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Solar Detection and Tracking System Using Artificial Intelligence: An ESP32-Based Automated Solar Panel Orientation System for Enhanced Energy Harvesting

[1]Karthik. G, [1]Velmurugan V, [1]Sridhar K, [1]Harinath M, [1]Jefrin. J, [1]Logeshwaran. B,
[1]Department of Mechanical Engineering,
V S B College of Engineering Technical Campus, Coimbatore, India
Corresponding author mail id: karthik4670@gmail.com,
Author mail,jefrinjoyal15@gmail.com, loki246825@gmail.com,

Abstract—The growing need for clean and sustainable energy has accelerated progress in solar power technologies. This project presents the development of an intelligent solar detection and tracking system designed to enhance energy harvesting efficiency. Fixed solar panels suffer from reduced performance because they cannot continuously follow the sun's movement. To address this issue, the proposed system combines automation with real-time monitoring using advanced embedded solutions. At the core of the system is an ESP32 microcontroller, selected for its high processing capability, energy efficiency, and integrated wireless features. A photovoltaic panel converts sunlight into electrical energy based on the photovoltaic effect. The output voltage is continuously measured through a voltage sensor module, which sends feedback to the controller for analysis and system optimization. A servo motor is used to adjust the panel's position dynamically, controlled by signals from the ESP32 to enable accurate angular movement so that ensuring the panel remains aligned with the sun throughout the day. This tracking system operates on a closed-loop mechanism, where sensor feedback is used to make real-time corrections. Additionally, a 16x2 LCD display provides a simple interface to show key data such as voltage levels and system status. This improves usability, especially in remote setups. Overall, the system offers an affordable and efficient solution for enhancing solar energy output and supports future upgrades like IoT-based monitoring and remote control.

1. Introduction

The rising global energy demand and the gradual exhaustion of fossil fuel reserves have increased the focus on sustainable energy alternatives. Among renewable resources, solar energy stands out due to its availability, environmental friendliness, and long-term viability. Solar power systems use photovoltaic panels to convert sunlight into electricity, but their efficiency is often reduced because fixed panels cannot maintain optimal alignment with the sun throughout the day. To overcome this drawback, solar tracking systems have been introduced. These systems automatically adjust the position of solar panels to follow the sun's path, ensuring maximum exposure to sunlight and improving energy output. Advances in embedded systems and automation have made these tracking solutions more accurate, reliable, and efficient. This project involves designing an intelligent solar detection and tracking system based on an ESP32 microcontroller. The setup includes a solar panel for power generation, a voltage sensor to monitor output levels, and a servo motor to control panel movement. A 16x2 LCD display is also integrated to show real-time data, making system monitoring easier for users. The system uses a feedback-driven control approach, where sensor readings are continuously processed to maintain the best possible panel orientation. By integrating automation, monitoring, and affordable components, this project aims to enhance solar energy efficiency and support the development of cleaner and more sustainable energy solutions.

1.1 OBJECTIVE

1. To design and develop an efficient solar detection and tracking system that maximizes solar energy absorption.
2. To utilize an ESP32 microcontroller for real-time monitoring, control, and processing of system operations.
3. To implement a solar panel that converts sunlight into electrical energy using the photovoltaic principle.
4. To measure and analyze the output voltage of the solar panel using a voltage sensor module for performance evaluation.
5. To develop an automatic tracking mechanism using a servo motor that adjusts the panel orientation based on sunlight direction.
6. To display real-time system parameters such as voltage output and system status using a 16x2 LCD display.
7. To improve the overall efficiency of solar energy systems compared to fixed-position solar panels.
8. To create a cost-effective and user-friendly renewable energy solution suitable for small-scale applications.
9. To provide a foundation for future enhancements such as IoT-based monitoring and remote control.

