Dual-Axis Solar Tracker for Maximum Power Generation

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***Abstract*—A dual axis solar light tracker is an intelligent photovoltaic positioning system that is capable of converting sun rays directly into electricity. It is named as designed to maximize solar energy. It comprises capturing by constantly pointing solar panels at the sun. This is a project that involves design, implementation, as well as performance evaluation of a dual axis tracking system that can modify both azimuth and elevation angles in order to ensure optimum panel alignment during the day. Utilizing the property of light-dependent photoreceptors' sensors, microcontrollers-based control decisioning, and a motorized actuation system, the tracker is dynamic. The solar panels are adjusted for the different positions of the sun in order to enhance the electrical power production. These experimental results show a highly significant increase. especially with regard to the production of energy through fixed-angle solar modules. confirming the validity of the dual axis tracking technology. This is likely to enhance efficiency in the system as well as renewable energy. This is attributed to the rising utilization of trackers of this type. This study points out the potential of trackers of such a type: for application in medium- to small-scale power plants where maximum power output Generation is critical**

***Index Terms*—Dual-axis solar tracker, photovoltaic systems, maximum power generation, sun tracking, renewable energy, LDR sensors, microcontroller control, solar efficiency improvement.**

I. Introduction

One of the most developing renewable power energy forms nowadays is solar energy. Currently, in the era of rapid technological growth, it is desirable for humanity to move from fossil fuels to renewable energy forms like solar energy, driven by the need to tackle global environmental pollution, fossil fuel resource depletion, as well as increasing demands for sustainable power production. Of all renewable forms of energy, solar energy is one of the easiest forms of energy that is widely utilized. One of the factors that influence the efficiency of a photovoltaic cell is the efficiency of a solar cell to absorb the solar energy.

In fixed-angle solar panels, the panels are fixed in one position throughout the day, (In sri Lanka roof top fixed angle solars are oriented to South direction for maximum efficiency) causing a substantial loss of potential energy as the sun moves from sunrise to sunset. This is due to the tilt of the Earth's axis as it revolves around the sun. As such, there are variations in the sun's position with respect to the solar panels throughout the day and seasons. This is the major issue for improving solar power efficiency since the solar panel must be in a position that is fixed relative to the position of the sun at any given time.

A dual axis solar tracker is engineered to tackle this issue by tracking the sun's movement both horizontally, also known as azimuth, and vertically, also known as elevation. This process of constantly orienting itself helps ensure that the surface is always perpendicular to the sun's rays, thus maximizing the amount of irradiance. This is far more effective at producing energy compared to other tracking systems.

Fig. 1: Conceptual representation of a dual-axis solar tracking system.

In this project, we propose the design and development of a dual-axis solar tracking system that is intended to provide maximum utilization of solar energy throughout the day. The principal objective of developing this solar tracking system is to implement an effective and low-cost solution for tracking that can enhance the power production of small-scale solar power systems. Currently, the commercially available solar tracking systems are very costly, which creates limitations for their implementation in educational institutions, homes, or small-scale communities for renewable energy applications. Therefore, this proposed solution can provide an effective alternative for meeting this need.

This dual-axis solar tracking system is more relevant in educational institutions, laboratories, sustainable development applications, or any other area where it is imperative to work with efficiency improvement as well as affordability. Therefore, with the implementation of low-cost light sensors along with a microcontroller-based control circuit and motors, it is possible to improve the efficiency of solar harvesting.

II. Literature Review

A major driving force for research on improving the efficiency of photovoltaic energy is the growing global need for renewable energy. Despite solar energy being abundant with zero pollution, it is limited by efficiency issues that occur if fixed solar panels are employed. It is optimum for fixed photovoltaic panels to receive maximum power from the sun if they are positioned perpendicularly to the sun's rays. But since the Earth rotates around its axis, there is a tilt in the axis, resulting in a change in the sun's position with respect to the Earth's surface both daily and seasonally [1]. This implies that fixed photovoltaic panels receive energy from the sun with some cosine losses, resulting in reduced efficiency. A solution to this problem is the use of solar tracking systems.

