Photovoltaic Station based on ESP32 and Two-Axis Movement Mechanism Controlled by Solar Tracking Algorithm for Rural Areas

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Abstract: - Rural areas suffer from an energy deficiency due to their difficult access and low economic conditions, which limits their development and quality of life. The conversion to renewable energies, such as photovoltaic solar energy, emerges as a viable alternative to meet this need, but it is necessary to consider the technical and economic challenges associated with its implementation to guarantee its long-term viability. Research background highlights the potential of solar-powered home PV stations as a clean alternative to fossil fuels in diverse climates such as Peru, where coastal regions can benefit from optimal charging infrastructure due to high projected solar radiation. The research shows an autonomous control system integrated into a photovoltaic station with solar tracking for which a validation prototype was developed. As a result, the prototype of the autonomous control system with solar tracking demonstrated its effectiveness in capturing energy and visual monitoring verified the dynamic adjustment to light conditions to optimize solar collection. The main conclusion is that the implementation and remote monitoring of a photovoltaic station with two-axis solar tracking demonstrated the viability of the technology in obtaining energy efficiently.

Key-Words: - photovoltaic station, ESP32, sun tracking, rural zones, remote monitoring, solar tracking, LDR.

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1 Introduction

Currently, there is an energy deficiency in rural areas or human settlements because they do not have electricity due to remote or poorly accessible areas. Furthermore, as they belong to areas of low economic level, they are not considered in future electrical planning, showing a lack of support from the state added to the difficulty of access, the investment in electrification, and the management of uncontrolled zonal growth of the population, [1], [2]. The lack of energy affects economic development and the quality of life of people, because there are limitations in areas such as health and education, [3], [4]. The conversion of renewable energy appears as a solution due to the absence of electricity in the sectors, since they are inexhaustible sources of energy, [5], [6]. With the use of renewable energy, installation, operating, and maintenance costs are reduced because photovoltaic stations with solar panels can support some of the basic services required by inhabitants of rural areas. However, there is a related problem because these systems must be placed over large areas of a region to meet the needs since they need a clear area to obtain sunlight. On the other hand, climate variability and adverse atmospheric conditions can reduce the efficiency of solar panels, [7], [8].

In the review of the literature, it was found that many investigations seek to promote the acquisition of a renewable energy system [9], based on the design and implementation of a domestic photovoltaic station, [10], [11]. For this reason, in the context of countries with a diversity of climates, such as Peru, optimal charging infrastructures are implemented to supply energy considering that the solar radiation projected for the year 2024 can generate the equivalent of 398 MegaWatts [12], [13]. For this reason, the rural areas of the coast of Peru are an optimal place for the use of solar panels, [14], [15].

In relation to the use of solar panels, some papers describe the use of bifacial solar cells, which increase energy generation in relation to the elevation of the module, [16], [17]. It is also indicated that a stable relationship between charge and energy consumed is increased with the use of Lithium-Iron Phosphate batteries [18], [19], Lead-Acid (Pb), ultracapacitors and Lithium-Ion capacitor,s [20]. Also, there are different types of energy charging techniques such as the application of constant voltage or current, [21], [22] using in some cases electronic curve plotting systems for characterization and evaluation, [11], [23].

Regarding the efficiency of the solar panel with a tracking system, the paper describes that it increases its performance by dynamically positioning its location perpendicular to the solar radiation for which a control stage, light sensors, and direction motors are used, [24], [25]. Furthermore, this control stage is integrated by a management algorithm, which reduces power losses by improving energy quality, [26], [27]. In some research, techniques based on artificial intelligence algorithms with MPTT and Shunt Active Parallel Filter algorithms are used to optimize energy capture, [28], [29].

On the other hand, web-based systems have been developed using the Python OTSun library to analyze solar collection devices and thermal simulation as photovoltaics. Users can use the application by installing it locally using Docker containers or by accessing the server provided, [30], [31]. In addition, other research highlights the importance of real-time monitoring due to the intermittent nature of solar energy and its focus on key aspects such as computer boards, sensors, and cloud platforms, concluding that Amazon Web Services, [32].

