DESIGN OF A DUAL-AXIS SOLAR TRACKING PHOTOVOLTAIC SYSTEM

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ABSTRACT: This paper presents the design and implementation of a dual-axis photovoltaic tracking system that optimizes solar energy capture through active positioning. The proposed system employs an automatic sun-tracking algorithm that continuously adjusts the solar panel's orientation along the vertical and horizontal axes. The control architecture integrates servo motors for mechanical movement, photoresistors for light intensity detection, and a voltage sensor for monitoring system performance. A microcontroller manages data acquisition and signal processing, ensuring real-time adjustment based on sensor feedback. The project development involved both hardware design and software programming stages. The hardware stage included the selection of appropriate components, electrical circuit assembly, and power management. The software stage focused on developing a control algorithm to process sensor data and drive the servomotors efficiently. Performance testing was conducted to assess parameters such as tracking accuracy, sensor reliability, and overall energy conversion efficiency. The obtained results demonstrate that the active tracking mechanism significantly enhances the photovoltaic system's effectiveness compared to fixed-panel configurations, confirming the system's potential for practical renewable energy applications.

KEY WORDS: photovoltaic system, dual-axis, tracking, optimization, renewable energy.

1. THEORETICAL BACKGROUND

Mobile solar tracking systems represent an advanced and efficient solution for optimizing the energy capture of photovoltaic panels. Their main objective is to dynamically orient the panels to follow the sun's movement across the sky throughout the day, maximizing the duration of direct solar exposure. Compared to fixed systems, tracking systems can significantly increase the overall energy conversion efficiency [5].

There are two main types of solar tracking systems: single-axis and dual-axis. Single-axis trackers allow panel movement along one axis, typically east–west, providing daily optimization but limited seasonal adjustment. Dual-axis systems, on the other hand, enable movement on both horizontal and vertical axes, allowing precise alignment with the sun's position during different times of the day and seasons. This leads to improved performance and higher energy yield, often increasing efficiency by up to 35% compared to fixed installations [3].

Although dual-axis trackers are more complex and costly, their capability to adapt to variable lighting conditions and seasonal angles makes them ideal for large-scale or high-efficiency photovoltaic applications. These systems ensure better space utilization and long-term energy cost reduction, representing a highly effective approach for maximizing solar energy production [4].

Light sensors are among the most commonly used means for tracking the sun's position in solar tracking systems. These sensors are employed to measure the intensity of sunlight incident on the photovoltaic panels, enabling the system to adjust the panel's orientation for maximum exposure. Another widely used approach for sun position detection is based on GPS coordinates. This method utilizes a GPS module to determine the exact geographic location of the solar panels, from which the optimal tilt and azimuth angles can be calculated to achieve proper alignment with the sun [4, 6].

A further technique relies on the calculation of the solar azimuth, a geographic parameter representing the angle between the true north direction and the position of the sun. Determining the azimuth depends on both the sun's apparent position in the sky and the geographical coordinates of the installation site.

Each of these detection methods presents specific advantages and limitations. The choice of method depends on several factors, including system complexity, cost constraints, environmental conditions, and performance requirements. In practice, combining light sensors with azimuth-based calculations provides an effective and reliable solution for most solar tracking applications.

A significant example of advanced solar tracking technology is the system developed by SunPower, a global leader in the solar energy industry. SunPower provides integrated solar energy solutions, including high-performance photovoltaic panels and tracking systems designed to optimize sunlight capture throughout the day [4, 7,8].

Another relevant example is Nextracker, a company specializing in single-axis solar tracking technology. Nextracker has developed systems that enable solar panels to tilt along a single axis, following the sun's movement from east to west to maximize solar irradiance and energy generation [7].

A further example is the tracking system offered by Soltec, an international provider of photovoltaic and tracking solutions. Soltec focuses on the development of dual-axis tracking technologies that allow solar panels to move along both the horizontal and vertical planes, ensuring precise solar alignment during the entire day.

These industrial examples highlight the continuous advancement of solar tracking systems, demonstrating how innovative mechanical and control solutions contribute to improved energy efficiency and optimized power generation in modern photovoltaic installations.