A. Dual-Axis Tracking Mechanisms and Axis Control

Solar tracking systems can be categorized into both single axis tracking systems and dual axis tracking systems. From the two, dual axis tracking systems can track the sun in both azimuth (horizontal) and elevation (vertical) angles, such that the solar array is constantly at a right angle to the solar rays [1]. It is evident that a number of studies have found dual axis tracking systems to be more effective in energy production by a considerable margin than other systems [6].

Dual axis trackers' orientation is commonly determined by using mathematical models developed through solar geometry principles. Some of the variables involved in determining these parameters include declination angle, hour angle, angle of altitude, and azimuth angles, which are determined by time and geographic information of the area [1]. Azimuth–altitude configurations are widely adopted due to their adaptability to different geographical locations and seasonal variations [3]. Techno-economic investigations further demonstrate that dual-axis tracking systems are particularly effective in off-grid and hybrid renewable energy applications [3].

There are various patented and research designs that improve the mechanics with features such as counterbalanced systems, rotational capability, and modularity. These features are intended to enable better tracking precision, alleviate mechanical stresses, and ensure that the technical feasibility of dual-axis tracking systems is still achieved [8].

The following are types of solar tracking systems. (Both Single and Dual axis)

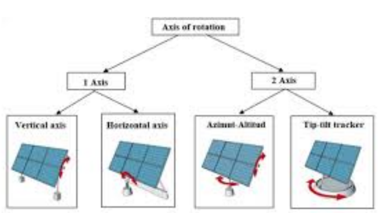


Fig. 2: Types of Solar tracking systems

B. Solar Position Sensing and Calculation Techniques

Accurately determining the position of the sun is a critical requirement for effective solar tracking. Two main approaches, as identified by the literature, are sensor-based tracking in a closed-loop manner and calculation-based tracking in an open-loop manner. [1], [2].Most sensor-based systems employ LDR or photodiode sensors for differentiation based on light intensity. The system compares outputs from sensors and recognizes the direction of maximum solar irradiance; then, it positions the panel to the direction recognized. [2]. These systems are favored due to their simplicity, low cost, and ease of implementation.

In contrast, calculation-based tracking systems rely on astronomical equations or solar position algorithms to predict the sun's trajectory throughout the day and year [1]. These systems, while potentially accurate, need accurate time and geographic information with a higher computational complexity. Some research works propose the combination of calculation-based approaches with sensor information to enhance the tracking process with cloud presence or absence, rainfall, etc. [1], [3].

C. Control Algorithms and Hardware Implementation

"Control Unit" is referred to as the major processing unit for dual axis solar tracking systems. In most of the solar tracking systems that have been documented, microcontrollers like Arduino UNO or AVR are primarily used for their low cost and universally widespread availability. [4]. Control strategies range from simple logic-based control to advanced techniques such as Proportional–Integral–Derivative (PID) control and fuzzy logic controllers implemented on embedded platforms [5].

This may be done using servo motors, stepper motors, or DC motors for actuation. For applications requiring high positional accuracy, stepper motors are favored; servo motors offer ease of control and compact implementation [3]. A typical design uses two motors-one for azimuth rotation and one for elevation adjustment-to provide accurate sun tracking throughout the day. These hardware and control combinations allow dual-axis solar tracking systems to operate reliably and continuously. [5].

D. Power Output Enhancement and Efficiency

Dual-axis solar tracking systems can significantly increase the power output of a PV array by 20-40% or more compared to fixed solar panels. This has been confirmed by numerous experimental studies and simulations. [1], [7]. Comparative analyses consistently show that dual-axis trackers outperform both fixed and single-axis systems in daily and annual energy generation [6].

In hybrid renewable energy systems, it was found that dual axis trackers are beneficial for improving the performance of the system by maximizing the contribution of photovoltaics and minimizing the need for auxiliary energy. It was revealed that optimized dual axis tracking systems help in minimizing the Levelized Cost of Energy (LCOE) and Net Present Cost (NPC) of the system in its lifetime. [3].