Due to the aforementioned, the research question arises: How can a photovoltaic station for homes in rural areas be designed? It is for this reason that this paper describes the design and implementation of a photovoltaic station with a two-axis solar tracking mechanism, for which it seeks to adapt its design to rural locations, which have exposure to the sun for most of the year. This station is made up of solar panels, a battery for energy storage, and a structure for the movement of the panel. In this way, a sustainable alternative is provided to meet the energy demands of communities that have limited energy resources.

The paper is presented in sections corresponding to the introduction; Section 2 of materials and methods describes the methodology; Section 3 shows the results; Section 4 focuses on the discussion and finally, the conclusions.

2 Materials and Methods

The research describes an autonomous control system integrated into a photovoltaic station with solar tracking for which a validation prototype was developed, in smaller size and power to demonstrate the integration of the technologies.

Therefore, the following specific activities are conducted: The components are defined, and the scientific method is applied by evaluating the interaction of the station processes through a block diagram of the battery charge management stage, the solar tracking process, and the ESP32 hardware (Figure 1).

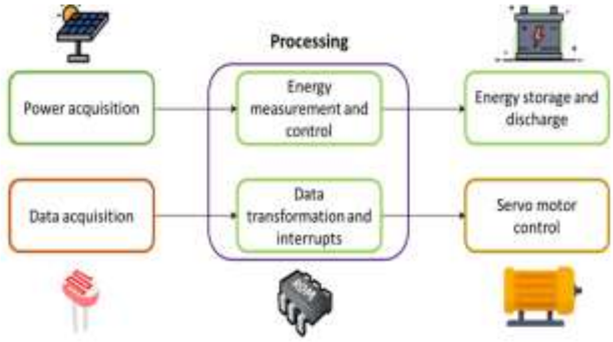

Fig. 1: General block diagram

On the other hand, the design of the electronic circuit is shown in Figure 2, which covers the aforementioned processes: battery management (green box), which displays the solar panel, the optocoupler and the battery with its Management System (BMS), and the solar tracking (orange box), whose devices are the switches such as switches, the LDRs connected with their resistors and the servomotors, connected to the ESP32 device, which acts as the processing block (purple box).

2.1 System Architecture Components

The station uses an HFK-7.5V polycrystalline photovoltaic solar cell because it is economical and for commercial use, with an operating voltage greater than 5V for battery charge management. In addition, an LDR 5528 photoresistor (LDR) is used for the acquisition of solar tracking data, comparing the best position of the light in horizontal and vertical directions.

The ESP32 development board that controls the algorithm has a 32-bit processor and WiFi connectivity and is programmed using the ARDUINO IDE environment to manage sensor data, power charging and actuator control. For energy storage, a compact device with a BMS system and 'Quick Charge 3' technology is used.

Finally, SG90 servomotors are used to move the base horizontally and the solar panel vertically.

