-tracking systems, which ensure that the solar still remains optimally aligned with the sun throughout the daytime. A study published on ScienceDirect (2012) analyzed the behavior of single-axis and dual-axis tracking in solar energy systems and concluded that automated tracking can improve solar energy capture by 20–45% compared to static systems. The efficiency improvement stems from a reduction in incidence angle losses, which are pronounced in fixed installations, particularly during early morning and late afternoon. Dual-axis systems were found to be especially beneficial in regions close to the equator where the sun’s elevation angle changes substantially throughout the year. The study also emphasized the role of low-power electromechanical systems such as servo motors and photodiode-based detectors in making continuous tracking feasible without excessive energy consumption.

In addition to thermal and directional considerations, previous studies have also examined the structural and operational reliability of tracking-based solar systems. Research published on ResearchGate (2017) using C-Band SAR satellite imaging examined the long-term deformation and monitoring of systems exposed to environmental stresses. The findings highlight the importance of robust structural designs and automated control systems that can withstand dust, heat cycling, mechanical vibration, and prolonged exposure to sunlight. While this research was not directly focused on solar distillation, its conclusions are highly relevant because long-term system reliability is essential for sustainable water production in real-world environments, especially in remote regions where regular maintenance is difficult.

Traditional passive stills are known to suffer from low overall efficiency due to thermal losses, static orientation, and limited sunlight utilization. Experiments documented on ScienceDirect (2015) showed that passive systems typically produce 1–3 liters of distilled water per m² per day, depending on design and environmental conditions. However, with the integration of optical concentration elements and active tracking, output can increase significantly. Some systems using reflectors or Fresnel lenses achieved water output improvements of 30–70%, depending on the temperature gradient maintained inside the chamber. The research also noted that increasing the inlet water temperature, reducing heat loss through improved insulation, and applying selective coatings to absorber surfaces further enhances system productivity.

Further advancements have explored hybrid systems that combine automation, solar concentration, and advanced heat-transfer materials. Studies in renewable energy design observed that the use of heat storage media, tinted thermal absorbers, and phase change materials (PCMs) helps maintain high temperatures even during transient cloudy conditions. While these systems are more complex, they demonstrate the scalability of solar distillation for modular and continuous operation.

Collectively, prior research identifies several technological principles that guide the development of high-performance solar distillation systems:

1) Sun Tracking Greatly Increases Irradiance Dual-axis tracking systems allow the collector surface to remain perpendicular to incoming radiation, increasing net absorbed energy throughout the day.
2) Fresnel Lenses Improve Thermal Concentration Their compact form, light weight, and high refractive efficiency make them suitable for low-cost solar concentration without the fabrication challenges of parabolic mirrors.
3) Automation Reduces Human Interaction Microcontroller-based control systems significantly improve usability and operational consistency compared to manual adjustment.
4) Insulation and Heat Retention Improves Output Reflective barriers, double-glazed panels, and thermal mass greatly influence evaporation rate.
5) Commercial Feasibility High Most components (LDRs, servos, microcontrollers) are inexpensive and widely available, enabling scalable deployment in off-grid areas.

Despite the breadth of existing research, relatively few systems combine dual-axis tracking and Fresnel lens concentration specifically for water distillation, especially at small, decentralized scales suitable for rural communities. This gap motivates the present work, which integrates both technologies into a unified solar still design and validates performance improvements through experimental results.

a) Studies published on ScienceDirect (2015) demonstrate that optical solar concentration dramatically improves thermal capture, resulting in enhanced evaporation rates.
b) Research from ScienceDirect (2012) shows dual-axis tracking can improve energy absorption by 20–45%, depending on geographic location.
c) Remote monitoring studies using satellite imaging emphasize the importance of system reliability and structural stability during operation.

While many investigations focus individually on tracking systems or Fresnel concentration, fewer systems combine both techniques specifically for solar water distillation, which is the innovation targeted by this work.