2. SOFTWARE DESIGN AND ALGORITHM IMPLEMENTATION

This work aims to develop an intelligent solar tracking system capable of optimizing the orientation of a photovoltaic panel to maximize energy collection efficiency. The project combines principles of automation, microcontroller programming, and sensor integration to create an innovative device that addresses the efficiency limitations of fixed solar panels. Through this system, the importance of applying smart technologies to enhance renewable energy performance is emphasized.

Key features of the system include:

- ✓ Use of an Arduino Nano microcontroller to coordinate data acquisition and servo motor control [2].
- ✓ Four photoresistors arranged in a square configuration to detect the direction of sunlight.
- ✓ Two SG90 servo motors enabling two-axis movement (horizontal and vertical).
- ✓ A 5V solar panel connected to a voltage sensor for performance monitoring.
- ✓ A dedicated power source for servo motors to prevent microcontroller overload.
- ✓ An active tracking algorithm that maintains the optimal panel position throughout the day.

2.1. System Architecture

The system is divided into three subsystems:

The sun position detection subsystem employs four photoresistors arranged in a square configuration to detect light intensity from different directions. The analog signals generated by these sensors are processed by

the Arduino Nano, which determines the sun’s relative position. Based on these readings, the control algorithm calculates the necessary corrections to realign the solar panel, ensuring accurate and responsive tracking even under varying light conditions.
The control and positioning subsystem utilizes two SG90 servo motors to adjust the panel along the X and Y axes. The Arduino Nano generates PWM signals to drive the servos, providing smooth and precise motion [1, 2]. A proportional control strategy minimizes positional error, while a dedicated power supply and safety constraints protect the system from overloads and mechanical stress.
The efficiency monitoring subsystem measures the voltage output of the solar panel through a dedicated sensor. The collected data allow the algorithm to evaluate performance in real time and adjust the panel’s orientation when efficiency decreases. This feedback mechanism ensures optimal energy capture and provides valuable insight into environmental influences on photovoltaic performance.
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2.2. Tracking system design

The block functioning diagram of the system is shown in figure 1.
The central unit of the system is *the Arduino Nano microcontroller*, which coordinates all components, collects sensor data, processes information, and sends control commands to the actuators. It executes the sun-tracking algorithm that continuously adjusts the solar panel to its optimal orientation.
The sun position detection unit consists of four photoresistors arranged in a square configuration. Each sensor measures light intensity, and the differences between their outputs indicate the sun’s relative position. The Arduino Nano processes these analog signals to determine the required movement direction, ensuring accurate and continuous tracking throughout the day.

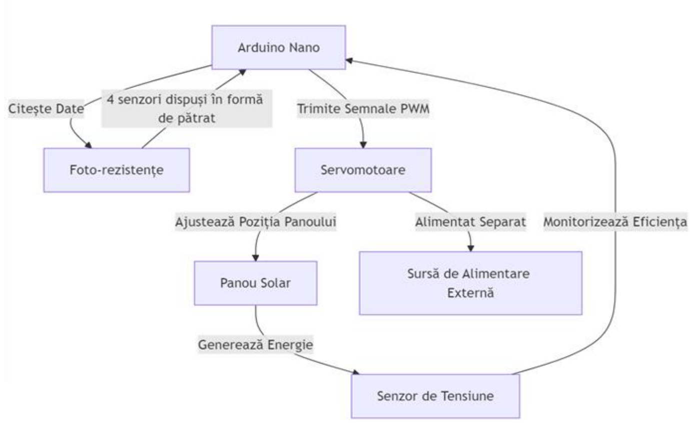

Figure 1. Block functioning diagram of the system

2.3. Tracking system components

The development board used in this project is the Arduino Nano ATmega328P, which serves as the main microcontroller responsible for data processing and control operations. The system employs two MG90S servo motors, chosen for their energy efficiency and ability to deliver a torque of approximately 2.2 kgf·cm at 4.8V, ensuring precise and stable movement of the solar panel.
The light detection system utilizes cadmium sulfide (CdS) light-dependent resistors (LDRs), which respond effectively to variations in solar intensity and provide accurate input data for the tracking algorithm.
The photovoltaic module used is a 5V, 1W solar panel, capable of supplying sufficient power for experimental validation and system monitoring.
For the voltage divider circuit, resistor R1, placed closest to the input voltage, has a value of 30 kΩ, while resistor R2, positioned near the ground, has a value of 7.5 kΩ. These resistors are used in conjunction with a voltage sensor module that measures the panel’s output

voltage, allowing the system to monitor performance and evaluate energy conversion efficiency in real time. The electrical circuit design of the system is shown in figure 2 and the physical design is presented in figure 3.