E. Cost-Effectiveness and Deployment Considerations

Although more effective energy-wise, dual-axis solar tracking systems still face some challenges, including cost factors. Most of the existing systems require multiple motors, complex mechanics, as well as sophisticated software or algorithms for their operations [6], [8]. These factors limit their adoption, particularly in developing countries and rural electrification projects where affordability is critical [3], [6].

To overcome these shortcomings, current literature focuses on low-cost and simpler tracker designs. These include the application of low-cost microcontrollers, LDR sensors, low-cost DC motors, and other mechanical systems that can lower the cost of the entire system [2], [8]. Innovative designs such as asymmetric or single-motor dual-axis trackers aim to balance efficiency and affordability [6].

F. Research Gap

The literature clearly demonstrates that dual-axis solar tracking systems offer superior efficiency compared to fixed and single-axis PV systems, with energy gains often exceeding 30%–40% [6]. However, there is a substantial research gap between efficiency performance and economic viability. A number of traditional dual axis trackers offer better efficiency gains, whereas their high upfront cost, complex mechanics, or maintenance issues are major obstacles to their implementation. [8]. These issues limit their suitability for small-scale and cost-sensitive applications, particularly in rural and developing regions.

Furthermore, advanced control algorithms and precise astronomical models, while improving tracking accuracy, often increase system complexity and reduce robustness in real-world conditions [4]. Although low-cost sensor-based systems have been proposed, achieving an optimal balance between efficiency, simplicity, reliability, and affordability remains a challenge [7].

G. Summary of Research Gap

According to the literature reviewed, the main demand of research on dual-axis solar trackers is to produce the maximum power with minimum cost of energy. Although it is very well-established that dual-axis trackers are superior in terms of solar energy harnessing, their utilization depends on the reduction of hardware complexity and capital and maintenance costs, thus ensuring better lifecycle economics. This project, therefore, attempts to develop an efficient, effective, and low-cost tracker that can be suitable for practical deployments.

III. Problem Statement

Solar energy is one of the most reliable and widely available forms of renewable energy. However, in traditional photovoltaic systems, fixed-position solar panels are commonly used, which makes it impossible to track the position of the sun at any time of the day. Due to the rotation of the Earth on its axis, the position of the Sun is changing over time, as a result of which fixed photovoltaic panels are tilted at non-optimal angles for a major part of the day, and then the angle of incidence between solar radiation and the photovoltaic cell surface increases, resulting in cosine losses. [2].

Although manually adjusting the orientation of the board helps improve energy output to some extent, it is very impractical, laborious, and inefficient for continuous applications. A dual-axis solar tracking system has been found in the literature to be an effective means of overcoming this problem, as it helps track the sun across both azimuth and elevation axes, ensuring that the solar panel is perpendicular to the sun for maximum power production. [1]. Numerous studies report efficiency improvements exceeding 30% compared to fixed systems.

Although they possess a proven technical advantage, some of the demerits associated with traditional two-axis solar trackers may include high capital expenditure costs, increased levels of complexity, as well as higher maintenance concerns, thus making it challenging for educational institutions within developing countries meant for rural power needs. [3], [6]. Advanced control algorithms and complex mechanical structures further increase system cost and reduce robustness.

Therefore, the core problem to be addressed in this project is that a solar tracking solution must be designed that maximizes the generation of energy with minimized system complexity and cost. In fact, there is a definite need for a dual-axis solar tracking system that must be efficient, compact, and low in cost to deliver greater performance than fixed photovoltaic panels while maintaining economic viability, reliability, and practical implementability.

