Design and Development of a GPS-Based Automatic Heliostat Solar Tracking System for Efficient Renewable Energy Utilization

Project Report

Submitted by

Tanmay Hiremath(01FE23BAR030)

Prajwal Mullolli(01FE23BAR032)

Shrigovinda T Kulkarni(01FE23BAR047)

Kridey Jangra(01FE23BAR004)

Under the Guidance of:

Dr. Rakesh P Tapaskar

Prof. Prashant Revankar

Department of Automation and Robotics

KLE Technological University

Hubballi. 2025- 2026

Acknowledgements

We would like to extend our heartfelt gratitude and appreciation to everyone who helped bring this project to a successful conclusion.

First and foremost, we want to express our sincere thanks to Dr. Vinayak N. Kulkarni, who oversaw our research and gave us tremendous advice and assistance. Their opinions and suggestions were really helpful in helping us to refine and improve our work.

We also like to express our gratitude to the teachers and employees of Automation and Robotics, KLE Technological University in Hubballi for their support and use of the project's resources. The development of the initiative was greatly aided by their dedication to supporting new ventures and to academic achievement.

Dr. Rakesh P Tapaskar
Prof. Prashant Revankar

ABSTRACT

The increasing demand for clean energy requires efficient utilization of available renewable resources. Solar energy is one of the most abundant renewable energy sources; however, conventional fixed solar systems suffer from reduced efficiency because they cannot continuously align with the sun's changing position throughout the day. To address this limitation, this project presents the design and development of a GPS-based automatic heliostat solar tracking system with single-axis tracking for improved solar energy utilization.

The proposed system uses a GPS module to obtain real-time geographical coordinates, date, and time, which are used to compute the solar azimuth and solar elevation angles through a solar position algorithm. An ESP32 microcontroller processes this data and controls a stepper motor to orient the heliostat according to the calculated solar azimuth angle. The system updates the heliostat position periodically to follow the sun's movement across the sky, ensuring optimal reflection or concentration of sunlight.

In addition, a web-based dashboard is implemented using the ESP32 WiFi capability to display real-time system parameters such as latitude, longitude, current time, solar azimuth, solar elevation, and tracker position. This monitoring interface allows users to observe system performance and solar tracking behavior in real time.

The developed system provides a low-cost, automated, and efficient solar tracking solution, which can significantly improve the energy capture of solar systems. Such technology has potential applications in solar concentrators, rural energy systems, solar thermal applications, and renewable energy management, particularly in regions where efficient solar utilization is essential for sustainable development.

Contents

Chapter No	Title	Page No
01	Introduction	6
02	Objectives	8
03	System Architecture	9
04	Hardware and Software Implementation	11
05	Working principle and mathematical model	15
06	Results and observations	18
07	Applications and advantages	20
08	Conclusions	22
	References	23

Tables

Table No	Title	Page No
6.1	Sample Observation Data	18

Figures

Fig No	Title	Page No
4.1	Prototype Hardware Setup of the GPS-Based Heliostat Solar Tracking System	11
4.2	Web-Based Monitoring Dashboard of the Solar Tracking System	14

Chapter 1
Introduction

1.1 Introduction

The rapid growth in energy demand and the environmental impact of conventional fossil fuels have increased the need for efficient renewable energy solutions. Among the various renewable energy sources, solar energy is one of the most abundant, clean, and sustainable resources available. Countries like India receive significant solar radiation throughout the year, making solar energy an important solution for addressing energy shortages and supporting sustainable development, particularly in rural areas.

Traditional solar energy systems such as fixed solar panels or reflectors are installed at a constant angle and cannot continuously face the sun as it moves across the sky during the day. As a result, a significant portion of available solar radiation is not utilized effectively, which reduces the overall efficiency of solar energy systems. To overcome this limitation, solar tracking systems are used to continuously adjust the orientation of solar collectors so that they remain aligned with the sun.

A heliostat system is a type of solar tracking mechanism that uses a reflective surface or mirror to direct sunlight toward a fixed target, such as a solar receiver or thermal collector. Accurate positioning of the heliostat is essential to ensure maximum reflection and energy capture. Conventional heliostat systems often rely on light sensors, which may become inaccurate due to weather conditions such as clouds, dust, or shading.

