



RASTREAMENTO SOLAR DE BAIXO CUSTO COM CONTROLE ANGULAR POR GIROSCÓPIO E SENSORES LDR

LOW-COST SOLAR TRACKING WITH ANGULAR CONTROL USING GYROSCOPE AND LDR SENSORS

Autores: Francisco Everton Silva Marinho¹, David Ciarlini Chagas Freitas², Gabriel Calixto Rodrigues Sampaio³, Antônio Guedes Cavalcante Júnior⁴, Maely Moreira Lopes⁵, Natan Vitorino de Oliveira⁶

¹Instituto Federal do Ceará | Campus Pecém – evertonmarinho353@gmail.com;

²Instituto Federal do Ceará | Campus Pecém – david.ciarlini@ifce.edu.br;

³Instituto Federal do Ceará | Campus Pecém – gabriel.calixto@ifce.edu.br;

⁴Instituto Federal do Ceará | Campus Pecém – guedes@ifce.edu.br;

⁵Instituto Federal do Ceará | Campus Pecém – maelymoreiralopes241@gmail.com;

⁶Instituto Federal do Ceará | Campus Pecém – vitorinonatan133@gmail.com;

RESUMO

A crescente demanda por fontes alternativas e sustentáveis de energia tem impulsionado o desenvolvimento de sistemas que aumentem a eficiência na captação de energia solar. Dentre essas alternativas, os sistemas de rastreamento solar têm se destacado como uma solução eficaz para maximizar o aproveitamento da luz solar ao longo do dia, ajustando dinamicamente a posição dos painéis de acordo com a movimentação do Sol. Neste contexto, este trabalho propõe o desenvolvimento de um sistema automatizado de rastreamento solar, com o objetivo de otimizar a captação de luz em painéis fotovoltaicos. O sistema é composto por sensores de luz, um motor de passo, um microcontrolador e um sensor giroscópio, integrados a uma lógica de controle que permite a movimentação autônoma do painel em direção à maior intensidade luminosa. A lógica de funcionamento baseia-se em uma abordagem proporcional, tanto em relação à variação dos valores dos sensores quanto ao cálculo angular com base nas leituras do giroscópio. O projeto foi desenvolvido com foco em baixo custo e fácil implementação. Testes práticos foram realizados para a calibração dos componentes e validação do sistema, demonstrando que o rastreador é capaz de responder com precisão às mudanças de iluminação no ambiente, melhorando o aproveitamento da energia solar em 4,29%, mesmo usando um sistema de controle que gasta uma certa quantidade de energia.

Palavras-chave: Rastreamento solar; Sistema fotovoltaico; Automação de baixo custo;

ABSTRACT

The growing demand for alternative and sustainable energy sources has driven the development of systems that improve the efficiency of solar energy capture. Among these alternatives, solar tracking systems have stood out as an effective solution to maximize sunlight utilization throughout the day by dynamically adjusting the position of solar panels according to the Sun's movement. In this context, this work proposes the development of an automated solar tracking system aimed at optimizing light capture in photovoltaic panels. The system is composed of light sensors, a stepper motor, a microcontroller, and a gyroscope sensor, integrated into a control logic that enables autonomous movement of the panel toward the highest light intensity. The operating logic is based on a proportional approach, considering both the variation in sensor readings and the angular calculation based on the gyroscope data. The project was developed with a focus on low cost and ease of implementation. Practical tests were conducted for component calibration and system



validation, demonstrating that the tracker can accurately respond to changes in ambient lighting, improving solar energy utilization by 4.29%, even when using a control system that consumes a certain amount of energy.

Keywords: Solar tracking; Photovoltaic system; Low-cost automation;

1 INTRODUCTION

The growth in global energy demand and the environmental impacts caused by traditional energy sources have driven the search for renewable alternatives. Solar energy, being clean, abundant, and silent, has stood out as one of the most promising solutions. However, many solar systems operate with fixed panels, which are not always in the optimal position to capture the maximum amount of sunlight throughout the day, compromising their energy efficiency [1].

One solution to this problem is the use of solar tracking systems (trackers), which automatically adjust the panel's position according to the apparent movement of the Sun. Studies indicate that solar tracking systems can achieve higher energy production compared to fixed systems, resulting in better utilization of captured energy [2]. However, many of these systems are expensive or require complex circuits and calculations.

This work proposes the development of a low-cost and easy-to-implement automated solar tracking system, using LDR (Light Dependent Resistor) sensors for light detection, a stepper motor for movement, an LCD (Liquid Crystal Display) for real-time reading, an MPU6050 gyroscope to improve positioning accuracy, and an Arduino Mega 2560 microcontroller to control the system.

2 STATE OF THE ART

Several academic projects and studies have already addressed the development of solar tracking systems using different technological approaches. Many employ LDR sensors in pairs or cross-shaped arrangements, as seen in works that developed photovoltaic microgeneration systems with solar tracking [3]. These systems used LDR sensors positioned at different points to compare the intensity of incident light and, based on this, adjust the position of a solar panel via an Arduino microcontroller, with the aim of maximizing energy capture throughout the day.

