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Original Article

Optimizing Solar Car Performance: GPS-Enhanced Dual-Axis Precision and Single-Axis Southward Orientation in Solar Tracking Solutions

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Abstract - *Designing solar vehicles is a challenging task from an engineering point of view, mainly because of the small surface area for the installation of photovoltaic (PV) panels, which both limits energy absorption and the efficiency of its conversion. The paper suggests simulating a dual-axis solar tracker for a solar vehicle in MATLAB/Simulink to analyze its performance on a specific route with frequent orientation changes of the vehicle. Another method is investigated, in which the photovoltaic array continuously orients itself to face the true south regardless of the vehicle's direction. The research also explores the feasibility of the suggested designs in optimizing electrical power generation. This includes examining the impact of dynamic tilt angle control and introducing aerodynamics considerations to negate the adverse effects of severe operating conditions, including airflow resistance. Both tracking systems are intended to integrate real-time GPS information to facilitate precise orientation control and system response.*

Keywords - *Tracking, Photovoltaic, Renewable, Energy, Vehicle.*

1. Introduction

According to statistics available from various countries around the world, it is clear that the transportation sector represents between 25% and 40% of global energy consumption, which is a high percentage. There exists an urgent and compelling necessity to transition towards sustainable alternatives to conventional forms of fuel, a heavy reliance influenced by a complex interplay of factors such as varying economic development levels, population sizes, and diverse geographical characteristics. Fossil fuel depletion, coupled with their volatility and harmful impacts on the environment, only works to highlight the exigency of diversifying into other alternative sources of transportation energy. Among these options is renewable energy; solar energy has become a viable and ecologically friendly option [1, 2].

As manufacturers progressively include solar energy technologies into their products, electric cars have become quite popular and are a significant move towards sustainability. Though they usually need grid power, which is mostly produced from traditional non-renewable sources, electric cars (EVs) cut reliance on fossil fuels. This raises a fundamental question: How can the transportation industry break free from its dependence on fossil fuels and operate entirely on renewable energy?

Hybrid automobiles are a temporary solution until solar cars are developed, which have the potential to replace petroleum fuels with renewable energy. A fully constructed solar car may be a giant leap towards a green future. Petroleum fuels are a problem for modern cars and the transportation industry because of their availability, potential depletion, and persistent price fluctuation. The same is true of electricity and its costs; laws controlling the energy used by electric vehicles may be imposed if conventional fuel prices rise. Energy rates for charging electric vehicles are expected to be changed. Accelerating the development of solar cars and their related technologies is essential to address the practical challenges that hinder their widespread adoption. This will provide a more sustainable and stable transportation energy source. Hence, it became necessary to continue researching and developing solar car technology and solutions to efficiency issues.

Although fully solar-powered vehicles do not yet exist, hybrid vehicles, such as electric vehicles augmented with solar panels, are now becoming available. These systems provide intermittent renewable energy but still require grid-based power to charge. The primary aim of this study is to go beyond hybrid technology and make fully solar-powered vehicles independent of the power grid. One potential remedy for this problem is solar-powered cars.

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Although the idea has advanced to the prototype stage, many technical and performance-related problems still exist. Current solar vehicle designs often give lightweight materials and minimal seating top priority in order to maximize energy efficiency; yet, they still have to focus on attaining the efficiency needed for mass-market acceptance. Furthermore, the small space available for solar cells on cars results in limitations in energy harvesting, making it challenging to run the car entirely on solar power [3].

These vehicles are still in the prototype stage and require additional work to reach the required level of effectiveness and affordability in today's motor vehicle market. Despite ongoing efforts from automakers and research institutions, these vehicles are not yet viable for the commercial market. Research is now concentrating on correcting these deficiencies so that solar cars can compete with conventional and electric cars.

Many solar car concepts and designs currently being explored tend to be inefficient and offer very limited space for passengers. Realistically, most solar-powered cars are still experimental; they need much improvement and updating before they are ready for the market.

Solar car engineers give top priority to lightweight materials and fewer seats to save weight and energy while travelling. Though the cars are aerodynamically designed to increase movement efficiency and lower wind resistance, these qualities are still inadequate for practical use since cars still lack the efficiency required to run only on solar power. The aim of this project is to make solar cars more efficient by streamlining key components and systems, particularly the incorporation of advanced solar cells and improved energy management [4].

Advancements in solar car technologies cover a wide array of innovations, including enhanced photovoltaic (PV) panels, cutting-edge energy storage solutions, high-efficiency battery charging systems, advanced electric motors, refined suspension and transmission systems, integration with Internet of Things (IoT) technologies, smart cruise control features, and the use of intelligent sensors. This study seeks to make a contribution to these innovations by optimizing solar cell performance specifically and exploring new energy management strategies to improve overall system efficiency and sustainability.