IV. System Overview

Dual-axis solar tracking systems are equipped with advanced control and actuation mechanisms that enable photovoltaic panels to continuously align with the sun's position throughout the day. The proposed system employs two independently controlled rotational axes, namely the azimuth (horizontal) axis and the elevation (vertical) axis, to maximize solar energy capture. Each axis is driven by a DC motor whose motion is governed by a model-based control strategy. Instead of relying on light-dependent sensors, the system utilizes a time-based solar position reference to determine the desired panel orientation. A Model Predictive Control (MPC) algorithm is implemented to ensure accurate tracking of the reference angles while respecting actuator constraints. The controller continuously compares the desired sun position with the measured motor position and computes optimal control inputs for the motors. The system operates in a closed-loop manner, enabling smooth motion and accurate reference tracking. Simulation-based validation is carried out to analyze the dynamic behavior and performance of the tracking system. Conventional dual-axis solar tracking systems often rely on light-dependent sensors to determine the sun's position. However, under cloudy or partially overcast conditions, these sensors may produce inaccurate or unstable readings due to uneven light distribution. This can result in unnecessary motor movements, incorrect panel orientation, increased actuator power consumption, and reduced overall system efficiency. In contrast, the proposed time-based MPC approach is independent of instantaneous light intensity, allowing the tracking accuracy to remain stable even during cloudy conditions. As a result, excessive motor actuation is avoided, leading to improved energy efficiency and reduced mechanical wear.