2. System Design

2.1 DESIGN OF SOLAR DETECTION AND TRACKING SYSTEM

The primary objective of this project is to design and develop an efficient and intelligent solar detection and tracking system that maximizes the utilization of solar energy. In conventional solar energy systems, solar panels are fixed in a single position, which limits their ability to receive maximum sunlight throughout the day. This project aims to overcome this limitation by implementing an automated tracking mechanism that continuously adjusts the position of the solar panel in accordance with the movement of the sun, thereby increasing overall energy efficiency and output. Another important objective of the project is to incorporate an advanced embedded system using the ESP32 microcontroller. The ESP32 acts as the central control unit, responsible for processing sensor data, executing control algorithms, and managing the interaction between different components of the system. Its high processing capability, low power consumption, and flexibility make it suitable for real-time applications and future enhancements. The project also aims to effectively utilize a photovoltaic solar panel to convert solar energy into electrical energy. By applying the principle of the photovoltaic effect, the system generates clean and renewable energy that can be used for various applications. In order to monitor the performance of the solar panel, a voltage sensor module is integrated into the system. This sensor continuously measures the output voltage and provides real-time data to the microcontroller, enabling performance analysis and ensuring proper system operation under different environmental conditions.

2.2 INTEGRATION OF SOLAR DETECTION AND TRACKING SYSTEM :

The integration of the solar detection and tracking system involves combining various hardware and software components into a unified and functional system. This process ensures smooth communication between all modules, enabling efficient operation and accurate solar tracking. The major components integrated in this system include the solar panel, ESP32 microcontroller, voltage sensor module, servo motor, and 16x2 LCD display. The solar panel is connected as the primary energy source, converting sunlight into electrical energy. The output from the panel is fed into the voltage sensor module, which safely measures the voltage level and sends the corresponding analog signal to the ESP3 microcontroller. This allows the system to continuously monitor the energy generated by the panel.

The ESP32 acts as the central controller, coordinating all system operations. It processes the input data received from the voltage sensor and determines the necessary adjustments required for optimal solar alignment. Based on this processed data, the ESP32 generates control signals in the form of Pulse Width Modulation (PWM) to drive the servo motor. The servo motor is mechanically integrated with the solar panel to adjust its orientation. It rotates the panel to specific angles as instructed by the microcontroller, ensuring that the panel remains aligned with the direction of maximum sunlight. This integration of sensing, processing, and actuation forms a closed-loop system that continuously improves energy efficiency. In addition, the 16x2 LCD display is connected to the microcontroller to provide real-time feedback to the user. It displays important information such as voltage output, system status, and tracking activity. This enhances the usability and monitoring capability of the system. Proper wiring, voltage regulation, and grounding are essential during integration to ensure stable and safe operation of all components. The system is programmed and synchronized in such a way that all components work together seamlessly without delay or conflict. Overall, the integration of the solar detection and tracking system results in a coordinated and automated setup that efficiently combines renewable energy generation with intelligent control and real-time monitoring, making it suitable for practical and real-world applications.

2.3 REAL-TIME MONITORING AND CONTROL SYSTEM:

The real-time monitoring and control system is a crucial part of the solar detection and tracking system, as it enables continuous observation and dynamic adjustment of system performance. This subsystem ensures that all components operate efficiently by providing instant feedback and control based on current conditions. In this project, real-time monitoring is achieved using a voltage sensor module that continuously measures the output of the solar panel. The sensor sends this data to the ESP32 microcontroller, which processes the information and evaluates the system's performance. This allows the system to detect variations in power generation due to changes in sunlight intensity, weather conditions, or panel orientation. The control system is implemented through the ESP32 microcontroller, which acts as the central decision-making unit. Based on the input data received from the sensors, the microcontroller generates appropriate control signals to adjust the position of the solar panel. These signals are sent to the servo motor in the form of Pulse Width Modulation (PWM), enabling precise and real-

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time movement of the panel to maintain optimal alignment with the sun. The system also includes a 16x2 LCD display, which provides real-time feedback to the user. It displays key parameters such as voltage output, system status, and tracking activity. This allows users to easily monitor the system's operation without the need for additional devices or complex interfaces. One of the key advantages of real-time monitoring and control is the ability to respond instantly to changing environmental conditions. For example, if the sunlight intensity decreases or the panel is not properly aligned, the system can quickly adjust its position to improve performance. This ensures maximum efficiency and reduces energy loss. Additionally, the system can be further enhanced by integrating wireless communication features of the ESP32, enabling remote monitoring and control through mobile applications or web platforms. This adds flexibility and convenience, especially for large-scale or remote installations. Overall, the real-time monitoring and control system ensures accurate, efficient, and reliable operation of the solar tracking system by continuously analyzing data and making instant adjustments. It plays a vital role in maximizing energy output and improving the overall performance of the system.