A solar electric vehicle usually comprises a number of interlinked subsystems such as electric motors, suspension, navigation, battery storage, a charging system, and solar panels for energy generation. While global research has focused on improving these elements, this project aims to integrate these advancements into a single, efficient system that can function solely on solar power, addressing energy efficiency and transportation sustainability [5].

The primary focus is to improve solar cell efficiency, which remains the system's most critical and underperforming element. Currently available PV technology cannot generate enough electricity to keep a car running without grid-based recharging or external fuel. This research aims to increase solar cell efficiency so that cars can run entirely on solar power, eliminating the need for external recharging.

Solar cells are the key component in solar vehicle technology, converting sunlight into usable energy. However, a limited area outside the vehicle may be utilized to disperse solar cells. Any increase in cell area typically causes a significant rise in weight, which in turn reduces efficiency and performance.

In an attempt to eliminate these limitations, companies have incorporated rechargeable battery systems in a bid to increase the driving range. Although this system maximizes car independence, it concurrently adds extra weight and takes more time to charge, consequently lowering the prospect for complete solar charging [6].

Although solar tracking systems are known to significantly improve efficiency by more than 30% in some stationary solar power applications, adapting them effectively for use in solar cars presents unique challenges. The main difficulties stem from cars frequently changing direction, maintaining aerodynamic designs to minimize drag, and incorporating tracking mechanisms, which can increase air resistance.

Under ideal conditions, solar-powered vehicles have demonstrated the ability to travel significant distances. However, environmental factors like solar irradiance and the intrinsic limitations of existing photovoltaic technologies significantly impact their operational efficiency. By advancing solar cell technology and energy storage options, the research seeks to get around these restrictions and enable solar vehicles to operate reliably in a range of scenarios. Figure 1 displays a road trip that lasted more than ten hours without a break. The journey portrayed in the image begins at sunrise and concludes at dusk, equivalent to a typical December winter day.

System efficiency in solar-powered vehicles, as with all engineered systems, is determined by the performance of individual components and their integration into a cohesive framework. Every component, from the mechanical systems and power management to the solar panels and energy storage units, must be optimized for optimal performance using a comprehensive design approach.

In order to develop a more durable, dependable, and sustainable mode of transportation, the current study focuses on the inefficiencies related to solar energy conversion and storage.

Fig. 1 Example of a continuous 10-hour solar-powered road trip

2. Methodology

This research focuses on boosting the solar cells' efficiency without making the panels physically larger, using innovative designs to get the most energy from the available area. Making the panels bigger would lead to heavier, bulkier cars that could hinder traffic and cause problems on the road. The study aims to overcome these issues to help make solar-powered vehicles a more practical reality. Two designs have been suggested, one utilize a novel design that features an integrated sun-tracking capability in order to pinpoint the precise position of the sun and avoid its posing an obstacle on the course of the automobile, The Global Positioning System (GPS), highly developed satellite navigation system, will be employed for precise guidance as well as energy harvesting. [7] The second design being considered involves a single-axis solar tracking system.

This system keeps the solar panels oriented in a fixed way, separate from the car's direction of travel. This approach helps reduce complexity and weight because it avoids the need for extra mechanisms or bulky structural parts, unlike some other designs. Electronic sensors keep track of the car's path and adjust the panels as needed through a simple closed-loop control system. To gauge how well the proposed designs perform, we will compare the electricity generated by the solar cells in the vehicle using these new designs against current setups, ensuring we use the same number of cells for a fair comparison. Additionally, we can use a simulated driving route that includes frequent turns to see how the energy output differs between the systems. This helps illustrate how factors like the car's changing position and environmental conditions, such as the season or time of day, impact the tracking system's effectiveness. When evaluating a new design, it is crucial to consider various elements that might impact solar cell efficiency. To eliminate seasonal changes, both designs must have constant departure times and dates. Avoid barriers like buildings, trees, or dust that might obscure sunlight. Clouds' influence on sunlight must be minimized. To accurately compare conventional and proposed designs, consider all relevant elements that can affect comparisons.

3. Tracking Systems

The main goal of a solar tracking system is always to keep the panels angled optimally towards the sun, ideally as close to perpendicular as possible. Adding the mechanisms needed to do this usually makes the system more complex and expensive. However, the significant efficiency gains often outweigh these costs, making the investment worthwhile. Research has demonstrated that solar tracking systems can substantially increase the power output from solar cells, justifying the added expense [8]. A number of solar energy collection system configurations have been investigated in the literature, including comparative studies contrasting the efficiency of tracking systems. Although performance results can be site-specific and dependent on operating conditions, the consensus in the literature is clear: Dual-axis tracking systems produce the greatest energy gains, while flat-panel arrays produce the least. Dual-axis tracking systems are efficiently followed by single-axis tracking systems and fixed-tilt mounts [9].