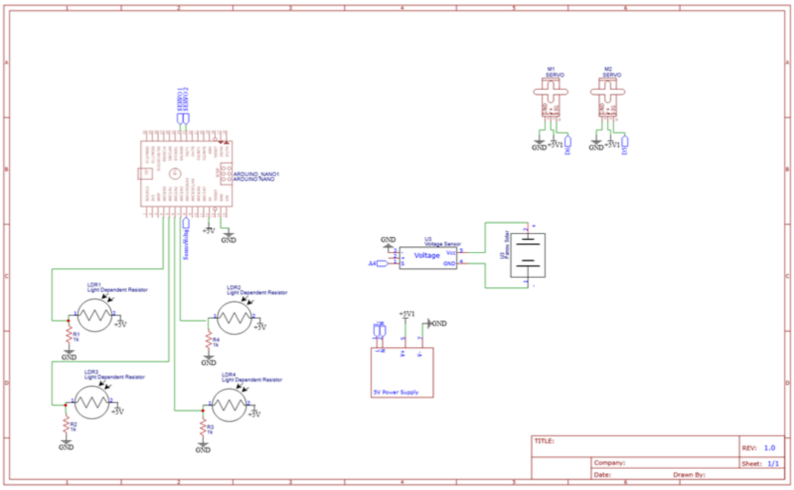

Figure 2. Electrical circuit design of the system

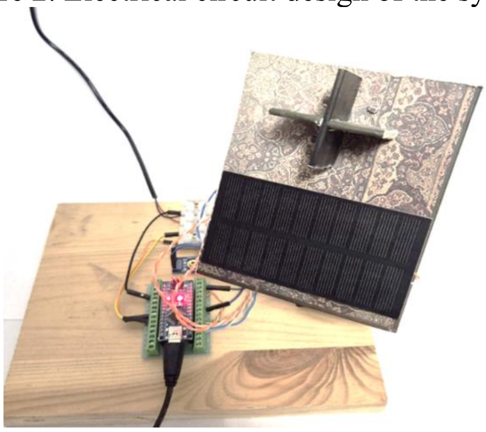

Figure 3. Physical design of the system

2.4. Software implementation for tracking system

The software component is essential for the proper operation of the system, as it manages hardware behavior, processes sensor data, and coordinates the servo motors to maintain the solar panel at its optimal orientation. The algorithms were developed in Arduino IDE using C++ to ensure maximum system efficiency.

The process begins with the initialization of servos and photoresistors, where all hardware components are activated and prepared for operation. Following initialization, the system proceeds to read the photoresistor values, acquiring analog signals from each of the four sensors. To minimize errors and fluctuations caused by ambient light variations, the program then calculates the average of the readings, providing a stable reference for determining the panel's optimal position.

Next, the algorithm checks whether a vertical adjustment is required by comparing sensor differences against a predefined threshold. If exceeded, the system performs vertical correction by activating the corresponding servo motor to adjust the panel's tilt. If the threshold is not exceeded, no vertical adjustment is made. A similar procedure is applied for horizontal adjustment, where sensor comparisons determine if a horizontal movement is necessary, followed by horizontal correction using the other servo motor.

After all adjustments, the system executes voltage measurement and display, evaluating the panel's efficiency, and finally checks stability, ensuring that the servo positions are steady and the panel is aligned optimally. This structured algorithm allows continuous, responsive tracking while maintaining precise control and real-time efficiency monitoring. The code sequence below (figure 4) is used for adjusting the position of the solar tracking system on the two axis, horizontal and vertical.

```
if (abs(medie_sus - medie_jos) > prag_sensibilitate)
{
  if (medie_sus < medie_jos)
  {
    pozitie_verticala = max(pozitie_verticala - 1, limita_inferioara_verticala);
  }
  else
      {
        pozitie_verticala = min(pozitie_verticala + 1, limita_superioara_verticala);
      }
      servomotor_vertical.write(pozitie_verticala);
      delay(10);
    }
 if (abs(medie_stanga - medie_dreapta) > prag_sensibilitate)
 {
   if (medie_stanga > medie_dreapta)
   {
     pozitie_orizontala = min(pozitie_orizontala + 1, limita_superioara_orizontala);
   }
   else
   {
     pozitie_orizontala = max(pozitie_orizontala - 1, limita_inferioara_orizontala);
   }
   servomotor_orizontal.write(pozitie_orizontala);
   delay(10);
 }

 delay(50);
}
```