To address these challenges, this project presents the design and development of a GPS-based automatic heliostat solar tracking system with single-axis tracking. The system uses a GPS module to obtain real-time latitude, longitude, date, and time, which are used to calculate the solar azimuth and elevation angles using a solar position algorithm. An ESP32 microcontroller processes these calculations and controls a stepper motor to orient the heliostat in the direction of the sun.

Additionally, the system includes a web-based monitoring dashboard, which displays real-time information such as GPS location, time, solar azimuth, solar elevation, and tracker position. This allows users to observe the tracking process and system performance in real time.

The proposed system provides an automated, low-cost, and efficient solar tracking solution that can improve solar energy utilization. Such technology has potential applications in solar concentrator systems, renewable energy installations, and rural energy development, where efficient solar energy management is essential for sustainable growth.

1.2 Problem Statement

Solar energy systems are widely used as a clean and renewable source of power. However, many conventional solar installations use fixed-position solar panels or reflectors, which remain stationary throughout the day. Since the sun continuously moves across the sky from east to west, fixed systems are unable to maintain optimal alignment with the sun. As a result, a significant amount of available solar radiation is not effectively captured, leading to reduced energy efficiency and lower power output.
In many solar concentrator and heliostat applications, accurate orientation toward the sun is essential to maximize the reflection and concentration of sunlight. Manual adjustment of solar collectors is impractical, especially in remote or rural areas where continuous monitoring is not feasible. Additionally, traditional sensor-based solar tracking systems that rely on light sensors may produce inaccurate results due to environmental conditions such as cloud cover, dust, or shading, which can affect sensor readings.

Therefore, there is a need for a reliable and automated solar tracking system that can accurately determine the sun's position and adjust the orientation of the heliostat accordingly. The system should operate efficiently with minimal human intervention while providing real-time monitoring of solar parameters.

This project addresses these challenges by developing a GPS-based automatic heliostat solar tracking system with single-axis tracking, which uses real-time location, date, and time data to calculate solar angles and automatically orient the heliostat for improved solar energy utilization.

Chapter 2
Objectives Of Study

The main objective of this project is to design and develop an automatic heliostat solar tracking system that can efficiently track the sun's position using real-time GPS data and improve the utilization of solar energy.

The specific objectives of the project are:

1. To design a single-axis heliostat solar tracking mechanism capable of following the sun’s movement from east to west.
2. To obtain real-time geographical location and time using a GPS module, including latitude, longitude, date, and time.
3. To calculate solar azimuth and elevation angles using a solar position algorithm based on the GPS data.
4. To control the orientation of the heliostat using a stepper motor driven by an ESP32 microcontroller.
5. To implement a web-based dashboard that displays real-time system parameters such as GPS location, solar azimuth, solar elevation, and tracker position.
6. To improve the efficiency of solar energy utilization compared to fixed solar systems.

Chapter 3

System Architecture

The proposed system is a GPS-based automatic heliostat solar tracking system with single-axis tracking, designed to automatically orient a reflective heliostat dish in the direction of the sun to improve solar energy utilization. The system integrates position sensing, solar angle computation, motor control, and real-time monitoring through a web-based dashboard.

The architecture of the system consists of the following main modules:

1. GPS Module

The GPS module provides real-time geographical data, including latitude, longitude, date, and time. This information is essential for calculating the position of the sun at a specific location and time. The GPS data is continuously received by the microcontroller through serial communication.

2. ESP32 Microcontroller

The ESP32 acts as the central processing unit of the system. It receives data from the GPS module and performs the following tasks:

- Processes latitude, longitude, date, and time information.
- Calculates the solar azimuth and solar elevation angles using a solar position algorithm.
- Controls the stepper motor through motor driver signals.
- Hosts a web server to display real-time solar tracking data on a dashboard.
- Communicates with connected devices using WiFi and WebSocket technology.

3. Solar Position Calculation

Using the GPS data, the system calculates important solar parameters such as:

- Day of the year
- Solar declination
- Equation of time
- Solar hour angle
- Solar elevation angle
- Solar azimuth angle

These calculations determine the exact position of the sun relative to the observer's location.