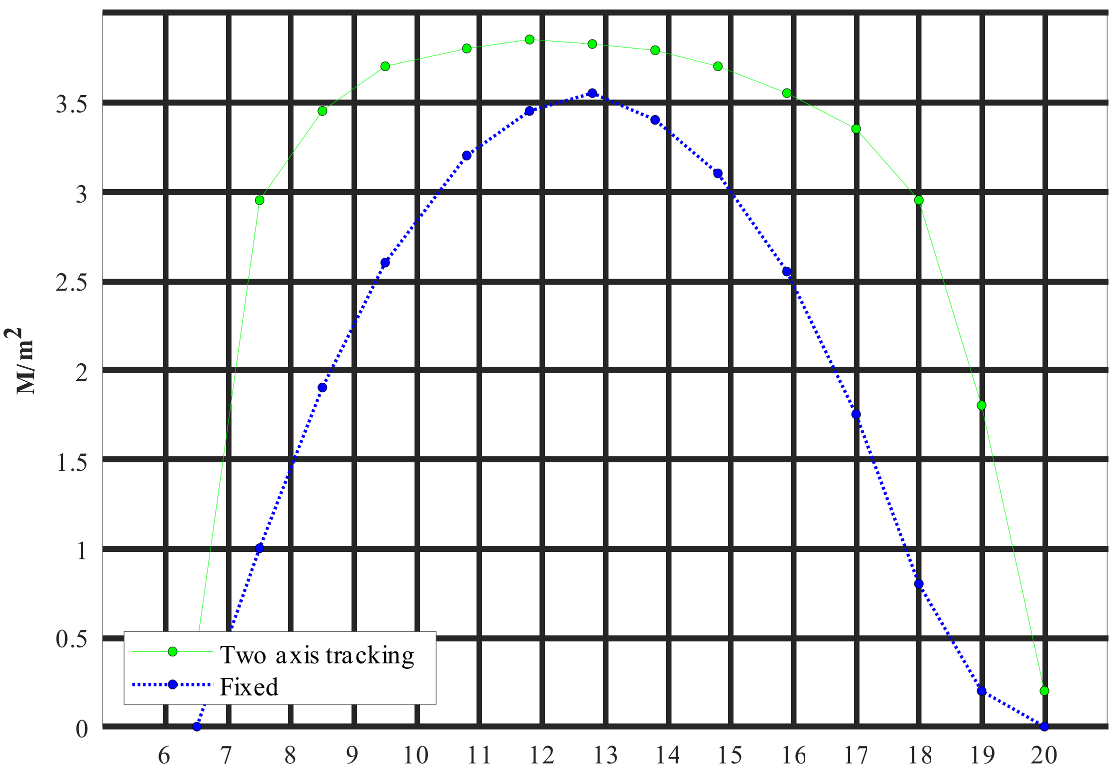


Fig. 2 Comparison of energy output from fixed-panel and dual-axis tracking systems [9]

As illustrated in Figure 2, dual-axis tracking systems have a clear superiority over fixed-panel systems in energy generation. This indicates the ability of tracking technologies to enhance overall system efficiency.

Figure 3 also illustrates the drastic effect of tilt angle and orientation on the energy collection efficiency. The graph indicates that deviation from ideal orientation and tilt produces low energy harvesting, a drawback especially pronounced in systems lacking active tracking capability. When there are no dynamic adjustments for panel position, it is hard to ensure optimum alignment, especially in mobile systems such as solar-powered vehicles.

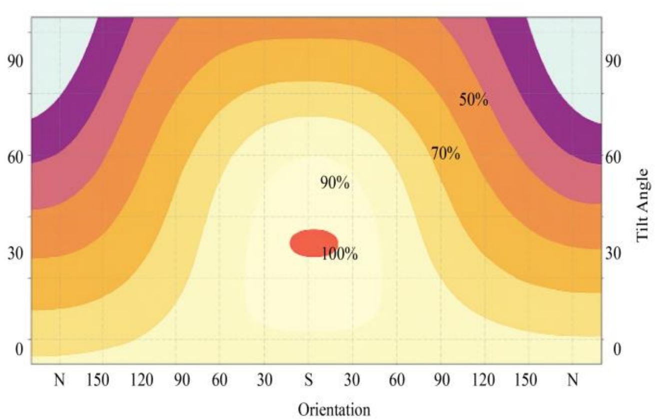


Fig. 3 Solar energy collection as a function of tilt angle and array orientation [10]

The solar tracking systems, whether single-axis or dual-axis, have demonstrated a commendable enhancement in the efficiency of solar energy collection. The ability of these systems to continuously alter the orientation of panels in accordance with the sun's position enables considerable enhancement in overall performance, especially in environments where the availability of the sun varies. As such, integrating similar tracking technologies is unavoidable in bringing out the best in solar energy systems, both in fixed and mobile applications.

4. Two Proposed Designs

Empirical observations from the application of solar energy show that tracking systems have the potential to improve photovoltaic efficiency by as much as 30%. The argument is that the same degree of improvement in efficiency is possible with the adoption of these tracking technologies in solar vehicles.

