Smart Solar Window System with Integrated Solar Tracking

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***Abstract*—There are significant challenges in installing conventional solar panel systems because of the lack of roof spaces and architectural constraints. In this case, we propose a smart solar window with an integrated solar tracking system. As this system would still be used for the primary purpose of providing ventilation while generating electricity, this smart window can be considered as a multi-functional component. In this system, energy generation is significantly increased compared to fixed panels as the integrated solar tracking mechanism optimizes sunlight capture. It is possible to make this system work automatically and manually. Automated control responds to environmental triggers such as rain and smoke ensuring safety and convenience while manual control enables users to have the required ventilation. This system provides a practical and feasible alternative for renewable energy integration in urban areas as this tackles the dual challenges of space limitation and energy efficiency.**

***Index Terms*—Smart solar windows, Solar tracking, Renewable energy, Ventilation**

I. Introduction

With the rapid growth of global demand for renewable energy, it is essential to have alternative solutions that can integrate smoothly into urban environments. Solar energy has a significant potential to minimize reliance on conventional energy sources. However, there are certain challenges in adopting conventional solar panels in urban areas such as rooftop space limitations, architectural confine and structural restrictions. Because of these challenges, it is difficult to acquire solar energy widely in buildings, where feasible energy solutions are crucially needed.

The smart solar window system with integrated solar tracking has been developed as a new perspective to to absorb ultraviolet and infrared light through windows and convert them into electricity while tackling the above-mentioned challenges. The primary purpose of designing windows is to provide ventilation and natural lighting for a building, but they are rarely considered for electricity generation. But this smart window system is a dual-functional window design that utilizes solar panels with existing window structure by integrating photovoltaic (PV) technology into the window surface to enable generating electricity without compromising ventilation. Hence it fulfills the requirement of a window and enables solar energy adoption where rooftops might not be able to support the use of solar panels.

Fig. 1. Solar window.

What makes this system unique is the composition of the solar tracking mechanism, which allows for a window to be adjusted at different angles throughout the day responding to real-time changes in sunlight. This mechanism enhances the energy efficiency.

This system allows users to control window openings manually or automatically to their required levels to have desired ventilation. Once the window opens for the desired level the solar tracking mechanism activates by detecting sunlight through sensors and align the window for maximum efficiency. In case of excessive smoke, smoke detectors deploy the solar window to fully open, and in case of rain, rain sensors deploy the window to close automatically.

The primary benefit of this system is improving energy efficiency while optimizing space. This allows energy production to be increased while still providing primary purpose of ventilation. This research offers a novel approach for encouraging use of renewable energy in urban areas where space is a constraint.

II. Literature Review

The evolution of solar energy system has indicated substantial improvements with solar windows and tracking systems. This system enables the optimization of electricity generation with the use of transparent photovoltaic technologies combined with a tracking mechanism. The concept of integrating solar technology into windows dates back to the mid-20th century. The early version of solar windows was static systems with embedded opaque solar cells into glass structures. However, they compromised transparency and aesthetic appeal while enabling electricity generation. With the advancement of thin film technology partially transparent solar windows were created. with the use of silicon and cadmium telluride, it was able to design semi-transparent windows with the ability to generate electricity. In the 21st century, the focus moved towards visibly transparent PVs that absorb non-visible wavelengths of light. However, the energy generation efficiency of those systems depended on the positioning of the window and the angle at which the sunlight hits the window. Due to their inability to optimize energy capture from varying sun positions, those systems had limited efficiency.

With the incorporation of tracking systems the efficiency of solar windows were increased. in earlier mechanical rotation and motors were used as tracking mechanism to have alignment of the PV cells with the sun's movement .

With the advancement of technology, the orientation of the window is dynamically adjusted with the use of sensors like light-dependent resistors and solar intensity resistors. The use of these sensors ensures energy efficiency.

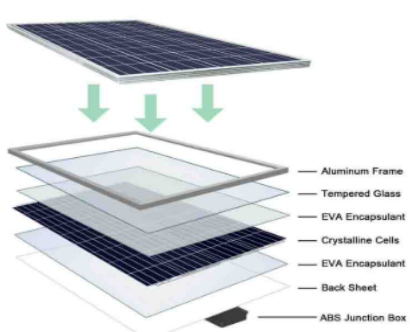

Fig. 2. Transparent Photovoltaic system.