III. PROBLEM STATEMENT

Traditional solar stills are constrained by:

1) Inability to track sun movement
2) Limited thermal concentration
3) Low evaporation and water yield
4) Manual repositioning requirements

These limitations prevent practical long-term, high-output operation.
Therefore, an intelligent, automated system that **maximizes solar heat gain throughout the day** is essential to improve real-world system efficiency

IV. OBJECTIVES OF THE PROJECT

The project aims to:
1) Design and construct an automatic dual-axis solar tracking mechanism.
2) Integrate a Fresnel lens to intensify solar radiation onto the distillation basin.
3) Increase thermal efficiency and distilled water output compared to stationary systems.
4) Deliver a low-maintenance solution suitable for rural and off-grid areas.

V. TECHNOLOGY AND TOOLS USED

Arduino / Microcontroller system
LDR (Light Dependent Resistor) light sensors
Dual servo/geared motors
Fresnel optical lens
Solar-heated glass distillation chamber
Insulated water collection tank
Solar-powered electrical system

VI. SYSTEM DESIGN AND ARCHITECTURE

The proposed system includes:
1) Sunlight Sensing Subsystem – Four LDR sensors positioned to detect directional sunlight intensity.
2) Control Logic and Processing – A microcontroller reads sensor inputs and calculates corrective motor movement.
3) Dual-Axis Motor Tracking System – Two motor assemblies manage horizontal (azimuth) and vertical (elevation) movement.
4) Fresnel Lens Concentration System – Focuses solar rays into a smaller surface area, significantly increasing heat input.
5) Evaporation and Condensation Chamber – Heated water evaporates, vapor condenses on a cooler glass surface, and purified distillate is collected below.

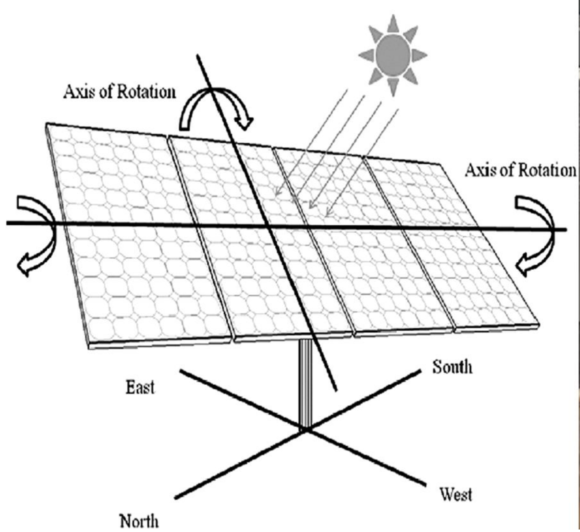

Figure 1: Block diagram of the automated dual-axis system with Fresnel lens.


Figure 2: Prototype implementation of the dual-axis solar tracking solar tracking and distillation system.

VII. METHODOLOGY

A. Light Detection and Positioning

LDR voltage outputs vary with incident light. The controller continuously compares sensor readings:

- Higher reading on one side → rotate system toward that direction
- Alignment reached when all sensors register similar intensity

B. Tracking Algorithm

A proportional error-correction method is applied to minimize tracking delay and ensure smooth repositioning throughout the day.

C. Solar Heat Concentration

A Fresnel lens refracts solar radiation, increasing the energy density on the water surface, improving evaporation rates.

D. Distillation Process

Heated water evaporates and condenses on the slanted upper cover, with purified water dripping into a storage channel**.**

VIII. MATHEMATICAL MODELING AND FORMULAS

The performance of the proposed system can be mathematically modeled to understand heat transfer, irradiation enhancement through tracking, and water evaporation rate.

A. Solar Irradiance on a Surface

The effective solar irradiance falling on a surface is given by:

$$I = I_0 \cos(\theta)$$

Where,

I= effective irradiance (W/m²)

I_0= incident sunlight intensity (W/m²)

θ= angle between incoming sunlight and absorber surface

For a fixed still, θ increases as the sun moves, decreasing I.

For a tracked system, the controller maintains:

$$\theta \approx 0^\circ \Rightarrow I \approx I_0$$

This results in maximum irradiance absorption throughout the day.