3. MATERIALS AND METHODS

BLOCK DIAGRAM

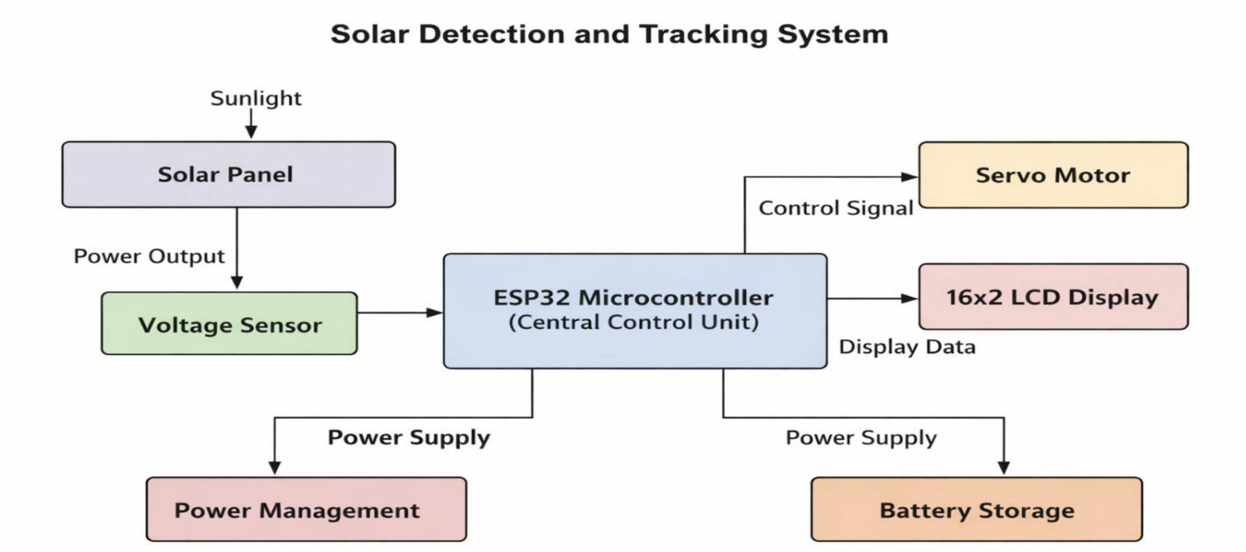


Fig 3.1 Block diagram

3.1 LCD Display

Overview

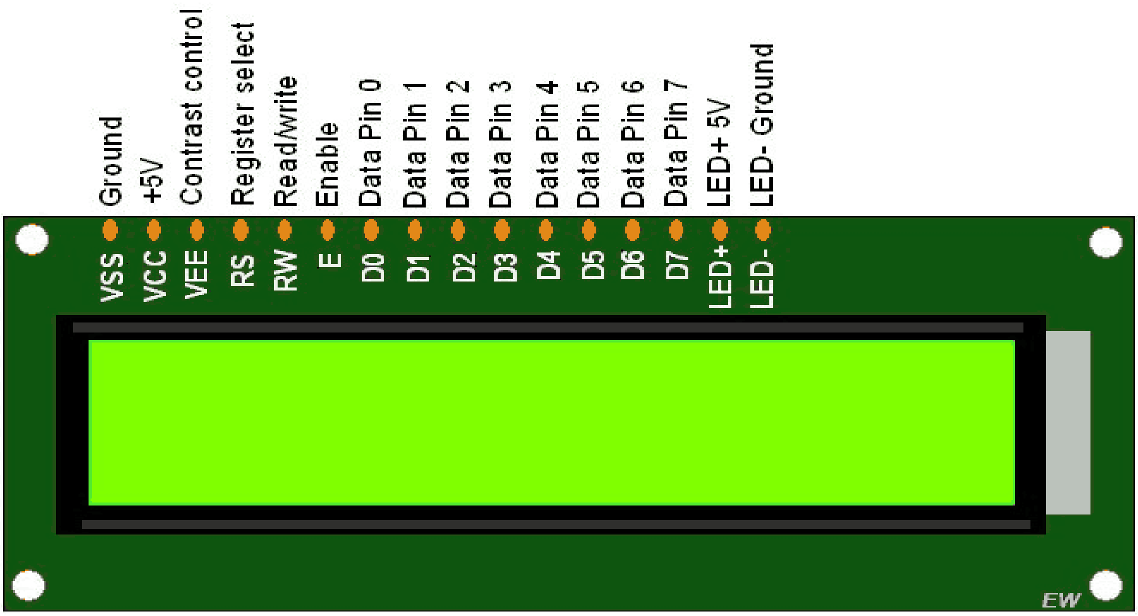
The 16x2 LCD (Liquid Crystal Display) is a character-based display module capable of displaying 2 lines with 16 characters each. It is commonly used in embedded systems and DIY electronics to provide user-readable output. It is based on the Hitachi HD44780 or compatible controller, which supports easy interfacing via parallel (and optionally I2C) communication.

Key Features- 2-line display with 16 characters per line- Each character is 5x8 pixel matrix- HD44780 or compatible controller- Parallel 4-bit or 8-bit data interface- Optional I2C backpack for serial interfacing- Adjustable contrast via potentiometer- Operating voltage: 4.7V to 5.3V (typically 5V)- Built-in LED backlight (white or green)

Display Specifications- Character format: 5x8 dot matrix- Display size: 16 characters x 2 lines- Viewing area: Approx. 66mm x 16mm- Module size: Approx. 80mm x 36mm- Backlight: LED, white/green (via pin 15 & 16)

Electrical Characteristics- Supply voltage (VCC): 5V DC- Operating current: ~1.5 – 2.5 mA (without backlight)

3.2 LCD DISPLAY



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- Backlight current: 15 – 25 mA (depending on model)

- Contrast adjustment: Using external 10K potentiometer connected to V0 pin

Pin Configuration (16-pin interface)
1. VSS – Ground
2. VCC – +5V supply
3. V0 – Contrast adjustment
4. RS – Register Select (0 = Instruction, 1 = Data)