There are two main configurations of solar windows as Transparent Photovoltaic (TPV) systems and concentrator technologies. Each category has different benefits and challenges.

Transparent photovoltaic systems enable the generation of electricity directly on the window surface. These TPV systems can be further divided as spatially segmented PV, Semi-Transparent Thin Film PV, and Transparent Thin Film PV.

Fig. 3. Semi-transparent Thin Film PV.

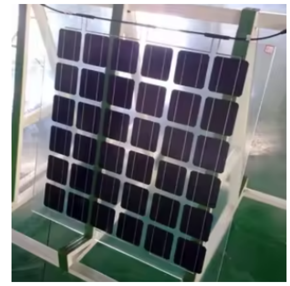

Fig. 4. Transparent Thin Film PV.

Spatially Segmented PV is a Transparent photovoltaic system that employs opaque solar cells implanted within a transparent surface. These systems compromise aesthetic appeal due to the lack of transparency while providing energy generation. These systems are primarily used in industrial applications.[1]

Semi-transparent thin film PVs are Non-wavelength Selective Thin Film Photovoltaic systems that use materials like amorphous silicon to absorb ultraviolet (UV) and infrared (IR) light while allowing partial light transmission.[1]

As these systems provide reduced solar gain without compromising visibility they are commonly used in partially tinted windows in residential and commercial settings.

Transparent Thin Film PVs are wavelength-selective photovoltaic systems designed to transmit visible light while absorbing UV and IR light. These systems use materials like polymers, nanotubes, and organic molecules to have high transparency.[1]

The tracking system increases the efficiency of solar window by aligning the window surface with sun's movements. These systems can be categorized as Single-Axis Tracking systems, Dual-Axis Tracking systems and Three-Axis Tracking systems based on the axis.

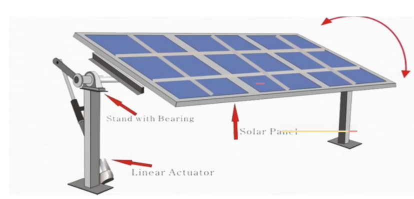

Fig. 5. Single Axis Tracking.

Single-axis trackers have one degree of freedom and they are simpler and more cost-effective making them popular in large-scale solar systems. Single-axis trackers can be further divided as Horizontal Singal Axis trackers, Vertical Single Axis trackers, Tilted single Axis trackers, and Polar Aligned Single Axis trackers depending on the axis orientation. In the Horizontal Single Axis Tracker, the axis of rotation is horizontal with respect to the ground. In Vertical single Axis tracker, the axis of rotation is vertical with respect to the ground. In Tilted single Axis tracker, the axis is inclined at an angle to the ground. The axis of Polar Aligned Single Axis tracker is aligned with the Earth's polar axis. [2]

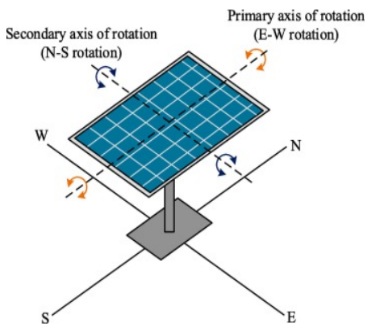

Fig. 6. Dual Axis Tracking.

Dual Axis trackers have two degree of freedom. In these trackers primary axis is the fixed one with respect to the ground and secondary axis is the one that is referenced to the primary axis. These trackers can be further categorized as Tip Tilt Dual Axis Tracker and Azimuth Altitude Dual Axis tracker. Tip Tilt Dual Axis trackers are the widely used dual tracking mechanism as they ensure maximum solar energy capture enabling adjustments in both the tilt (elevation) and tip (azimuth) directions. Even dual axis trackers are more complex and expensive their ability of maximizing energy capture make them valuable.[2]

III. Problem Statement

Traditional windows allow sunlight to illuminate and ventilate buildings but fail to harness its full potential for renewable energy generation. The integration of solar panels with windows has been explored as a means to address this limitation, yet current designs are often static, lacking the capability to track the sun's movement. This significantly reduces their energy efficiency, as solar panels perform best when optimally oriented toward sunlight. Furthermore, existing solar windows frequently compromise transparency and aesthetic appeal, making them less desirable for residential and commercial buildings. This trade-off limits their adoption, despite the growing demand for renewable energy solutions in sustainable construction.