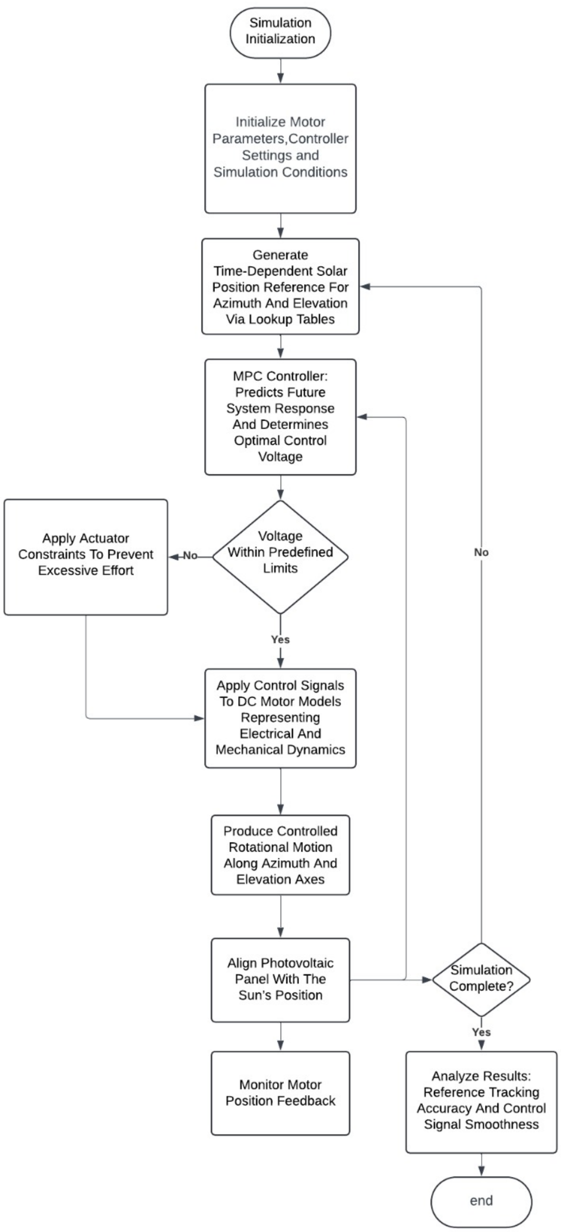


Fig. 3: Flow Chart for the Process

V. System Design

The system design begins with the initialization of motor parameters, controller settings, and simulation conditions. Each axis of the solar tracking system is modeled using a physics-based DC motor representation that captures both electrical and mechanical dynamics. The motor model is formulated in state-space form to facilitate advanced control design and predictive control implementation. Solar position reference signals for the azimuth and elevation axes are generated using time-dependent lookup tables that represent the apparent movement of the sun throughout the day. These reference angles are supplied to the MPC controller, which also receives feedback from the motor position outputs. Based on this information, the MPC algorithm predicts the future system response and determines the optimal control voltage for each motor while minimizing tracking error and control effort. The computed control signals are applied directly to the DC motor models, producing controlled rotational motion along the azimuth and elevation axes. The mechanical effects of the solar panel and mounting structure are implicitly represented through equivalent inertia and friction parameters within the motor dynamics. The system continuously monitors tracking performance and updates the control actions at each sampling instant. This design ensures precise alignment of the solar panel with the sun's position, leading to improved energy harvesting efficiency.

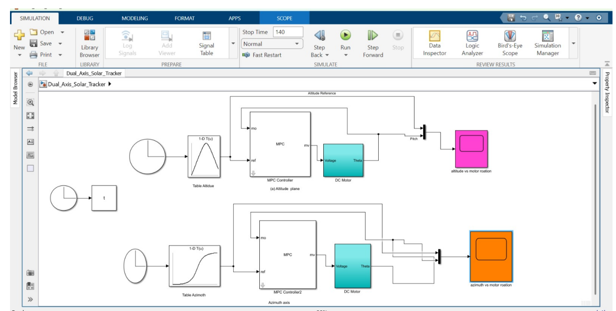


Fig. 4: Block diagram of the dual-axis solar tracking system

A. Actuation System

The actuation system consists of two DC motors responsible for driving the azimuth and elevation axes of the solar tracking mechanism. These motors provide smooth and continuous rotational motion required for precise solar tracking. In the proposed simulation model, the motors are represented using first-principle electrical and mechanical equations, incorporating parameters such as armature resistance, inductance, torque constant, back electromotive force constant, equivalent inertia, and viscous friction. This modeling approach enables an accurate representation of the actuator dynamics while remaining suitable for control-oriented analysis.

B. Control and Processing Unit

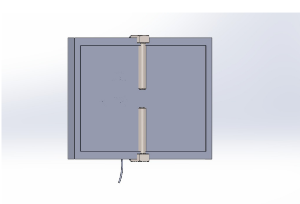
The control and processing unit is implemented using a Model Predictive Control framework within the MATLAB/Simulink environment. The MPC controller processes the reference angles and feedback signals to generate optimal motor control inputs. By predicting future system behavior over a finite horizon, the controller ensures accurate tracking, reduced overshoot, and smooth actuator operation. Key functions of the control unit include reference tracking, constraint handling, disturbance rejection, and optimization-based decision making. The use of MPC allows the system to anticipate future sun movement and adjust panel orientation proactively.

C. Motor Drive Interface

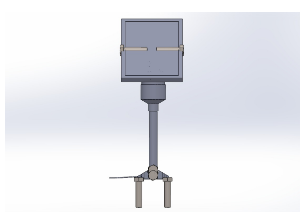
The motor drive interface represents the application of control voltage to the DC motor within the simulation environment. In this work, the drive stage is implicitly modeled by directly applying the control voltage generated by the MPC controller to the electrical subsystem of the DC motor model. The motor dynamics include armature resistance, inductance, back electromotive force, torque generation, inertia, and viscous friction, thereby capturing the essential electrical and mechanical behavior of the actuator. Voltage constraints are enforced within the MPC framework to reflect practical actuator limitations and to prevent excessive control effort.

D. Solar Panel Structure

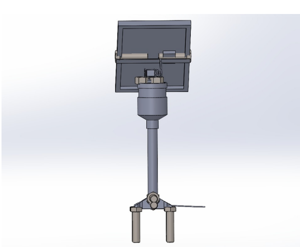
The solar panel is mechanically mounted on a dual-axis structure that allows independent rotation in horizontal and vertical directions. In the proposed simulation model, the mechanical effects of the panel and mounting structure are implicitly represented within the motor dynamics through equivalent inertia and friction parameters. This modeling approach enables the control strategy to focus on accurate orientation tracking while maintaining a realistic representation of the physical system. Such a configuration allows the panel to maintain optimal orientation with respect to the sun throughout the day, thereby improving overall energy capture compared to fixed or single-axis systems.



