

Performance Enhancement of Dual-Axis Solar Tracking Systems Using Pneumatic Actuation

Vinesh P¹, Tharun M², Sujan R³, Mohammed Raashidh S⁴, Dr. G. Suresh Kannan⁵

^{1,2,3,4} B. E Mechanical Engineering, Coimbatore Institute of Technology, Coimbatore, India

⁵ Associate Professor, Dept of Mechanical Engineering, Coimbatore Institute of Technology, Coimbatore, India

Abstract - Solar photovoltaic (PV) systems suffer significant efficiency losses when installed under fixed mounting conditions due to the continuous variation of solar incidence angle throughout the day. Dual-axis solar tracking systems provide a practical solution by maintaining optimal alignment between the PV surface and incoming solar radiation. This study presents the design evolution, modeling, analysis, and performance evaluation of a dual-axis solar tracking system developed through three mechanical configurations. Model I utilizes a Quad Rack Linear Elevation Tracker (QRLET) based on rack-and-pinion actuation. Model II introduces a Hinge-Assisted Rack Tilt Tracker (HARTT) enabling controlled angular motion. Model III proposes a Pneumatic Dual-Axis Solar Tracker (PDST) using four double-acting cylinders for distributed load actuation. Detailed load calculations, torque estimation, wind force modeling, and CAD-based motion simulations were conducted to validate mechanical feasibility. Energy yield comparison demonstrates a 38.2% improvement in daily energy output compared to a fixed panel configuration. Battery sizing using lithium iron phosphate (LiFePO₄) technology is also presented to ensure autonomous operation. The results indicate that pneumatic actuation offers superior angular flexibility, load distribution, and mechanical reliability for scalable solar tracking applications.

1. INTRODUCTION

1.1 Global Renewable Energy Demand

The increasing global demand for electrical energy has placed enormous pressure on conventional fossil-fuel-based power generation systems. Environmental concerns such as greenhouse gas emissions, global warming, and air pollution have accelerated the transition toward renewable energy resources. Among various renewable energy technologies, solar photovoltaic (PV) systems have emerged as one of the most promising solutions due to their modularity, scalability, and decreasing installation cost.

Despite technological advancements in PV cell materials such as monocrystalline silicon, polycrystalline silicon, and thin-film technologies, the overall system efficiency remains constrained by geometric and environmental limitations. One of the most critical parameters influencing PV performance is the angle of solar incidence.

1.2 Problem of Fixed Solar Panels

In fixed solar panel installations, the tilt angle is chosen based on geographical latitude to optimize annual energy production. However, the position of the sun continuously changes due to:

- Earth's axial tilt
- Earth's rotation
- Seasonal variation
- Solar declination shift

As a result, the angle between incoming solar radiation and the panel normal (θ) changes throughout the day. This variation directly affects the effective irradiance received by the panel.

The instantaneous power generated by a PV module can be expressed as:

$$P = A \cdot G \cdot \eta \cdot \cos(\theta)$$

Where:

P = Output power (W)

A = Surface area (m²)

G = Solar irradiance (W/m²)

η = Module efficiency

θ = Angle of incidence

As θ increases, $\cos(\theta)$ decreases, thereby reducing effective irradiance.

For example:

- At $\theta = 0^\circ$, $\cos(\theta) = 1$ (maximum power)
- At $\theta = 60^\circ$, $\cos(\theta) = 0.5$ (50% effective irradiance)

Thus, fixed systems lose substantial energy during early morning and late evening hours.

1.3 Need for Dual-Axis Tracking

Solar tracking systems are designed to maintain the panel surface perpendicular to the sun's rays. They are categorized as:

- Single-axis tracking systems
- Dual-axis tracking systems

Single-axis trackers adjust along one axis, typically east-west.

Dual-axis trackers adjust both azimuth and elevation, allowing full sun-following capability.

Research studies report energy gains of 30–40% using dual-axis systems compared to fixed panels. However, conventional motor-driven dual-axis trackers introduce mechanical and control complexities.