4. Motor Control System

A stepper motor is used to rotate the heliostat along a single axis (east to west). The ESP32 generates control signals to the motor driver, which then drives the stepper motor. The motor moves in small increments to adjust the heliostat position according to the calculated solar azimuth angle.

To reduce unnecessary movement and mechanical wear, the system updates the heliostat position only when the change in azimuth exceeds a predefined threshold.

5. Web-Based Dashboard

The ESP32 hosts a local web server that provides a real-time dashboard accessible through WiFi. The dashboard displays key system parameters such as:

- Latitude and Longitude
- Current time
- Solar azimuth angle
- Solar elevation angle
- Tracker azimuth position

This interface allows users to monitor the system operation and verify solar tracking performance.

Overall, the system architecture combines GPS-based solar position calculation, microcontroller-based control, motorized heliostat movement, and wireless monitoring, creating an automated and efficient solar tracking solution suitable for renewable energy applications.

Chapter 4

Hardware and Software Implementation

The proposed GPS-based automatic heliostat solar tracking system integrates both hardware components and software algorithms to automatically determine the position of the sun and adjust the heliostat accordingly. The hardware provides the sensing, control, and actuation mechanisms, while the software performs solar position calculations, system control, and real-time monitoring through a web dashboard.

4.1 Hardware Components

Figure 4.1 Prototype Hardware Setup of the GPS-Based Heliostat Solar Tracking System

Figure 4.1.1 shows the experimental prototype of the heliostat solar tracking system. The setup consists of a reflective heliostat dish mounted on a rotating support structure, driven by a stepper motor and controlled by an ESP32 microcontroller placed inside the enclosure. The GPS module provides real-time location and time information, which is used by the controller to calculate solar position and orient the heliostat accordingly.

1.ESP32 Microcontroller

The ESP32 serves as the main controller of the system. It processes data received from the GPS module, calculates solar position parameters, and controls the stepper motor. In addition, the ESP32 uses its built-in WiFi capability to host a web server for displaying real-time data on a dashboard.

2. GPS Module

The GPS module provides real-time latitude, longitude, date, and time information. These parameters are essential for calculating the solar azimuth and solar elevation angles using a solar position algorithm.

3. Stepper Motor

A stepper motor is used to rotate the heliostat along a single axis (east–west direction). The motor moves in precise angular steps, allowing accurate positioning of the heliostat based on the calculated solar azimuth angle.

4. Stepper Motor Driver

The motor driver receives control signals from the ESP32 and supplies the required current and voltage to operate the stepper motor. It ensures stable and controlled rotation of the heliostat mechanism.

5. Heliostat Reflector Structure

The heliostat consists of a reflective dish or mirror mounted on a rotating structure. The stepper motor rotates this structure so that the reflective surface follows the sun's movement throughout the day.

6.Power Supply

A regulated power supply is used to provide electrical power to the ESP32, GPS module, and motor driver for stable system operation.

5.2 Software Implementation

The software for the system is developed using the Arduino IDE and is executed on the ESP32 microcontroller. The program performs several important functions, including data acquisition, solar position calculation, motor control, and dashboard communication.

1.GPS Data Acquisition

The system uses a GPS library to read data from the GPS module. The following parameters are obtained:

- Latitude
- Longitude
- Date
- Time

This information is continuously updated and used for solar position calculations.

2. Solar Position Calculation

The ESP32 calculates the sun's position using mathematical equations based on:

- Day of the year
- Solar declination
- Equation of time
- Solar hour angle

Using these parameters, the system calculates:

- Solar elevation angle
- Solar azimuth angle

These angles determine the direction in which the heliostat must be oriented.

3. Motor Control Algorithm

The calculated solar azimuth angle is compared with the current position of the heliostat. If the difference exceeds a predefined threshold, the ESP32 sends control pulses to the motor driver to rotate the stepper motor in the appropriate direction. This ensures that the heliostat gradually follows the sun's movement throughout the day.

Additionally, the system performs a daily reset operation, returning the heliostat to its initial east-facing position early in the morning to prepare for the next tracking cycle.