(a) Top View



(b) Front View



(c) Back View

(d) Side View

Fig. 5: Dual Axis Solar Tracking System (SolidWorks)

VI. MATLAB MODELS AND SIMULATION RESULTS

A. Reference Tracking Performance

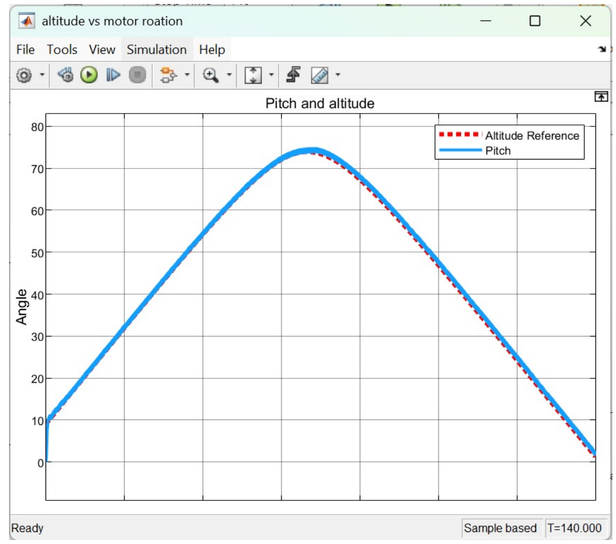


Fig. 6: Elevation (pitch) reference and motor tracking response

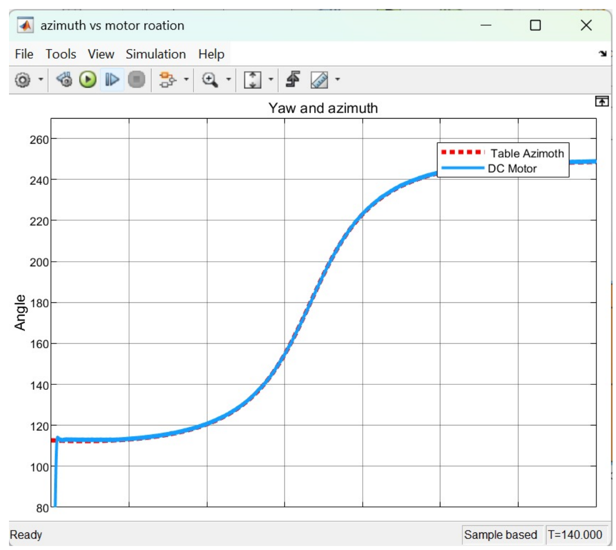


Fig. 7: Azimuth reference and motor tracking response

The MATLAB/Simulink environment is used to simulate the complete dual-axis solar tracking system. Time-based reference signals representing the sun's azimuth and elevation angles are applied to the MPC-controlled DC motor models. The reference trajectories are generated using lookup tables that emulate the apparent motion of the sun over time. The simulation results demonstrate that the proposed MPC-based control strategy is capable of accurately tracking the desired reference angles for both azimuth and elevation axes. The motor responses closely follow the reference trajectories with minimal steady-state error and smooth transient behavior, indicating effective predictive control and stable closed-loop operation.

B. Control Signal Analysis

The control voltages generated by the Model Predictive Control (MPC) algorithm are constrained within predefined limits to reflect practical actuator capabilities. Throughout the simulation, the control inputs remain within these bounds while maintaining accurate reference tracking for both azimuth and elevation axes. The smooth variation of the control signals indicates effective optimization of the control effort, preventing excessive or abrupt motor actuation. This behavior demonstrates the ability of the MPC strategy to balance tracking performance and actuator limitations, resulting in efficient and stable system operation.