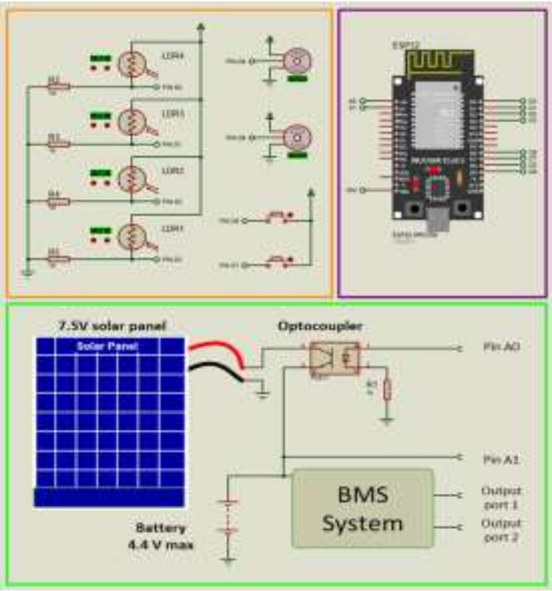

Fig. 2: Electronic diagram of the system

2.2 Electronic Circuit for Battery Charge Management

Once the system components have been defined, the design process of the energy management stage is defined, which begins with the ADC module of the ESP32, energy control with the switches, storage with a battery, and regulation with the internal BMS system. of the battery and the delivery of power to other external components (Figure 3). The design of the electronic circuit of the energy management stage is shown in Figure 4, consisting of the solar panel on the left side, the optocoupler in the upper central part, the battery, the internal BMS system in the lower central part, and the module ESP32 on the right side.

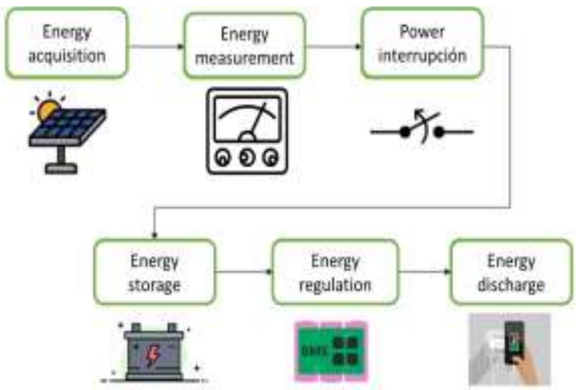

Fig. 3: Block diagram for battery charge and discharge management

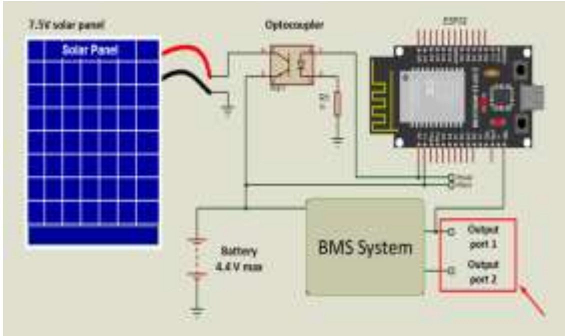

Fig. 4: Electronic circuit for battery charge management during discharge

The processes related to energy management are the following:

- Energy Acquisition. It converts solar energy into electricity using the solar panel with the support of the solar tracking system.
- Energy Measurement. It is done through the ESP32, which measures the battery voltage through pin A1 connected to the positive side, performing an analog-digital conversion.
- Power Outage. It interrupts the flow of energy from the solar panel to the battery when it is 100% charged, using the data obtained from the ESP32. An optocoupler is used for this function.
- Energy storage. The battery is constantly charged while it is not 100% charged using the regulator system. Adjust the battery charge from 4.4V to 5V.
- Energy Discharge. The last process involves discharging the battery through two ports: one to charge the ESP32 device and another to charge an additional device.

2.3 Control Algorithm for Solar Tracking

The operation diagram of the algorithm is shown in Figure 5, where it begins with the process of acquiring data from the sensors and the time until the correct positioning of the solar panel facing the sun. The algorithm that was implemented for this project includes a library for the use of servomotors, ADC functions, and a system interrupt in the Arduino IDE program. The LDR sensors are connected to bias resistors for light-intensity data collection along with external switches that activate the interrupt functions.

The algorithm performs data acquisition through the LDRs using the ADC and the trigger signal detection as an external switch. The trigger variables are "pos" and "ps2", which will take the angular position data for the servomotors and the variables "int1" and "int2" to control the internal interrupt function (Table 1). The libraries used to control the servomotor are in “ESP32Servo.h”, while “WiFi.h” and “time.h” allow to initialize the Wi-Fi network.