4. Web-Based Monitoring Dashboard

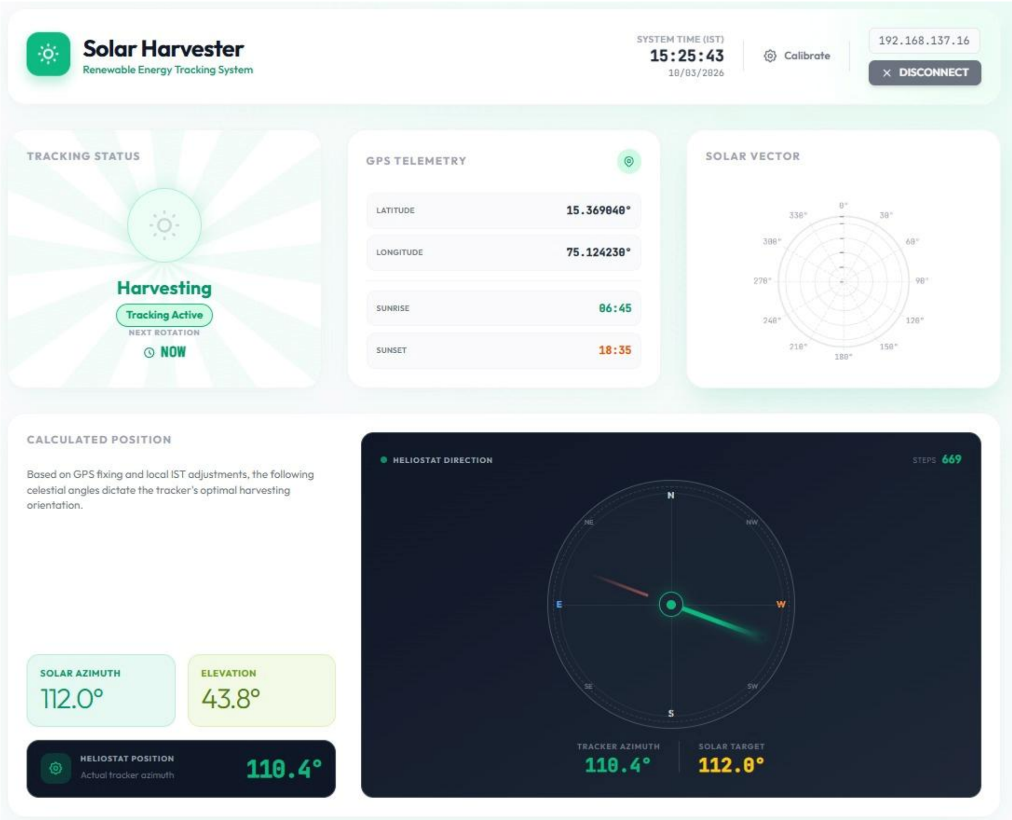

Fig 4.2 GPS-Based Solar Tracking Monitoring Dashboard

Figure 4.2 shows the web-based monitoring dashboard of the heliostat solar tracking system. The ESP32 hosts a web server that generates a dashboard displaying real-time system parameters. The dashboard shows the latitude and longitude obtained from the GPS module, the current time, solar azimuth angle, solar elevation angle, and the current heliostat tracker position. These parameters allow users to observe the calculated solar position and the corresponding movement of the heliostat.

The system transmits data using WiFi and WebSocket communication, enabling real-time updates on the dashboard without refreshing the page. This allows users to monitor the solar tracking system through a web browser connected to the same local network. By integrating hardware components with software-based solar position calculations, the system is capable of automatically tracking the sun and providing continuous real-time monitoring of the solar tracking performance.

Chapter 5

Working Principle and Mathematical Model

The proposed system operates by determining the real-time position of the sun and automatically orienting the heliostat in that direction. The system uses GPS data, solar position calculations, and motor control mechanisms to continuously track the sun using a single-axis tracking mechanism.

1. Acquisition of GPS Data

The GPS module continuously receives signals from satellites and provides latitude, longitude, date, and time. This information is transmitted to the ESP32 microcontroller through serial communication. The GPS time is provided in UTC format, which is converted to Indian Standard Time (IST) for accurate calculations.