5. RW – Read/Write (0 = Write, 1 = Read)
6. E – Enable (starts data read/write)

7-14. D0 to D7 – Data bus (4-bit: D4–D7 only)

15. LED+ – Backlight Anode (optional)
16. LED− – Backlight Cathode (optional)

Communication Modes
Parallel Interface: - 8-bit mode: Uses D0 to D7- 4-bit mode: Uses D4 to D7 (common for microcontrollers)
I2C Interface (optional with backpack module):- Reduces required pins to 2 (SDA & SCL)- I2C address usually 0x27 or 0x3F (depends on module)- Controlled via PCF8574 I/O expander chip
Character Set & Custom Characters- Default ASCII character set- Supports up to 8 user-defined characters (CGRAM)- Each custom character: 5x8 dot matrix- Characters stored in CGRAM, addressable via commands
Power Considerations- Backlight may require a series resistor (usually built-in)- Contrast pin (V0) must be adjusted for proper visibility- Use 10K potentiometer between VCC-GND-V0
Typical Applications- User interfaces for embedded systems- Displaying sensor readings (e.g., temperature, humidity)- Digital clocks and timers- Arduino and Raspberry Pi projects- Menu systems for microcontroller applications
Development Support- Libraries: Liquid Crystal (Arduino), LCD.py (Python), etc.- IDEs: Arduino IDE, Python (with RPi), Micro Python- Can be controlled via GPIO, I2C, or SPI (with adapters)- Widely available tutorials and schematics
References & Resources- HD44780 Datasheet: https://www.sparkfun.com/datasheets/LCD/HD44780.pdf- Arduino LiquidCrystal Library: https://www.arduino.cc/en/Reference/LiquidCrystal