The system designs proposed tackle significant issues such as changes in vehicle orientation, aerodynamic optimization, and reduction of air resistance, while seeking to optimize solar irradiance capture. These advancements are expected to greatly enhance the efficiency of the system overall and enable realistic implementation. One unique feature of the proposed designs is their ability to maximize solar energy collection without increasing the panel surface area. This maximization is achieved through strategic orientation and tracking mechanisms, which allow the existing panel size to collect greater amounts of solar energy.

4.1. The First Design: GPS-Based Dual-Axis Tracking

The first proposed system incorporates a two-axis sun-tracking system based on GPS data to optimize solar energy collection while maintaining the integrity of the vehicle's operation. The photovoltaic panels are encapsulated in a clear, low-drag material (e.g., glass) that optimizes sunlight penetration while ensuring aerodynamic performance. Enhanced solar energy conversion efficiency could potentially enable the reduction of battery capacity or even the elimination of external infrastructure charging.

This system is made up of a segmented solar panel arrangement with the entire array divided into smaller, individually adjustable sections. Each section includes its actuation system to achieve dynamic orientation without significantly affecting vehicle aerodynamics or stability.

A centralized controller exists for controlling the tracking of each section of panels. Previous work has established that movement of rigid, large solar panels adversely affects the vehicle's handling; hence, the segmented design reduces this risk. To reduce drag, the solar modules are encased in a transparent housing. The design considers air permeability and features provisions for the potential integration of cooling systems intended to mitigate potential overheating.

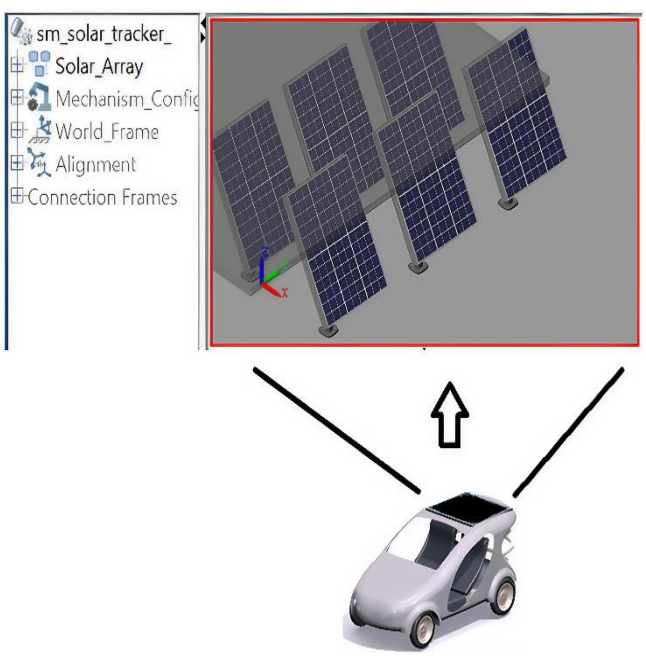


Fig. 4 MATLAB simulation of the mechanical tracking mechanism, built using Simulink worm and gear constraint block

Figure 4 is a MATLAB simulation of the mechanical tracking mechanism of the proposed design, built using Simulink Worm and Gear Constraint Block. A representative flowchart of the control system is given in Figure 5, outlining the steps involved in acquiring GPS data and determining the altitude and solar azimuth angles. The system regularly updates these parameters at fixed intervals to support the vehicle's movement. The GPS unit provides raw, machine-readable binary data. This data must be translated into usable latitude, longitude, and altitude coordinates. You can see an example of how GPS data is retrieved in Figure 6.

Using the vehicle's latitude and longitude, the MATLAB code calculates the sun's azimuth and elevation angles. The azimuth angle refers to the direction of the sun's compass (bearing from north) along the horizon. The angle between the horizon and the sun is the solar altitude angle. Figure 7 illustrates both the elevation and azimuth angles in this context.

To figure out the sun's azimuth and elevation angles, you need the current time and date, along with the vehicle's latitude and longitude. The MATLAB code handles this by first calculating the local solar time (LST). It does this by using the local time (LT) term, which is taken from the GPS and adding a time correction factor (TC), as shown in equation (1).

$$LST = LT + \frac{TC}{60} \tag{1}$$

To calculate the time correction factor (TC), Equation (2) is applied. This formula incorporates the vehicle's GPS-determined longitude, subtracts the standard meridian's longitude (LSTM), and adds the equation of time (EoT):

$$TC = 4 \times (Longitude - LSTM) + EoT \tag{2}$$

The longitude of the standard meridian (LSTM) is computed using Equation (3):

$$LSTM = 15^{\circ} \times \Delta T\_GMT \tag{3}$$

Equation (4) provides the expression used to determine EoT:

$$EoT = 9.87 \sin(2B) - 7.53 \cos(B) - 1.5 \sin(B) \tag{4}$$

In this context, the difference between Greenwich Mean Time (GMT) and local time (LT), expressed as (ΔT_GMT), is essential for determining LSTM.