2. Determination of Day of the Year

The system first calculates the day number of the year (N) using the current date obtained from the GPS module. This value is required to determine the seasonal position of the sun.

$$N = d + \sum_{i=1}^{m-1} D_i$$

Where:

d= day of the month

m= month

D_i= number of days in the previous months

3. Solar Declination Angle

The solar declination angle (δ) represents the angular position of the sun relative to the Earth's equatorial plane. It varies throughout the year due to the tilt of the Earth's axis.

$$\delta = 23.45 \times \sin\left(\frac{360}{365}(284 + N)\right)$$

Where:

N= day of the year

4. Equation of Time

The equation of time (E) accounts for variations in solar time due to Earth's orbital eccentricity and axial tilt.

$$B = \frac{360}{364}(N - 81)$$

$$E = 9.87\sin(2B) - 7.53\cos(B) - 1.5\sin(B)$$

Where:

N= day of the year

5. Solar Time Calculation

Solar time is calculated using longitude and the equation of time.

$$SolarTime = LocalTime + \frac{4(L_{local} - L_{std}) + E}{60}$$

Where:

L_{local}= local longitude

L_{std}= standard meridian longitude

6. Solar Hour Angle

The hour angle (H) represents the angular displacement of the sun east or west of the local meridian.

$$H = 15(SolarTime - 12)$$

7. Solar Elevation Angle

The solar elevation angle (α) indicates the height of the sun above the horizon.

$$\alpha = \sin^{-1}(\sin \phi \sin \delta + \cos \phi \cos \delta \cos H)$$

Where:

ϕ= latitude

δ= solar declination

H= hour angle

8. Solar Azimuth Angle

The solar azimuth angle (Az) indicates the horizontal direction of the sun relative to the observer.

$$Az = \tan^{-1}\left(\frac{\sin H}{\cos H \sin \phi - \tan \delta \cos \phi}\right)$$

The calculated azimuth value is adjusted to ensure it lies within the 0°–360° range.

9. Heliostat Orientation Control

The ESP32 compares the calculated solar azimuth angle with the current position of the heliostat. If the difference exceeds a predefined threshold (e.g., 10°), the controller sends pulses to the stepper motor driver.

The stepper motor rotates the heliostat in small increments to align it with the sun's position. Since the system uses single-axis tracking, the heliostat rotates only in the east–west direction to follow the daily movement of the sun.

10. Daily Reset Operation

At the start of each day, the system resets the heliostat to an east-facing position (approximately 90°). This ensures that the tracker begins the tracking cycle correctly at sunrise and continues to follow the sun until sunset.

By combining real-time GPS data, solar position equations, and automated motor control, the system continuously tracks the sun's movement and maintains optimal heliostat alignment, thereby improving solar energy utilization.

Chapter 6
Results and Observations

The developed GPS-based heliostat solar tracking system was tested to evaluate its ability to determine the position of the sun and orient the heliostat accordingly. The system successfully acquired real-time location and time data from the GPS module and used these parameters to calculate the solar azimuth and solar elevation angles.

During operation, the ESP32 microcontroller processed the GPS data and executed the solar position algorithm to determine the sun's direction. Based on the calculated solar azimuth angle, the stepper motor adjusted the orientation of the heliostat along the single tracking axis. The system updated the heliostat position periodically, ensuring that the reflector followed the sun's movement from east to west throughout the day.

The web-based dashboard hosted on the ESP32 displayed real-time information including latitude, longitude, current time, solar azimuth angle, solar elevation angle, and the current tracker position. This interface allowed continuous monitoring of the system and verified that the calculated solar angles were correctly reflected in the movement of the heliostat.

Table 6.1 Sample Observation Data

Time (IST)	Solar Azimuth (°)	Solar Elevation (°)	Tracker Position (°)
08:00 AM	95°	25°	95°
10:00 AM	125°	45°	125°
12:00 PM	180°	75°	180°
02:00 PM	220°	55°	220°
04:00 PM	260°	30°	260°

Observations

- The system successfully obtained real-time latitude, longitude, date, and time from the GPS module.
- The calculated solar azimuth and elevation angles changed continuously as the sun moved across the sky.
- The stepper motor rotated the heliostat in response to changes in the calculated solar azimuth angle.
- The single-axis tracking mechanism allowed the heliostat to follow the sun from east to west.
- The web dashboard provided real-time monitoring of solar parameters and system status.
- The automated tracking mechanism reduced the need for manual adjustment and improved solar alignment accuracy.