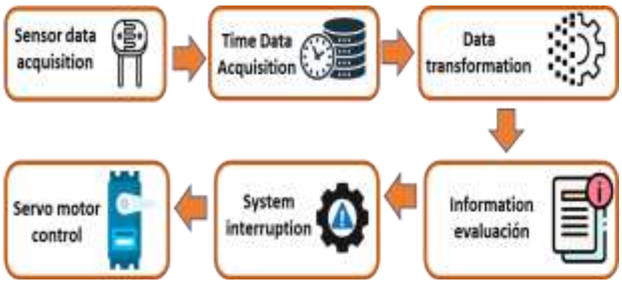

Fig. 5: Block diagram of the control algorithm for solar tracking

Table 1. Algorithm variables

Input variables	Transformed variables	Activation variables
Ldr_1	v_ldr1	int1
Ldr_2	v_ldr2	int2
Ldr_3	v_ldr3	pos
Ldr_4	v_ldr4	ps2

The mathematical model used for system calibration is essential to ensure the accuracy and efficiency of the solar tracking mechanism operation. During the data acquisition process, the voltages obtained from the photoresistors (LDR) are calibrated because each one has different resistance values. To do this, a set of equations is implemented that directly relate the sensor signals to the movement of the system in the four main directions: up, down, left and right.

During the data acquisition process, the LDR voltages are calibrated, they already have different resistance values. Therefore, as a result, we have the equations shown in Table 2 with respect to the variable “v_ldr1” (equation 1), “v_ldr2” (equation 3), “v_ldr3” (equation 5) and “v_ldr4” (equation 7). Subsequently, these values are transformed so that they are related to the movement and directions up, down, left and right, using the variables “prom_top” (equation 2), “prom_bot” (equation 4), “prom_left” (equation 6) and “prom_right” (equation 8).

Figure 6 shows the algorithm diagram for transforming and updating the position variables of the servomotors, which starts by reading the data in four positions. Then, the difference between the upper and lower values is evaluated by updating it in 10 units, checking if its angle is greater than 90. When it is less than 90 in the vertical position, it rotates horizontally clockwise, however, the opposite occurs when it is greater than 90. The algorithm detects when the limits of the conditioned values, which are configured for the rotation of the servomotors, are exceeded, not taking negative values or greater than 180 due to its working range.

Table 2. Calibration and transformation equations

Calibration equation	Transformation equation
(eq. 1) v_ldr1 = $13 * analogRead(Ldr\_1)/15$	(eq. 2) prom_top= $(v\_ldr1 + v\_ldr4)/20$
(eq. 3) v_ldr2= $analogRead(Ldr\_2)$	(eq. 4) prom_bot = $(v\_ldr2 + v\_ldr3)/20$
(eq. 5) v_ldr3 = $analogRead(Ldr\_3)$	(eq. 6) prom_left = $(v\_ldr3 + v\_ldr4)/20$
(eq. 7) v_ldr4 = $13 * analogRead(Ldr\_4)/14$	(eq. 8) prom_right = $(v\_ldr1 + v\_ldr2)/20$