3.3 Servo Motor – Technical Documentation

1. Overview
A servo motor is a rotary or linear actuator that enables precise control of angular or linear position, velocity, and acceleration. It consists of a motor coupled to a sensor for position feedback and a control circuit. Servo motors are widely used in robotics, CNC machinery, camera systems, and automated manufacturing.
2. Principle of Operation
Servo motor's function based on closed-loop control:

1. Control Signal – Receives a Pulse Width Modulated (PWM) signal that defines the target position.
2. Feedback Mechanism – A potentiometer or encoder provides actual position data to the controller.
3. Error Correction – The control circuitry adjusts the motor's movement until the desired position matches the feedback reading.

3. Types of Servo Motors - AC Servo Motors – Operate on AC supply; suitable for high-power applications. - DC Servo Motors – Operate on DC supply; preferred for low-power and precision tasks.- Positional Rotation Servos – Move to a specific angle within a limited range (e.g., 0°–180°).- Continuous Rotation Servos – Rotate continuously in either direction at variable speeds.- Linear Servos– Convert rotary motion into linear displacement.
4. Technical Specifications (Example for Standard Hobby Servo Motor)

Parameter	Value
Operating Voltage	4.8V to 6.0V DC
Stall Torque	~1.8 kg·cm at 4.8V
Operating Speed	~0.1 s/60° at 4.8V
Control Signal	PWM (Pulse Width Modulation)
PWM Frequency	50 Hz (20 ms period)
Rotation Range	0° to 180°
Gear Material	Plastic or Metal
Weight	~45 g

5. Wiring and Connections
Standard servo motors have three wires:- Red → VCC (Power Supply)- Brown/Black → GND (Ground)- Orange/Yellow/White → Signal (PWM input from microcontroller)
6. Control and PWM Timing
Servo position is determined by the PWM pulse width:- 1.0 ms pulse → 0° position- 1.5 ms pulse → 90° position (center)- 2.0 ms pulse → 180° position (Values may vary depending on the servo model.)
7. Applications- Robotics – Joint control in robotic arms and mobile robots.- RC Models – Steering systems in cars, planes, and boats.- CNC Machines – Precision motion control.-Home Automation – Adjustable camera mounts, automated locks.- Antenna Positioning Systems – Fine directional adjustments.
8. Maintenance & Precautions- Avoid exceeding rated voltage to prevent overheating.- Do not block the servo horn while powered to prevent motor strain.- For heavy loads, use metal-gear servos for durability.- Keep gears lubricated (if serviceable) for smoother operation.- Avoid exposure to water unless using waterproof models.

3.4 SOLAR PANEL

A solar panel is a device that collects and converts solar energy into electricity or heat. It known as Photovoltaic panels, used to generate electricity directly from sunlight Solar thermal energy collection systems, used to generate electricity through a system of mirrors and fluid-filled tubes solar thermal collector, used to generate heat solar hot water panel, used to heat water. It is energy portal. A solar power technology uses solar cells or solar photovoltaic arrays to convert light from the sun directly into electricity. Photovoltaics, is in which light is converted into electrical power. It is best known as a method for generating solar power by using solar cells packaged in photovoltaic modules, often electrically connected in multiples as solar photovoltaic arrays to convert energy from the sun into electricity. The photovoltaic solar panel is photons from sunlight knock electrons into a higher state of energy, creating electricity.
Solar cells produce direct current electricity from light, which can be used to power equipment or to recharge a battery. A less common form of the technologies is thermophotovoltaics, in which the thermal radiation from some hot body other than the sun is utilized. Photovoltaic devices are also used to produce electricity in optical wireless power transmission.
Solar Panel SKU:
SO.PO.1624862 Watt: 5 Watt
Warranty Duration: 25 Years of warranty
Rated Power Range: 1-30 W
Module Voltage: 12 V
Solar cells pShort Circuit Current: 0.3 A
Module Dimension (L x W x T): 304 x 184 x 15 mm
Type of Product: Polycrystalline