Beyond energy generation, conventional windows also lack adaptability to dynamic environmental and user needs. They do not offer features to automatically adjust to weather conditions or emergencies, such as closing during rain to protect the interior or opening during smoke detection to provide ventilation. Additionally, manual operation remains the norm for most windows, which can be inconvenient and inefficient. The absence of scheduling capabilities further restricts their usability, as users cannot optimize window settings for ventilation, shading, or energy efficiency at different times of the day.

To overcome these challenges, this research aims to design and develop an innovative smart solar window system that integrates solar tracking technology to maximize energy output. Unlike existing solar windows, the proposed system will dynamically adjust its orientation throughout the day to align with the sun's position, significantly improving energy harvesting efficiency. This will be achieved while maintaining transparency and aesthetic appeal, ensuring the system's viability for widespread use in modern architectural designs.

In addition to energy generation, the smart solar window will feature advanced functionalities, including user-controlled opening and closing. The system will automatically close during rain to protect the interior and will fully open when smoke is detected to enhance safety during emergencies. These capabilities will be complemented by a scheduling function, enabling users to optimize the system's operation based on daily or seasonal needs.

By integrating solar tracking and smart functionalities, the proposed system offers a comprehensive solution that addresses the limitations of existing solar windows while enhancing safety, usability, and energy efficiency. This smart solar window represents a significant step forward in the adoption of renewable energy technologies and sustainable building practices, offering a versatile and innovative solution for modern homes and commercial spaces.

IV. System Overview

The smart solar window system is an innovative solution designed to enhance energy efficiency and ensure safety by automating window operations and optimizing solar energy capture. It integrates advanced sensors, precise actuators, and solar tracking mechanisms to respond adaptively to environmental changes.

The Smart Solar Tracking Window System is implemented using combining following components. A Chain Driven Actuator for opening and closing, a Rotary Motor for rotating the window, Rain Sensors to detect rainfall, Smoke Sensors to detect smoke, Light Dependent Resistors (LDRs) to continuously monitor sunlight intensity and a Microcontroller to process inputs from the sensors and controls the actuators and motor. Additionally, an Energy Storage System may be included to store solar energy. These components work together to enhance energy efficiency and prioritize safety in an automated system. The block diagram of the system is given in Figure 7.

Workflow

The system begins by monitoring smoke and rain conditions of the environment using the smoke and rain sensors. First, the system checks the smoke sensor output to ensure that