Figure 4. Coding of the tracking system positioning

2.5. Results and performance of tracking system

Using the designed dual-axis solar tracking photovoltaic system live data were collected on the level of energy absorption (figure 5) and two tests were performed.

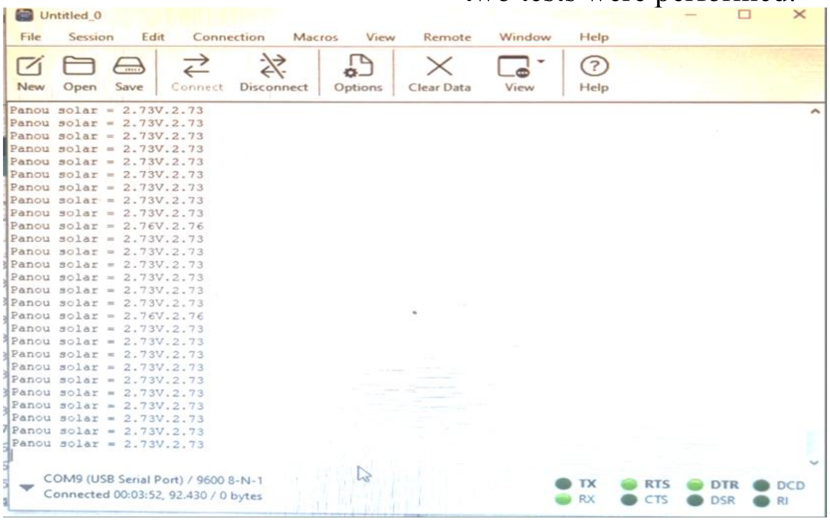

Figure 5. Collecting data from the tracking system

For the first part of the test, the active sun-tracking functionality was employed. In this configuration, the solar panel continuously oriented itself toward the light source, with servo motors adjusting its position to maintain optimal incident angles throughout the day. The panel's voltage and current were monitored using a voltage sensor. The average measured voltage was approximately 4.8 V, with minimal hourly variation, indicating consistent optimal positioning. The average current was 200 mA, resulting in an average power output of approximately 0.96 W, close to the panel's nominal power of 1 W, demonstrating efficient and stable energy generation.

In the second part of the test, the solar panel was fixed at a static angle, simulating a typical stationary installation. Measurements were taken under identical lighting conditions and at the same times of day. The panel produced an average voltage of 4.3 V and a current of 180 mA, corresponding to an average power of approximately 0.774 W.

Table 1. Performance comparison

Parameters	Values for panel in fixed position	Values for panel with dual-axis tracking
Voltage	4.3 [V]	4.8 [V]
Current	180 [mA]	200 [m]A
Power	0.77 [W]	0.96 [W]
Nominal power	0.8 [W]	1 [W]

Comparing the two configurations (table 1), active tracking improved energy capture by about 24% relative to the fixed panel. These results clearly demonstrate that active sun-tracking significantly enhances the performance of photovoltaic systems, maximizing solar energy collection throughout the day and confirming the practical benefits of implementing dynamic orientation mechanisms.

3. CONCLUSION

The experimental results confirm that the proposed dual-axis solar tracking system operates effectively. The servo motors provided precise and responsive movement along both axes, allowing the solar panel to continuously align with the sun throughout the day. The control algorithm successfully coordinated the system, ensuring efficient sun tracking and maximizing energy capture. The photoresistor sensors offered stable and accurate measurements, enabling precise panel positioning, while the voltage sensor reliably monitored the power output under varying lighting conditions. Overall, the tests demonstrated that the system meets its design objectives, maintaining optimal panel orientation and generating energy close to the panel's nominal capacity. These findings validate the concept and indicate that the system is a practical solution for improving photovoltaic efficiency in real-world applications.

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