C. Simulink Model Implementation

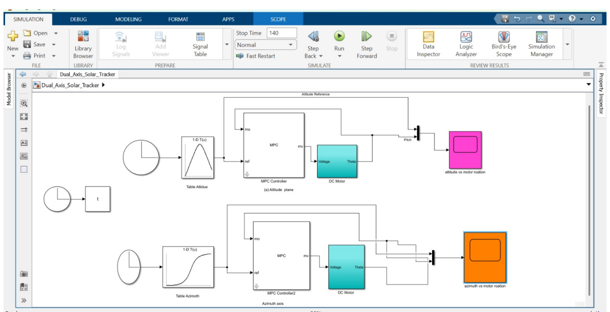


Fig. 8: Overall dual-axis Simulink model

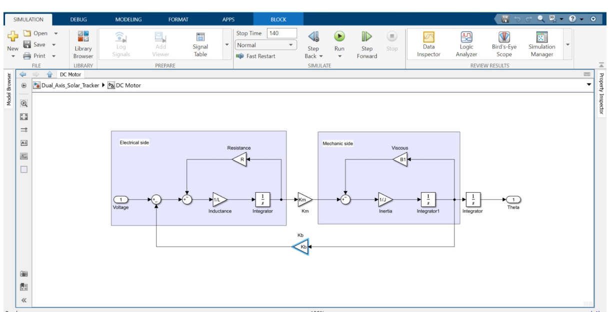


Fig. 9: DC motor electrical–mechanical subsystem

The complete dual-axis solar tracking system is implemented using MATLAB/Simulink blocks, integrating the DC motor dynamic models, time-based solar position reference generation, Model Predictive Controllers, and closed-loop feedback paths for both azimuth and elevation axes. Each subsystem is modeled independently and interconnected to form the overall tracking architecture. The modular structure of the Simulink model facilitates clear separation between the plant dynamics, control logic, and reference generation, allowing straightforward tuning, extension, and modification for further studies. This implementation approach provides an effective platform for evaluating control performance and system behavior under different operating conditions.

VII. Conclusion

This work presents a model-based dual-axis solar tracking system controlled using Model Predictive Control (MPC). The proposed approach enables accurate alignment of a photovoltaic panel with the sun's position through independent control of the azimuth and elevation axes. MATLAB/Simulink simulations demonstrate effective reference tracking, smooth motor responses, and efficient control performance under the considered operating conditions. The results indicate that MPC is a suitable control strategy for dual-axis solar tracking applications, offering improved tracking accuracy and efficient actuator usage compared to conventional control methods. Future work may incorporate hybrid sensor fusion techniques that combine time-based solar positioning with irradiance sensing to further enhance tracking performance under rapidly changing weather conditions. Additionally, hardware implementation and real-time experimental validation can be explored to assess practical performance and energy gains.

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Individual Contribution

First we need to mention we all contribute all the parts of our project but for our convenience, we appointed a leader to each section.

- **Maththegama M.R.L.S.(230401L)**- Responsible for the 3D computer-aided design (CAD) modeling of the dual-axis solar tracking system using SolidWorks. This included designing the mechanical structure, panel mounting assembly, and axis support components, ensuring proper alignment, mechanical stability, and feasibility for practical implementation.
- **Mendis T.A.S.D.(230409T)**- Led the literature review and research study, including reading and analyzing related research papers on dual-axis solar tracking and Model Predictive Control to derive suitable system concepts and design ideas. Played a key role in idea formulation and technical guidance, supporting the team during the MATLAB/Simulink simulations through constructive technical inputs. Additionally, handled the LaTeX-based documentation and final manuscript preparation, ensuring proper structuring, formatting, and compliance with IEEE publication standards.
- **MUHAMATH M.A.A.A.(230416L)**- Contributed to the design, modeling, and simulation of the dual-axis solar

tracking system. This included developing the mathematical model of the azimuth and elevation axes, implementing the control strategy in MATLAB/Simulink, and integrating the motor dynamics with the reference generation for sun-tracking. Additionally, assisted in simulation analysis, result validation, and system performance evaluation to ensure accurate tracking and improved energy harvesting.

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