These results demonstrate that the developed system can effectively track the sun's movement and maintain proper orientation of the heliostat, thereby improving the utilization of solar energy.

Chapter 7
Applications and Advantages

The GPS-based automatic heliostat solar tracking system can be used in several renewable energy applications where efficient utilization of solar energy is required. By continuously aligning the heliostat with the sun's position, the system improves the effectiveness of solar energy collection and reflection.

Applications

1. Solar Concentrator Systems

The heliostat can reflect sunlight toward a fixed receiver in solar concentrator systems, increasing the intensity of solar radiation for thermal energy generation.

2. Solar Thermal Power Plants

Heliostat mirrors are widely used in solar tower systems to direct sunlight toward a central receiver, where heat energy is converted into electricity.

3. Rural Renewable Energy Systems

The system can be implemented in rural areas to support solar-based applications such as solar cooking, water heating, and small-scale energy generation.

4. Solar Research and Educational Projects

The system can be used in academic institutions and research laboratories to study solar tracking techniques and solar position calculations.

5. Smart Solar Energy Management

With the integration of a monitoring dashboard, the system can assist in observing solar parameters and improving solar energy management in renewable energy installations.

Advantages

- **Improved Solar Energy Utilization**

By continuously aligning with the sun's position, the system increases the efficiency of solar energy capture compared to fixed solar systems.

- **Automatic Operation**

The system operates automatically using GPS data and solar position calculations, eliminating the need for manual adjustment.

- **Higher Accuracy**

GPS-based solar position calculations provide more reliable results compared to sensor-based tracking systems that can be affected by clouds or shading.

- **Low-Cost Implementation**

The use of widely available components such as ESP32, GPS modules, and stepper motors makes the system affordable and suitable for small-scale applications.

- **Real-Time Monitoring**

The web-based dashboard allows users to monitor solar parameters and system performance in real time.

- **Suitable for Renewable Energy Applications**

The system supports sustainable energy utilization and can contribute to improved renewable energy solutions, particularly in areas with high solar potential.

Chapter 8
Conclusions

This project presents the design and development of a GPS-based automatic heliostat solar tracking system with single-axis tracking for improving the efficiency of solar energy utilization. The system successfully integrates a GPS module, ESP32 microcontroller, stepper motor, and a web-based monitoring dashboard to create an automated solar tracking solution.

The GPS module provides real-time information such as latitude, longitude, date, and time, which are used to calculate the solar azimuth and solar elevation angles through a solar position algorithm. Based on these calculated angles, the ESP32 controls the stepper motor to adjust the orientation of the heliostat, allowing it to follow the sun's movement from east to west throughout the day.

The implementation of a web-based dashboard enables real-time monitoring of important parameters including GPS location, solar angles, and tracker position. This improves system transparency and allows users to observe the operation of the solar tracking system.

The results demonstrate that the proposed system can effectively track the sun's position and automatically adjust the heliostat orientation with minimal human intervention. Compared to fixed solar systems, this approach can significantly improve solar energy utilization.

Overall, the developed system provides a low-cost, automated, and efficient solar tracking solution that can be applied in renewable energy systems, solar concentrator applications, and rural energy development initiatives. Future improvements may include dual-axis tracking, enhanced control algorithms, and integration with larger solar energy systems to further increase efficiency and performance.

References

[1] Ibrahim Reda and Afshin Andreas, *Solar Position Algorithm for Solar Radiation Applications*, National Renewable Energy Laboratory (NREL), USA.

[2] John A. Duffie and William A. Beckman, *Solar Engineering of Thermal Processes*, Wiley Publications.

[3] National Renewable Energy Laboratory, *Solar Position Algorithm Documentation*, NREL Technical Report.

[4] International Energy Agency, *Renewable Energy and Solar Technology Reports*, IEA Publications.

[5] OpenWeather, *Weather API Documentation for Sunrise and Sunset Data*.