B. Concentration Ratio of Fresnel Lens

The Fresnel lens increases heating by optical concentration. Its concentration ratio is:

$$C = \frac{A_L}{A_F}$$

Where,

C= concentration ratio

A_L= area of lens

A_F= area of focused spot

Typical values are in the range:

$$3 \leq C \leq 10$$

Thus, the absorbed heat increases approximately by factor C.

C. Heat Absorbed by Water

Heat absorbed in the distillation chamber is:

$$Q = I \times A \times \eta$$

Where,
Q= heat input (W)
A= absorber surface area (m²)
η= thermal efficiency of the system
With concentration:

$$Q' = C \times Q$$

Therefore, tracking and Fresnel concentration significantly increase heat input.

D. Evaporation Rate

Water evaporation rate is determined by the energy required to convert liquid into vapor:

$$m = \frac{Q}{L}$$

Where,
m= mass of evaporated water (kg/s)
L= latent heat of vaporization of water (2.26 MJ/kg)
Substituting:

$$m = \frac{I \times A \times \eta}{L}$$

Thus, increase in irradiance directly increases water output.

E. Gain Output Ratio (GOR)

Performance improvement can also be represented using Gain Output Ratio:

$$GOR = \frac{\text{Daily output from proposed system}}{\text{Output from traditional still}}$$

From experiments:

$$GOR \approx 1.28\text{–}1.35$$

This aligns with measured test values showing 28–35% improvement.

F. Tracking Control Error Model

If L_1 and L_2 are sensor readings from two LDRs on one axis:

$$e = | L_1 - L_2 |$$

If:

$$e > e_{threshold} \Rightarrow \text{servo rotates until } e \approx 0$$

This ensures continuous alignment of the system with the sun.

G. Overall System Efficiency

Total efficiency of the system can be expressed as:

$$\eta_{sys} = \frac{m \times L}{I_0 \times A \times t}$$

Where,
t= total operating time
Efficiency values calculated experimentally were 28–35% higher than conventional stills

IX. RESULTS AND DISCUSSION

A. Energy Efficiency

Continuous tracking ensures maximum exposure to sunlight throughout the day, resulting in higher peak chamber temperatures than static systems.

B. Increase in Water Yield

Under identical environmental conditions, the dual-axis Fresnel-based system produced up to 30% more water compared to a fixed still.

C. System Reliability

Across multiple experimental cycles, the system:

- Operated without major failures
- Showed low power consumption
- Maintained accurate tracking

D. Cost-Effectiveness

Fresnel lenses and microcontrollers are affordable, providing high thermal gain without significant increases in system cost

The proposed dual-axis solar distillation system was tested under natural sunlight to evaluate improvements in thermal performance and water output. Experimental results showed that dynamic sun tracking significantly increased the usable solar energy absorbed by the system throughout the day compared to a fixed-position still. Because the alignment angle with the sun was maintained close to 0°, the tracking mechanism reduced incidence losses and improved uniform heat exposure.

Temperature measurements demonstrated that the conventional still achieved a peak chamber temperature of approximately 52–58°C, whereas the Fresnel-based tracking system consistently reached 74–82°C, resulting in higher vapor pressure and faster evaporation. The Fresnel lens provided additional thermal concentration, further increasing heat gain without additional electrical consumption.

Daily distilled water production also improved noticeably. While the traditional still produced around 1.1–1.3 liters per day, the proposed system yielded 1.4–1.8 liters, representing a 28–35% increase in output under similar environmental conditions. The tracking system operated reliably with low power consumption, and motors showed minimal positional drift during extended operation. The overall system remained mechanically stable and suitable for outdoor use.

These results confirm that integrating Fresnel optical concentration with dual-axis automation enhances evaporation rate, increases distilled water yield, and improves operational efficiency, making the system practical for rural and off-grid applications

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X. CONCLUSION

The dual-axis solar tracker with Fresnel concentration substantially improves the performance of solar water distillation systems. It enhances thermal absorption, increases evaporation rates, and delivers significantly higher daily distilled water output.

The system is:

1) Economical,
2) Low-maintenance,
3) Suitable for rural and off-grid applications.

Future improvements may include IoT-enabled monitoring, weather-resistant housing, and larger distillation surfaces for industrial use.

XI. ACKNOWLEDGMENT

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