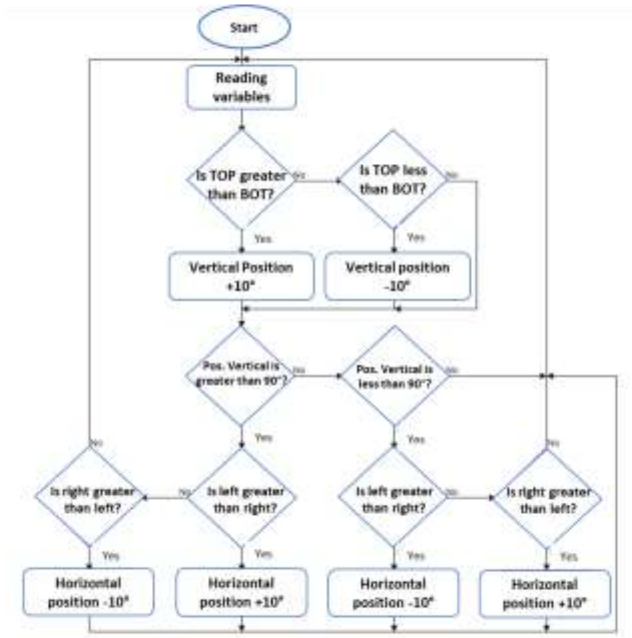

Fig. 6: Position Variables Update Flowchart

2.4 Integration of System Components in the Pilot Test Model

The assembly of the prototype model was conducted (Figure 7), which is integrated by the prototype base with the servomotor, energy stage, ESP32 device, and mechanical structure for vertical and horizontal movement.

Additionally, the photovoltaic panel is mounted so that it can be oriented towards the sun, with external cables to avoid entanglement during the platform's rotation. Safety considerations, such as overload protection, have been considered, ensuring safe operation of the station.

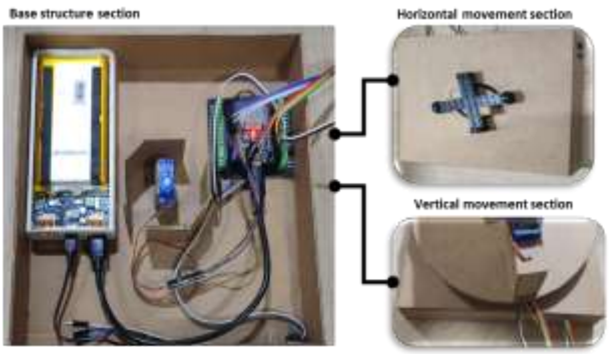

Fig. 7: System structure components

3 Results

This section describes the results related to the integration of the components, the electronic circuit developed for battery charging and the control of solar tracking based on two axes focused on the prototype. Figure 8 shows the integrated components such as the battery, the ESP32 SoC that controls the servomotor to perform the horizontal movement of the platform, along with the LDRs and the solar panel.

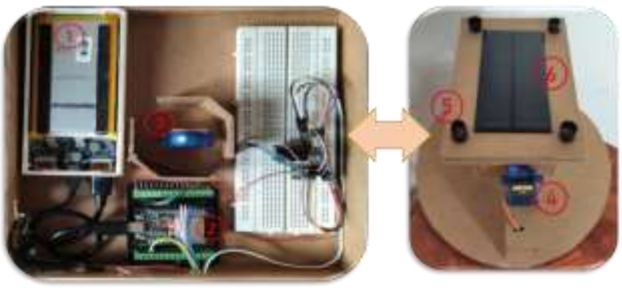

Fig. 8: Electronic components of the base and upper part of the structure

To evaluate the energy supply behavior of the photovoltaic station, battery load tests were conducted in the circuit, conducting voltage measurements to determine its behavior (Figure 9), obtaining full load values of 4.08V (68% load). (Figure 9 (a)) and current of 80.1 mA in series (Figure 9 (b)), when the solar panel is positioned horizontally directly to the sun (Table 3).

To monitor the data, the position and direction of the solar cell location mechanisms, LDR data, and servomotor status, an information visualization stage was integrated using a ThingSpeak web service, which provides an interface for remote access. The ESP32 module sends this information via the Internet to monitor widgets, using the HTTP protocol, to display the LDR data, servomotor status, and activation of the tracking system as seen in Figure 10. This is done using the ThingSpeak Platform which allows for monitoring real-time data such as solar cell position, LDR data, and servo motor status. Setup involves creating a channel, generating API keys, and programming the ESP32 to send data at minimum 15 second intervals.