To compute the variable B in Equation (4), Equation (5) is used, where d represents the count of days since the beginning of the year:

$$B = \left(\frac{360}{365}\right) \times (d - 81) \tag{5}$$

Next, the degrees that the sun traverses across the sky, or the Hour Angle (HRA), is then computed by equation (6).

$$HRA = 15^{\circ} \times (LST - 12) \tag{6}$$

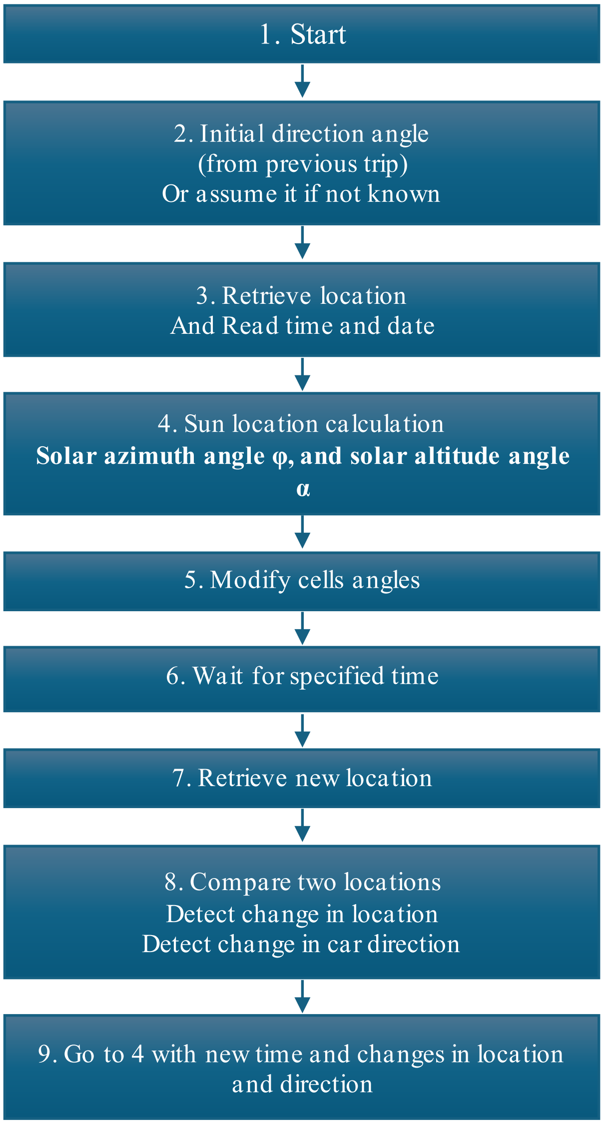


Fig. 5 Flowchart for the proposed GPS-based control system

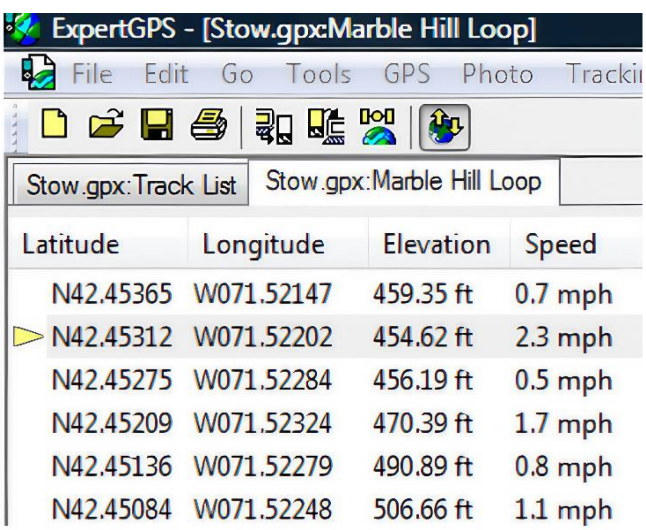


Fig. 6 Sample screen of GPS data retrieval

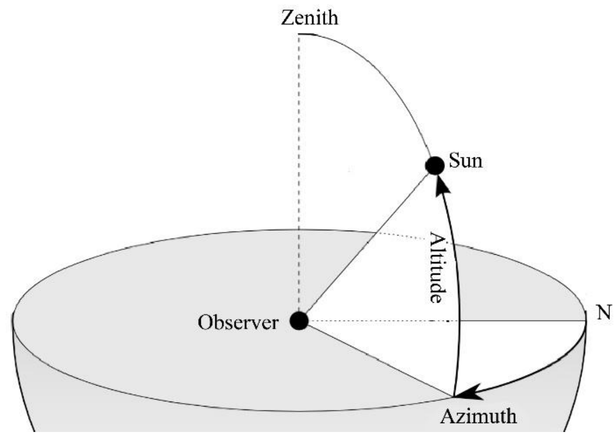


Fig. 7 Angles of azimuth and height of the sun

4.2. The Second Design: For Maintaining Southward Orientation: A Single-Axis Solar Tracker System

Equation (7) can be used to calculate the declination angle (δ), with (d) representing the number of days since the start of the year.