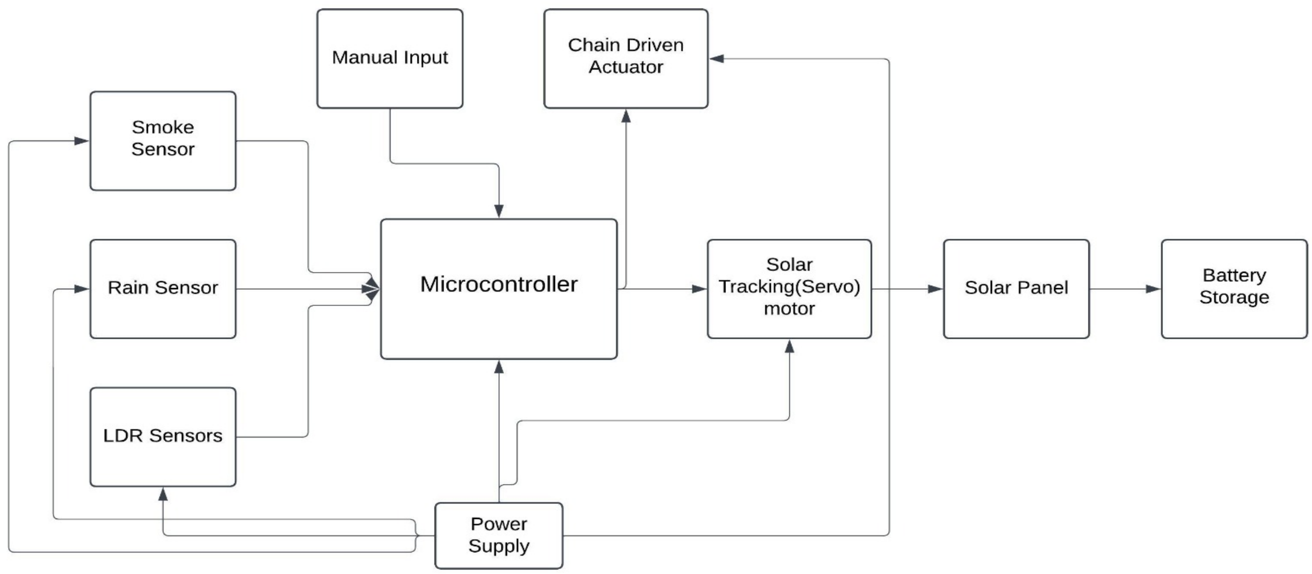

Fig. 7. System Block Diagram

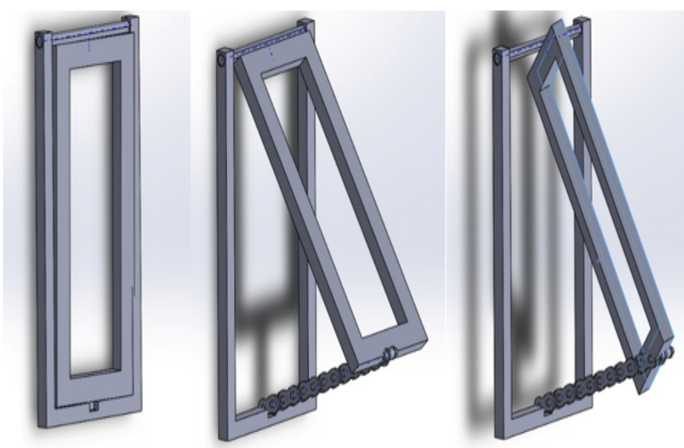

Fig. 8. Solid Works Diagrams showing Closed, Opened and Solar Tracking positions of the Window

there's no fire threat. If the smoke sensor detects smoke in the environment, it signals the microcontroller to immediately open the windows to its maximum postion. This ensures that the safety mechanisms are always prioritized.

If the smoke sensor detects no smoke, then the system checks the rain sensor to check whether it's raining. If there is rain while the window is open , the system checks whether the sun tracking motor is in its original position to ensure the window panel is correctly postioned before it is closed using the chain driven actuator.

When no safety triggers are active (smoke or rain), the system proceeds to the pre-safety-action state.

The window can be opened by the user to a preferred amount in order to get the required ventilation and light. Once the window is opened and no safety triggers are active, it starts the sun tracking process and starts generating power.

The sun tracking process involves comparing the light intensities measured by the two LDRs. If $V_1 - V_2 > V_{\text{th1}}$ (If the voltage across the left LDR exceeds the voltage across the right LDR by a value greater than the specified threshold), the motor moves right.

If $V_2 - V_1 > V_{\text{th2}}$ (If the voltage across the right LDR exceeds the voltage across the left LDR by a value greater than the specified threshold), the motor moves left.

This threshold defines the minimum difference in light intensity required to activate the motor, preventing constant minor adjustments and allowing the system to maintain a stable position unless a significant realignment is necessary.This approach not only enhances stability but also ensures energy-efficient operation.

If the voltage difference between the LDRs is below the specified threshold, the sun-tracking motor halts operation.

After each sun-tracking movement, once the sun-tracking motor stops, or after the window is closed due to rain, the system restarts by rechecking the smoke sensor output to ensure proper ventilation and safety. The window panel can be manually closed by the user at any preferred time or scheduled to close automatically at a specific time. Solar energy harvested by the system is first converted by solar panels into DC electricity, then converted to AC using an inverter, and either stored in batteries or sent to the main grid. The system ensures that energy is used efficiently to power the window's operations or any other connected devices.

The flowchart given in Figure 9 illustrates the control algorithm used for Smart Solar Window System with Integrated Solar Tracking.