(a)

(b)

Fig. 9: Measurement tests of (a) voltage generation and (b) current consumption

Table 3. Battery charge and voltage ratio

Battery charge	Voltage
1%	3.4 V
25%	3.65 V
50%	3.9 V
100%	4.4 V

4 Discussion

The selection of system components was appropriate in relation to the choice of devices that are adequately integrated at an electrical level in a reduced space, which was validated in a pilot test. The system components, such as the battery, allowed the ESP32 SoC device and the servomotors that perform the horizontal and vertical movement to be adequately powered. In addition, the four LDR sensors allow adequate sunlight detection, acting automatically to modify the orientation of the servomotors.

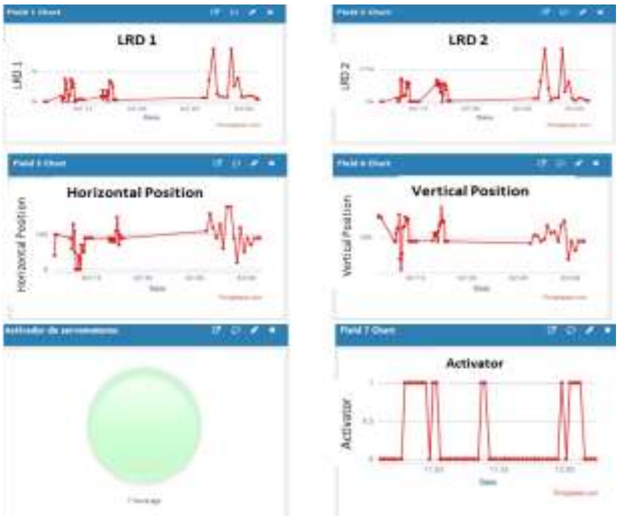

Fig. 10: Measurement of LDR values: ADC Voltage vs Time

In relation to the energy supply behavior, it was verified that the solar panel turned out to be efficient in converting solar energy into electrical energy, generating an average current of 80mA during a short-circuit measurement and managing it effectively, guaranteeing optimal operation of the prototype in the pilot test.

The integration of an information visualization stage, using the ThingSpeak web service, allowed effective monitoring of data related to the position and direction of the solar cell location mechanisms using the monitoring widgets. The generated graphs adequately showed that the system operated continuously 24 hours a day, optimizing the obtaining of light for the solar panel during the hours of greatest intensity, verifying the visualization of the LDR data obtained for real-time verification. Therefore, the system's ability to dynamically adjust to lighting conditions is evident, maximizing solar collection efficiency.

The tracking system is a contribution to solar energy harvesting, making it cost-effective and sustainable in rural settings, with the potential to save energy and reduce dependence on non-renewable sources. Despite its scalability, durability in harsh conditions and internet availability are barriers that could be overcome by rugged materials and local connectivity solutions such as LoRa.

5 Conclusion

The implementation of a photovoltaic station was conducted with a two-axis solar tracking mechanism based on light-intensity sensors. In addition, the successful integration of solar panels, an energy charging system, and ESP32 control device was validated. The appropriate components for the construction of the system were identified in relation to the limitations inherent to the development of a pilot-scale prototype, checking the energy generation necessary to charge the 3.7V battery and power the device and sensors. The remote Web monitoring application resulted in an efficient way to determine the performance of the system operation due to the ease and accessibility of the information.

Compared to other solutions, the system proposed in this work stands out for its simplicity and efficiency in implementing solar tracking using light sensors, in contrast to previous works that employ more complex or expensive mechanisms such as predictive algorithms or control systems. Unlike these approaches, which require more robust infrastructure and higher processing resources, this solution focuses on maintaining energy efficiency and accessibility in limited environments.

In future work, it is recommended that the solution be evaluated on a scale of experimental tests in the field and with a dedicated power stage for servomotors, since it alters the proper calibration of positioning and other devices. In addition, you should consider using more solar panels of the same voltage or others with greater power. Finally, for greater solar tracking control, the use of an algorithm based on fuzzy logic is suggested, since environmental alterations that do not follow a deterministic pattern could appear.

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Conflict of Interest

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