$$\delta = 23.45^{\circ} \sin\left(\frac{360}{365}(d - 81)\right) \quad (7)$$

To calculate altitude (α) and azimuth angles, use equations (8) and (9), respectively:

$$\propto = \sin^{-1}(\sin\delta \, . \sin\varphi \, + \, \cos\delta \, . \cos\varphi \, . \cos(HRA)) \quad (8)$$

$$Azimuth = \cos^{-1}\left(\frac{\sin\delta . \cos\varphi - \cos\delta . \sin\varphi . \cos(HRA)}{\cos\propto}\right) \quad (9)$$

Where (φ) represents the vehicle's latitude [11].

The second design proposes a simplified single-axis solar tracking system with a stationary south-facing direction. This setup is particularly advantageous in the northern hemisphere, where the sun travels east to west through the southern sky, allowing continuous solar exposure throughout the day.

Like the first, this design incorporates a clear protective cover permitting full solar penetration and reducing aerodynamic drag. Enhanced energy harvesting per cell may allow reductions in battery size or full solar autonomy.

The panel in this configuration is divided into a number of small pieces, and each piece is mounted on a fixed, tilt-adjustable rotating platform. Each piece rotates about a single axis to permit south alignment. This particular design, as opposed to a two-axis system, does not need real-time location data, GPS information, or temporal processing, which means the system is less complicated and cheaper.

This approach divides the main solar panel into smaller sections or cells, like the earlier design. The proposed design operates in two stages. Initially, the emphasis is placed on safeguarding the solar cells by implementing an appropriate motion mechanism. This involves dividing the primary panel into smaller sections, each positioned at a fixed angle, and incorporating a pivot system to enable rotational movement. Dividing the board this way makes it easier to adjust the orientation of these smaller cells. What sets this second design apart is its use of a single axis for rotation control combined with a fixed tilt angle, simplifying the overall system. A single control system manages the rotation axis for all cells, ensuring they consistently face the desired direction (like south). Figure 4 shows an example of this proposed design, created using MATLAB with the Gear Constraint Block and Worm Toolbox from Simulink.

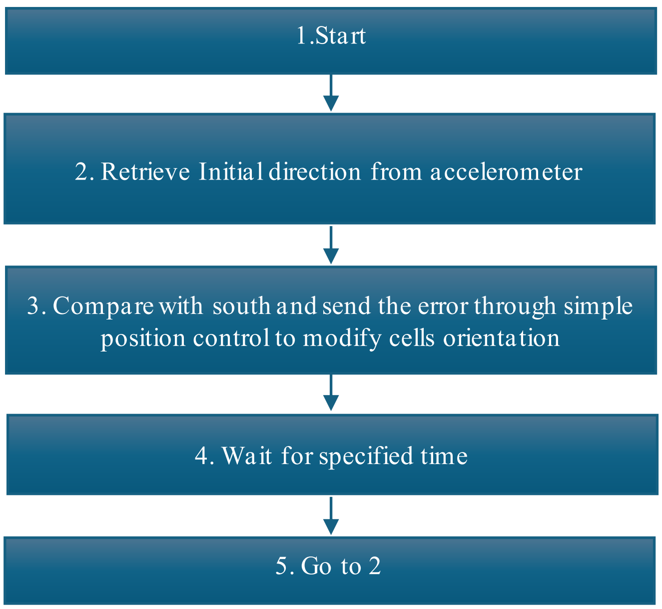
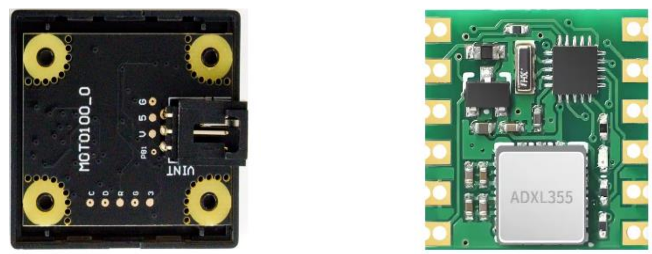


Fig. 8 Proposed control system flowchart

The control system's stages are illustrated in the flowchart in Figure 8, highlighting the need for an accelerometer to detect directional shifts. Several affordable accelerometers are available, with examples shown in Figure 9. The accelerometer provides data on direction changes in the x, y, and z axes. The system uses this information to compare the x and y directions to the desired southward orientation, adjusting the cells' alignment accordingly.

Within MATLAB's Simulink environment, angle correction was simulated using a position control model. A waiting period based on iteration was introduced to identify directional changes in the vehicle. Figure 10 displays the corresponding block diagram of this control setup. Unlike dual-axis tracking configurations, this second design adopts a fixed tilt angle, making the system simpler and less complex. This eliminates the need for time, date, and position data (such as latitude and longitude), and instead, a preset southward direction is used throughout the trip, avoiding the need for GPS. This approach reduces complexity and is more practical than dual-axis systems, requiring more components and calculations.