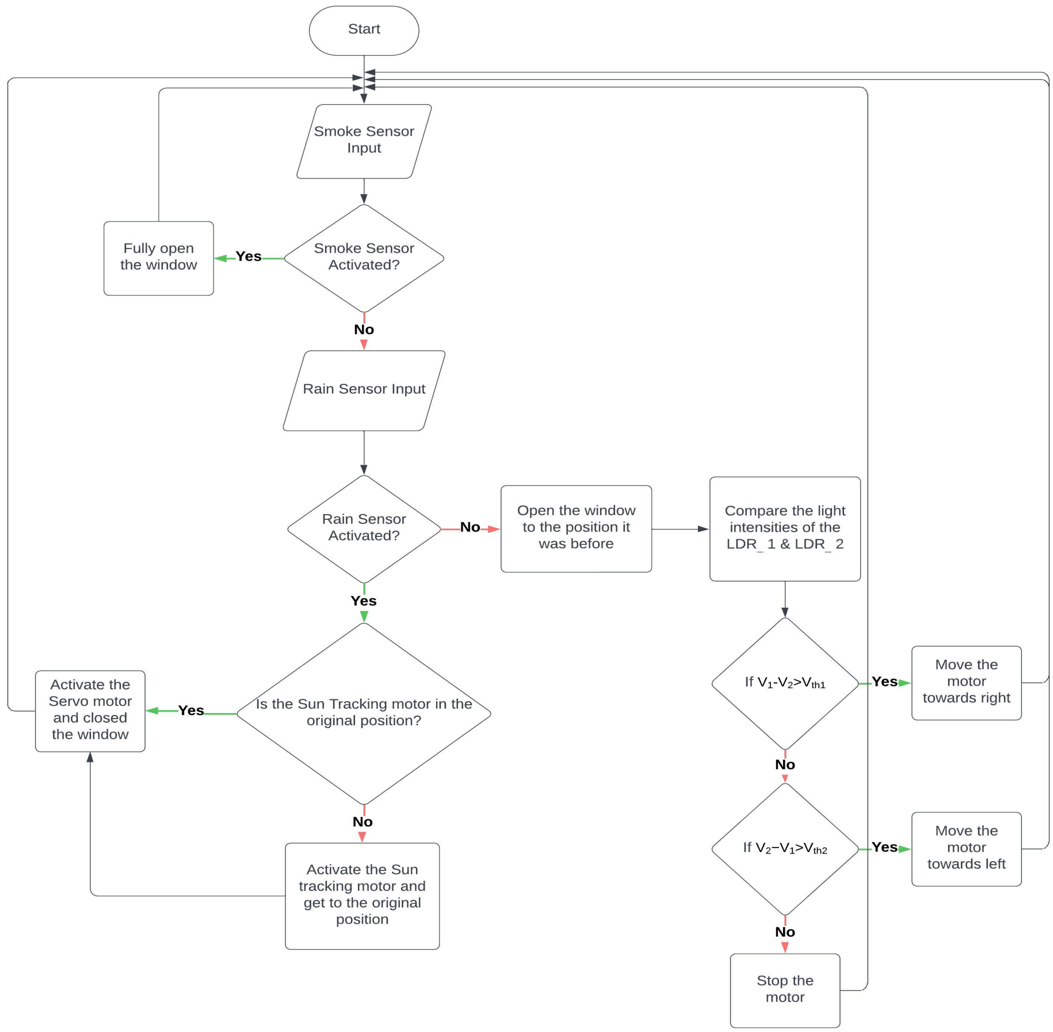

Fig. 9. Control Algorithm

V. System Design

The smart solar window system integrates various components, each playing a critical role in the practical implementation of a functional prototype.

A. Microcontrollers(ATmega328P)

The Arduino Uno microcontroller is vital in solar tracking systems, enabling enhanced energy efficiency and automation. It collects real-time data from sensors to adjust the solar panel's position based on sunlight intensity, ensuring maximum energy harvesting.The Arduino Uno allows remote monitoring and control, optimizing the system's performance while reducing the need for manual intervention. Its versatility and ease of use make it an ideal choice for implementing smart solar window functionalities.

B. Photovoltaic (PV) Solar Windows

Photovoltaic (PV) solar windows play a critical role in solar tracking systems by combining energy generation with natural

Fig. 10. Arduino Uno

lighting. Integrated with transparent or semi-transparent solar cells, they capture sunlight to produce electricity while allowing light to pass through, ensuring efficient energy utilization without compromising visibility.