This study proposes a novel mechanical evolution leading to a Pneumatic Dual-Axis Solar Tracker (PDST) to enhance reliability and performance.

2. SOLAR GEOMETRY AND TRACKING THEORY

2.1 Solar Position Angles

The position of the sun relative to Earth is defined by:

- Solar declination (δ)
- Hour angle (H)
- Latitude (ϕ)
- Solar altitude angle (α)
- Solar azimuth angle (γ)

Solar altitude angle is given by:

$$\sin(\alpha) = \sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\cos(H)$$

Declination angle:

$$\delta = 23.45^\circ \sin\left(\frac{365}{300}(284+n)\right)$$

Where n = day of the year.

Hour angle:

$$H = 15^\circ(t-12)$$

Where t = solar time in hours.

These continuously varying angles justify real-time dual-axis tracking.

3. DESIGN EVOLUTION

3.1 Model I – Quad Rack Linear Elevation Tracker (QRLET)

3.1.1 Mechanical Configuration

The QRLET design employs four rack-and-pinion assemblies positioned vertically at each corner of the solar panel support frame. Each rack converts rotary motor motion into linear vertical displacement.

3.1.2 Force and Torque Analysis

Total Mass (panel + frame) = 15 kg

$$F = m \cdot g = 15 \times 9.81 = 147.15N$$

Load per rack:

$$F_{rack} = \frac{147.15}{4} = 36.79N$$

Pinion radius = 0.016 m

$$T = F \cdot r = 36.79 \times 0.016 = 0.5886Nm$$

Including 30% safety factor:

$$T_{required} \approx 0.8Nm$$

3.1.3 Limitations

- No azimuth tracking
- Synchronization complexity among four motors

- Gear backlash
- Structural misalignment under wind load



Fig -1: Quad Rack Linear Elevation Tracker

3.2 Model II – Hinge-Assisted Rack Tilt Tracker (HARTT)

3.2.1 Structural Modification

A rear hinge axis is introduced to allow tilting motion. A front rack-and-pinion assembly drives angular displacement up to $\pm 20^\circ$.

3.2.2 Moment Calculation

Distance from hinge to panel centroid = 0.5 m

$$M = W \cdot d \cdot \sin(\theta)$$

$$M = 15 \times 9.81 \times 0.5 \times \sin(20^\circ)$$

$$M \approx 25.1Nm$$

Required force at rack location (0.7 m from hinge):

$$F = \frac{25.1}{0.7} = 35.9N$$

Torque $\approx 0.75Nm$

3.2.3 Observed Issues

- Gear wear over repeated cycles
- Motor synchronization errors
- Increased control logic complexity

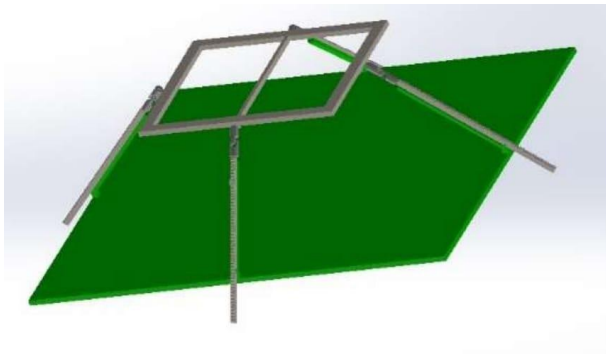


Fig -2: Hinge-Assisted Rack Tilt Tracker

3.3 Model III – Pneumatic Dual-Axis Solar Tracker (PDST)

3.3.1 System Architecture

The final design uses four double-acting pneumatic cylinders mounted at each corner of the panel frame. Selective extension and retraction produce:

- Vertical elevation
- X-axis tilt
- Y-axis tilt

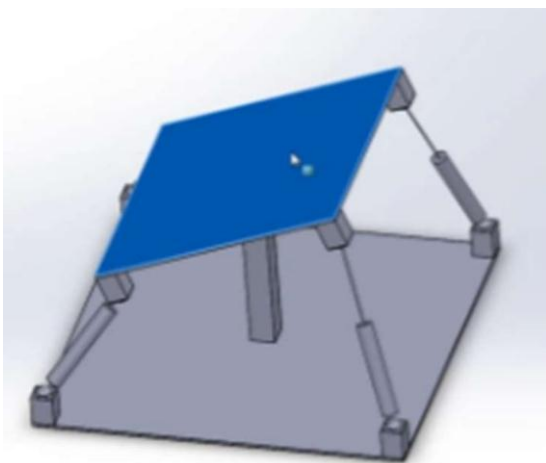


Fig -3: Pneumatic Dual-Axis Solar Tracker

4. PNEUMATIC SYSTEM ANALYSIS

4.1 Pneumatic Force Generation

Cylinder force:

$$F = P \cdot A$$

Where:

P = Pressure

A = Piston area

Design load per actuator \approx 40N

At 4 bar pressure (400 kPa):

$$A = \frac{40}{400000} = 1 \times 10^{-4} m^2$$

Cylinder diameter:

$$A = \frac{\pi d^2}{4}$$

$$d \approx 11.3 mm$$

4.2 Wind Load Analysis

Wind force equation:

$$F = 0.5 \rho V^2 A C_d$$

For:

$$\rho = 1.225 \text{ kg/m}^3$$

$$V = 10 \text{ m/s}$$

$$A = 0.245 \text{ m}^2$$

$$C_d = 1.28$$

$$F \approx 19.2 N$$

Including gust factor, maximum design load increases.

4.3 Structural Stability

Moment due to wind:

$$M = F \cdot h$$

Where h = centroid height.

Distributed pneumatic support reduces stress concentration.

5. CONTROL SYSTEM DESIGN

5.1 Open Loop Control

Astronomical algorithm-based tracking using solar position equations.

5.2 Closed Loop Control

Light Dependent Resistor (LDR) sensors detect differential illumination.

5.3 PID Control Frame work

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de}{dt}$$

Ensures smooth motion without oscillation.

6. ENERGY PERFORMANCE ANALYSIS

Fixed Panel Output = 170 Wh/day

PDST Output = 235 Wh/day

$$\text{Efficiency Gain} = \frac{235 - 170}{170} \times 100 = 38.2\%$$

7. COMPARATIVE MODEL ANALYSIS

Parameter	QRLET	HARTT	PDST
Degrees of Freedom	1	1.5	2
Actuation Type	Rack	Rack + Hinge	Pneumatic
Angular Range	Limited	±20°	Full 2DOF
Synchronization Complexity	High	Moderate	Low
Energy Improvement	Moderate	High	Very High
Maintenance	Moderate	Moderate	Low

8. BATTERY SIZING

Daily energy = 340 Wh

Autonomy = 2 days

$$Energy = 680Wh$$

Considering 80% DoD:= 850Wh

With 15% margin:= 977.5Wh

Selected battery:

12V, 100Ah LiFePO₄

Capacity = 1200 Wh

9. ECONOMIC ANALYSIS

Initial Cost Components:

- Frame fabrication
- Pneumatic cylinders
- Compressor
- Battery
- Controller

Payback period:

$$Payback = \frac{Initial\ Cost}{Annual\ Additional\ Energy\ Value}$$

10. RELIABILITY ANALYSIS

Mechanical racks suffer from:

- Tooth wear
- Lubrication dependency
- Backlash

Pneumatic systems offer:

- Fewer rotating components
- Reduced friction
- Smoother load transfer

11. FUTURE WORK

- IoT integration
- AI-based predictive tracking

- Hybrid electro-pneumatic systems

12. CONCLUSION

The Pneumatic Dual-Axis Solar Tracker (PDST) achieved a 38.2% improvement in daily energy output compared to fixed installations. Mechanical optimization through distributed pneumatic actuation significantly enhanced reliability and performance.

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