(a) (b)

Fig. 9 displays examples of commercially available accelerometer models: (a) the Phidget 3-Axis Accelerometer [12], and (b) the Witmotion BWT61 Accelerometer [13].

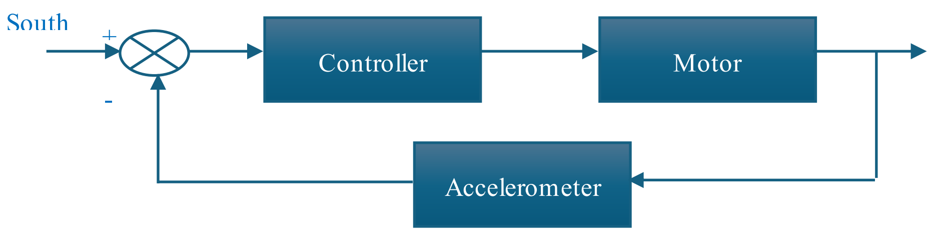


Fig. 10 illustrates the schematic representation of the position control system

5. Results

As indicated in Figure 1, the simulation above consisted of many direction changes along the vehicle's route. A simpler journey was established to reduce the simulation and facilitate ease of understanding, as seen in Figure 11. The modified trip starts at point A and concludes at point D, comprising three different travel routes. The initial part (A–B) spans about 214 kilometres and is completed in a time interval of two hours. The second section (B–C) is the same length, 140 kilometres, and also requires the same time.

The final section (C–D) is the longest at 416 kilometres and lasts approximately six hours. Simulation outcome for the suggested GPS-assisted dual-axis tracking system for two different control response times is indicated in Figure 12. The outcomes validate that the longer the delay in changing the panel orientation, the sharper and more instantaneous the tracking response, whereas the tracking response is smoother for a shorter delay. A shorter delay, however, elevates the power consumption because the tracking system adjusts more frequently.