C. Sensors

1) Rain sensors(YL-83 rain sensor): The YL-83 rain sensor is essential in smart window systems, enabling automatic responses to rain by detecting resistance changes when water bridges its conductive tracks. This functionality allows the smart window to close or adjust based on rainfall.

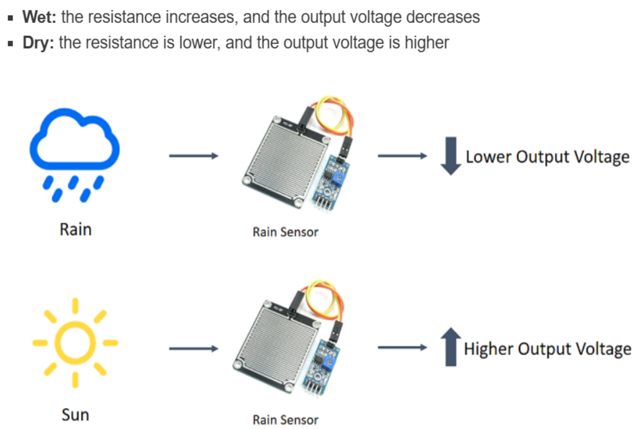

Fig. 11. Rain Sensor

2) Smoke Sensors(MQ - 2): The MQ-2 smoke sensor plays a crucial role in smart windows by detecting smoke and flammable gases through changes in electrical conductivity. Its versatility makes it ideal for fire and smoke detection in residential or commercial environments. By integrating the MQ-2 into a smart window system, it can trigger automated responses such as ventilation or window opening, ensuring safety and improving air quality when smoke is detected. This sensor's reliability and broad detection range make it an essential component for enhancing the functionality and safety of smart windows.

Fig. 12. MQ-2 Smoke Sensor

3) Light intensity Sensors: A photoresistor, also referred to as a Light-Dependent Resistor (LDR) or photoconductive cell, is a resistor whose resistance varies in response to the intensity of light it receives. Typically, the resistance of an LDR decreases as the light intensity increases. In the proposed system, the microcontroller processes the light levels detected by the LDR sensors. Based on this data, the microcontroller determines the optimal direction and adjusts the position of the solar panel to align with the highest intensity light, ensuring maximum energy capture and efficiency.

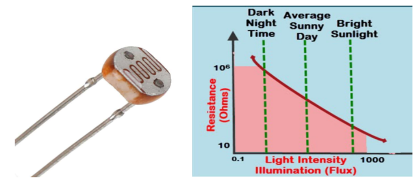

Fig. 13. LDR and Variation of Resistance with Light

4) Motors(Servo Motor): Servo motors are essential in solar tracking systems, providing precise angular control and dynamic positioning to align solar panels with the sun for optimal energy capture. They receive control signals from the microcontroller, which processes data from light intensity sensors to determine the best panel orientation. Servo motors are particularly effective due to their high torque at varying speeds, allowing the panels to adjust to the sun's movement even under load or environmental resistance. Their built-in feedback systems enable real-time corrections, ensuring continuous and accurate alignment throughout the day for maximum energy efficiency.

Fig. 14. Brushless DC (BLDC) Servo Motor

5) Chain driven actuators: Chain-driven actuators provids precise control over the window's angle and position. These actuators use a chain mechanism to adjust the window, allowing for smooth and reliable operation.Chain-driven actuators are robust, capable of handling heavy loads, and offer fine control over window movement, making them ideal for applications where precise positioning is required for both ventilation and energy optimization in smart window systems.

Fig. 15. Mingardi MICRO-S Chain actuator and its practical implementation

VI. Simulations and Results

Solar Tracking feature of the solar window

The glass of the panel of the window is made up of Transparent Photovoltaic Materials which produces solar power during the day. In the design of the solar window we have integrated a solar tracking feature to be activated once the window is opened by the user to a preferred amount. The purpose of the solar tracking feature is to maximize the production of solar power during the day time.

In order to make sure that the user gets the required amount of ventilation and the light through the window as well as to improve the efficiency of of the solar window more than a normal solar window we have implanted a Single Axis Solar Tracking System.

A Dual Axis Solar Tracking System can also be used; however, the problem is that it may limit ventilation and restrict airflow through the window while adjusting its orientation to follow the direction of the sun.