Voltage at Pmax (V): 17.3 V
Junction Box: Normal Junction Box With Diode
Applications: Home, Outdoor And Commercial Use
Open Circuit Voltage: 21.6 V
Tolerance: 0.01Cell
Efficiency: 0.176
No. of Cells: 36Panel
Type: Polycrystalline
Warranty Type: 25 Years Power Output Warranty

4. RESULT AND DISCUSSION

The solar detection and tracking system was evaluated through simulation and real-time implementation, confirming its ability to enhance energy efficiency. The system automatically adjusts the solar panel's position according to sunlight direction to maximize power generation.In the simulation stage, Proteus software was used, with an Arduino UNO substituting the ESP32. Core operations such as sensor data handling, servo control, and LCD output were tested. A potentiometer simulated varying sunlight by changing input voltage. The controller responded effectively, adjusting the servo position and displaying real-time voltage and system status on the LCD. Although environmental conditions could not be fully replicated, the simulation verified the control logic and system behavior. For hardware testing, components including the ESP32, solar panel, voltage sensor, servo motor, and LCD were assembled and exposed to actual sunlight. The system successfully monitored voltage and adjusted the panel orientation using PWM signals. It consistently aligned the panel with the sun, improving energy capture compared to fixed systems, particularly during morning and evening hours.The LCD enabled continuous monitoring, and the system showed stable operation with minimal delay. However, factors like dust, shadows, and cloud cover affected accuracy, and slight delays occurred due to motor movement. Power usage of the servo was also noted. Despite these limitations, the system performed reliably. With further improvements such as better algorithms, calibration, or dual-axis tracking, efficiency can be increased. Overall, the system offers a practical and cost-effective solution for sustainable energy applications

5.CONCLUSION

The project titled *"Design and Development of Solar Detection and Tracking System"* has been successfully designed, implemented, and tested to improve the efficiency of solar energy utilization. The main objective of the project was to overcome the limitations of conventional fixed solar panels by introducing an automated tracking mechanism that continuously aligns the panel with the direction of maximum sunlight. The results obtained from both simulation and hardware implementation confirm that the system performs effectively and achieves its intended purpose. The integration of the ESP32 microcontroller with components such as the solar panel, voltage sensor, servo motor, and 16x2 LCD display resulted in a well-coordinated and functional system. The microcontroller played a crucial role in processing real-time data and controlling the movement of the servo motor through PWM signals. This enabled precise adjustment of the solar panel's position, ensuring optimal exposure to sunlight throughout the day. The system demonstrated significant improvement in energy efficiency compared to traditional fixed solar panels. By continuously tracking the sun's movement, the system was able to maximize energy absorption, especially during early morning and late evening hours when fixed panels are less effective. The real-time monitoring feature, implemented using the voltage sensor and LCD display, provided valuable insights into system performance and made the system user-friendly.

Throughout the development and testing phases, the system showed reliable and stable performance under different environmental conditions. Although minor challenges such as environmental variations, mechanical delays, and power consumption were observed, they did not significantly affect the overall functionality of the system. These challenges can be further minimized through optimization techniques and advanced design improvements. The project also highlights the importance of combining renewable energy technologies with modern embedded systems to create smart and efficient solutions. It promotes the use of clean and sustainable energy, contributing to environmental protection and reducing dependence on fossil fuels. The modular and scalable design of the system allows for easy upgrades and future enhancements, such as dual-axis tracking, IoT-based monitoring, and intelligent control algorithms. In addition, the system is cost-effective and suitable for practical applications in homes, agricultural fields, and remote areas where efficient energy utilization is essential. It provides a foundation for further research and development in the field of solar energy and smart energy systems.

In conclusion, the solar detection and tracking system proves to be an efficient, reliable, and sustainable solution for improving solar energy generation. The project successfully demonstrates how automation and intelligent control can enhance the performance of renewable energy systems, making it a valuable contribution towards a greener and more energy-efficient future.

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