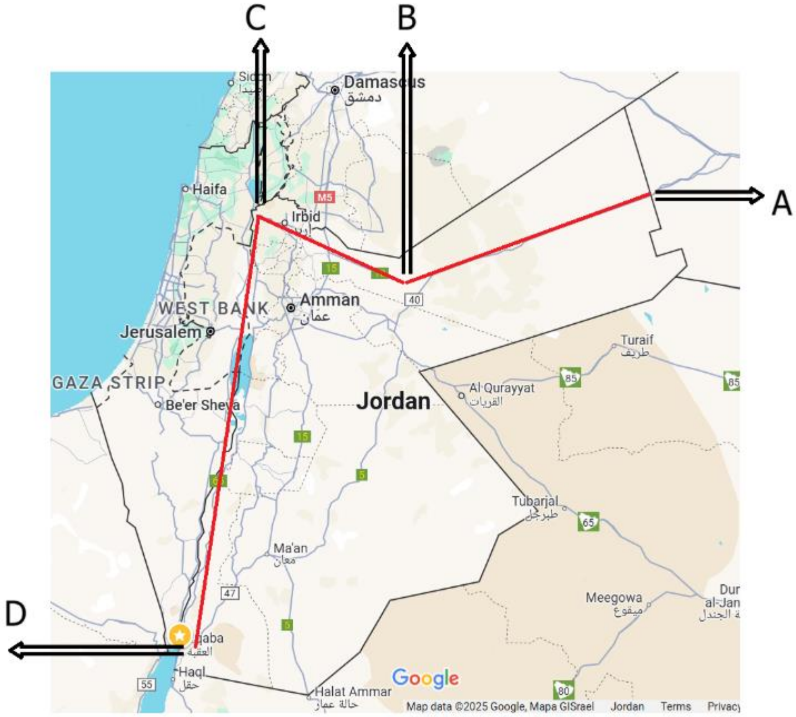


Fig. 11 The simulated 10-hour travel route

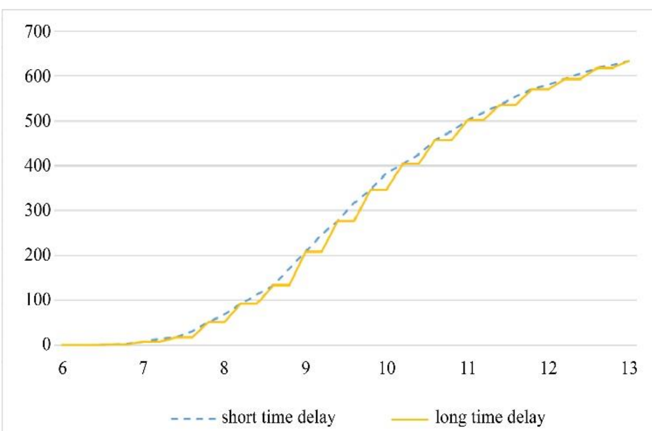


Fig. 12 With two different time delays: Dual-axis simulated results

Assuming a 10-hour journey that starts at 7:00 AM and ends at sunset, Figure 13 compares three solar system configurations and the proposed GPS-enabled dual-axis tracker. Among the options evaluated are a flat panel setup that stays fixed, a configuration where the panels are tilted (e.g., facing south while stationary and remaining at an angle during motion), and a single-axis tracker that continuously adjusts to face south. The purpose of conducting this comparison is to assess the performance of the suggested dual-axis tracking system with respect to overall efficiency and energy output. Although the south-oriented cells demonstrate encouraging results, the findings reveal that the GPS-assisted dual-axis design delivers considerably superior performance compared to the other configurations. Based on the preliminary findings, energy output was significantly higher when using a tracker system with dual axes than the other approaches assessed. In particular, this method produced 20% more energy than the static flat cell panel in its conventional form, highlighting the superior performance of the dual-axis configuration.

It is worth noting that these simulations were conducted under specific conditions that did not account for diffuse and reflected light (from buildings or clouds). Additionally, potential shading effects were not considered as a factor in these results.

Upon assembly, the system must be installed onto the vehicle, involving electrical and mechanical linking of every tracking unit. Once installed, routine maintenance is crucial to system efficiency. This includes routine checking, lubricating moving parts, cleaning of solar modules, and effective repair of any malfunction or inefficiency encountered.

The design, parts, and installation techniques must all be carefully studied to turn the proposed idea into a viable system. The initial phase of planning and constructing the system is determining the number of cells and their size. After the design is completed, elements such as the dual-axis trackers' motors, gears, bearings, and the wiring and connectors of the electrical connections must be chosen to ensure that they meet the system's requirements.

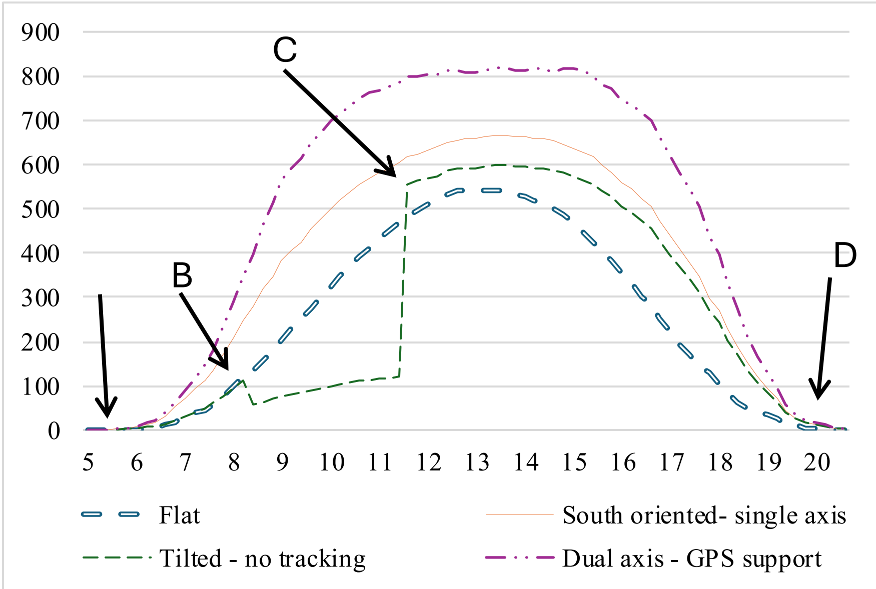


Fig. 13 Performance comparison among the GPS-enabled dual-axis tracking system, traditional static flat-panel arrays, fixed-tilt configurations, and a single-axis tracker aligned southward

6. Conclusion

This research investigated the technical constraints of solar vehicles through the proposition and assessment of novel solar tracking mechanisms to improve solar energy harvesting efficiency. A dual-axis tracking mechanism, informed by real-time GPS information, was modelled and simulated in MATLAB/Simulink and compared with the performance of a standard static flat-panel photovoltaic arrangement.

Simulation outcomes revealed that the GPS-enabled tracker with dual-axis capability resulted in an energy efficiency gain of around 20% when compared to the performance of the flat-panel static system. This significant enhancement highlights the value of tracking systems in maximizing solar energy capture, especially given the limited surface area generally available on solar-powered vehicles. Although encouraging results are observed, real-world deployment of such systems in commercial settings continues to struggle with limitations posed by increased complexity and the economics of tracking technologies. Nevertheless, the gains in efficiency warrant continued research and development in this direction. Research in the future must be directed at creating more affordable, light, and aerodynamically optimized tracking solutions that can be readily integrated into vehicle bodies without performance compromise. In summary, this research is a fundamental addition to enhancing the performance of solar vehicles. The early findings present an urgent argument for ongoing investigation into solar tracking mechanisms to foster the sustainability and practicability of solar transportation alternatives.

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