A. Methodology

One axis sun tracking systems use only two sensors , which in this case two LDRs have been used for the practical implementation of the model. The main idea is to read the value of light density from LDR_1 and LDR_2 then take the difference between the two values. Depending on the difference between the two values , the system will decide and send commands to the motor and change its angle in order to make the difference equals to zero. (LDR_1-LDR_2=0), then the light intensity on the both LDRs will be the same.This process, which enables the system to align optimally with the sun, is illustrated in the block diagram provided in the Figure 16.

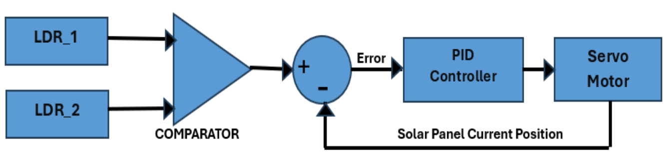

Fig. 16. Block Diagram of the solar tracking feature.

B. PID Controller

A PID controller (Proportional-Integral-Derivative controller) is a widely used control system mechanism designed to maintain a desired setpoint by minimizing the error between the setpoint and the actual process value.

Let us examine each component of the PID controller. The Proportional controller (P) offers a simple design with a quick response time but is unable to fully eliminate the error signal. The Integral controller (I) is effective for systems with slow-changing dynamics and can correct the error signal, although it is less suited for rapidly changing systems. The Derivative controller (D), while unable to correct the error signal and prone to amplifying noise, is ideal for fast-changing systems that require a rapid response.

In the context of solar tracking, a PI controller is sufficient as the sun's movement across the sky is slow and predictable. The proportional component (P) ensures a quick response to any misalignment, while the integral component (I) gradually eliminates any steady-state error, ensuring precise alignment over time. Since the sun's position does not change rapidly, the derivative component (D), which is designed to handle fast-changing dynamics, is not necessary. This simplifies the control system while maintaining efficient and accurate tracking performance.

The PI controller used in this system was tuned with a proportional gain of 240 and an integral gain of 180. These parameters were selected to achieve an optimal balance between response speed and steady-state accuracy. The chosen values ensure that the system can quickly reduce misalignment while effectively eliminating any residual error, enabling precise and stable solar tracking performance.

C. Simulating the panel motion

The simulation was conducted to verify the correctness of the panel's motion in response to the torque input from the motor. By using the panel's equation of motion given in Figure 17 and applying constant torque values, the simulation focused on ensuring that the panel's rotation aligns with the expected direction based on the sign of the input torque.

$$\frac{d^2\theta}{dt^2} = \frac{1}{J}\left(T - K_d \frac{d\theta}{dt}\right)$$

Fig. 17. Panel equation of motion

With a constant torque the panel starts turning and then settles to rotating at a fixed rate. When the sign of the constant torque is negative the panel rotates in the opposite direction.This can be seen as the angle of rotation increases and the velocity is slowly reaching a constant value.

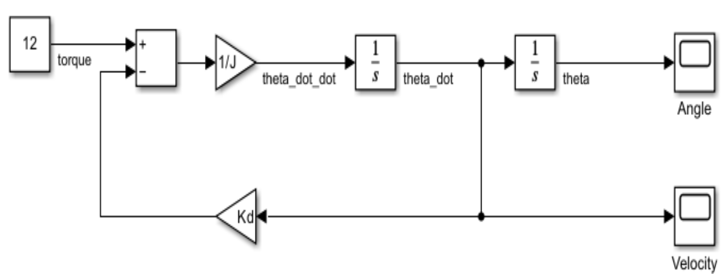

Fig. 18. Simulink Model for the Panel Equation

Simulations were done using the simulink model provided in Figure 18 and the variations of the Angle and the Velocity of the Panel were taken as observations.

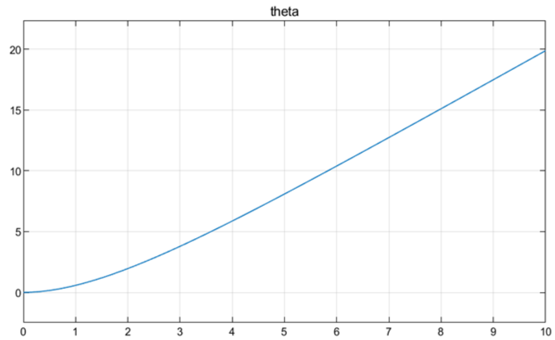

Fig. 19. Variation of Panel Angle with time

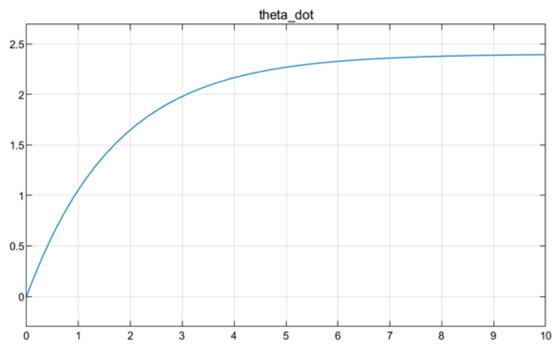

Fig. 20. Variation of Panel Velocity with time

D. Overall Solar Tracking System Simulations

In the simulation, instead of using the two LDRs and a comparator to detect the light intensity difference, a unit step function has been used to simulate a sudden change in the sun's position. This unit step function represents the difference in light intensity that would typically be detected by the LDRs as the sun moves. Figure 21 shows how the panel postion alongs with the sun's position to maximize the power generation.

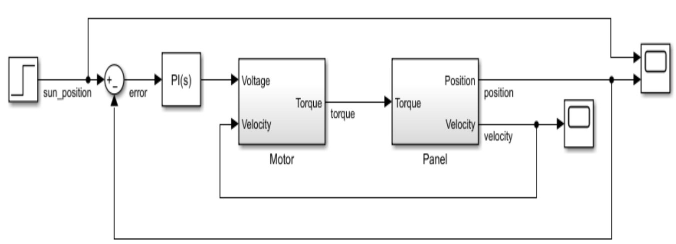

Fig. 21. Simulink model for Single Axis Solar Tracking Simulation

By using this simplification, the simulation focuses on evaluating the system's response to a discrete shift in light intensity, allowing the control mechanism to adjust the solar panel's position accordingly.

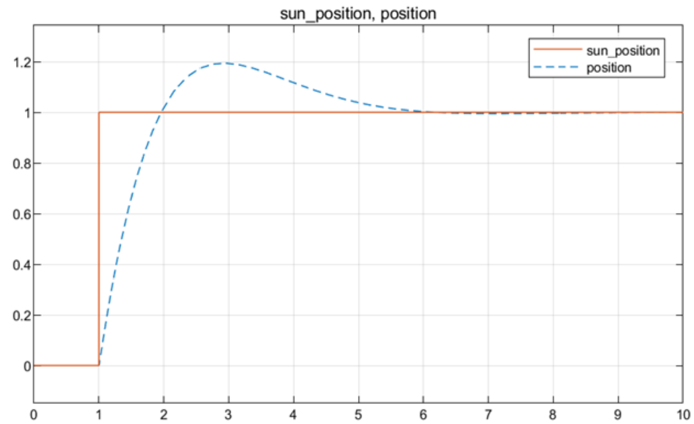

Fig. 22. Alignment of the Panel Position with the Sun's Movement

VII. Conclusion

The Smart Solar Window System presents a novel approach to enhancing energy efficiency and safety through automated window operations integrated with solar energy optimization. By utilizing advanced sensors, precise actuators, and solar tracking mechanisms, the system ensures adaptive responses to environmental changes, prioritizing safety during smoke or rain events while maximizing sunlight capture for energy harvesting. The integration of an energy storage system further supports sustainable energy utilization, enabling the system to operate efficiently and autonomously.

Despite its promising capabilities, the system has certain limitations. The reliance on environmental conditions, such as consistent sunlight for optimal solar energy capture, and potential delays in response due to sensor or actuator constraints may affect performance in adverse conditions. Additionally, the cost and complexity of implementing and maintaining the system could pose challenges for large-scale adoption.

For future enhancements, we aim to implement a dual-axis solar window system that not only improves solar tracking but also considers ventilation needs. By incorporating user preferences and environmental data, the system can dynamically adjust to determine the most efficient angles for ventilation and solar energy optimization. This advancement would further enhance the system's adaptability and energy efficiency, addressing the limitations of the current design while expanding its practical applications.

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