In more advanced projects, such as the one developed by [4], hybrid dual-axis solar tracking systems are used, combining light sensors (LDRs) and GPS-based time data to calculate the sun's position. This system significantly improves energy efficiency, especially under cloudy sky conditions, by integrating astronomical calculations with geographical location information. Although accurate, these systems require greater computational capacity, making them more expensive and complex to implement.

Another common approach is the use of servomotors instead of stepper motors. Although easier to control, servos have a limited range and lower torque, which can be a drawback in real-world applications with larger panels [5]. Another studies applied in Brazil context also demonstrates significant gains with the use of low-cost solar trackers. [6] For example, a system that uses a DC motor powered by the photovoltaic panel itself in a simple tracker results in average generation increases of 19.9% in June and 26.3% in December on clear-sky days.

In this project, the use of a stepper motor was chosen precisely for its precision in control and adaptability to wider movements. The main difference between the present work and the aforementioned ones is the introduction of proportional step logic and,



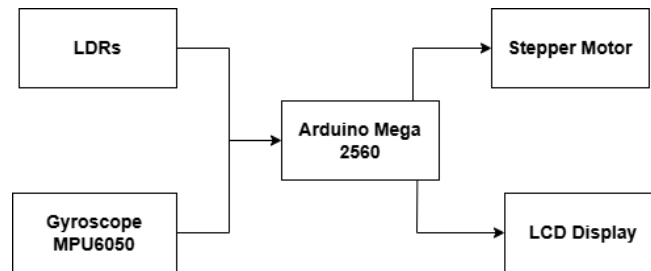
subsequently, the use of a gyroscope for angle-based control. This feature ensures greater accuracy, flexibility, and independence from the initial position, allowing the system to self-correct automatically without the need for constant manual calibration.

3 METHODOLOGY

The project development was divided into five stages: architecture, positioning of the LDRs, calibration of the panel position, calibration using the gyroscope, and data collection.

The first stage involved designing the system architecture, as illustrated in Figure 1.

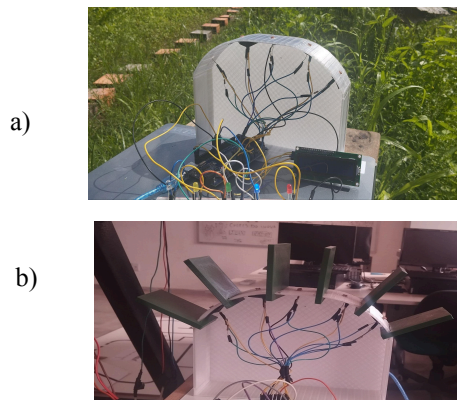
Figure 1. Project Architecture Plan



Components were selected based on related works and implementation feasibility, considering cost and simplicity. Five LDR sensors, a NEMA 26 stepper motor, a TB6600 driver, an Arduino Mega 2560 microcontroller, and an LCD display with I2C communication were used. These elements were integrated into a structure printed in PETG (Polyethylene Terephthalate Glycol).

In the second stage, the LDR sensors were initially mounted on a semicircular base without dividers (Figure 2a), allowing a wide incidence of light. However, initial tests showed that the values read by the five LDRs were very similar to each other, making it difficult to accurately identify the direction of the highest light intensity. Therefore, vertical barriers were added between the sensors (Figure 2b) to ensure a more precise reading of the solar position.

Figure 2. Strategy used for positioning the LDRs.





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In the third stage, a proportional movement system for the panels was implemented using only the LDR sensors and the stepper motor. The logic consists of identifying the position with the highest light intensity based on the LDR readings and moving the motor proportionally to the distance between the current position and the new one, measured in steps. However, after some testing, it was observed that the stepper motor did not exhibit good positional repeatability. This limitation compromised the system's stability and accuracy over time, making continuous and reliable solar tracking difficult.

The algorithm implemented in the project is presented in Figure 3. Its main function is to read the values from the LDR sensors and identify which one is receiving the highest light intensity. Based on this information, the stepper motor moves proportionally to the position, using a base variable of steps per position. For example, if from position 1 to position 3 (center) there are two base steps, the motor moves $2 \times \text{base\_steps}$.

In line 1, the algorithm starts a loop from $i \leftarrow 1$ to 5, where the LDR sensor values are read and stored in the `LDR[i]` array. In line 2, the initial comparison value (`maxValue`) is set using the first sensor, and in line 3, the corresponding position (`maxPosition`) is set to 1. From line 4, the algorithm loops from $i \leftarrow 2$ to 5 to identify which sensor has the highest light intensity. When a higher value is found, it updates `maxValue` and `maxPosition`.

Figure 3. Algorithm used in the calibration tests.

```
1  for i ← 1 to 5 do
2  LDR[i] ← ReadLDR(i)
3  maxValue ← LDR[1]
4  maxPosition ← 1
5  for i ← 2 to 5 do
6  if LDR[i] > maxValue then
7  maxValue ← LDR[i]
8  maxPosition ← i
9  highlight ← TRUE
10 for i ← 1 to 5 do
11 if i ≠ maxPosition and (maxValue - LDR[i]) < 50 then
12 highlight ← FALSE
13 if highlight and maxPosition ≠ currentPosition then
14 direction ← (maxPosition > currentPosition)
15 steps ← abs(maxPosition - currentPosition) × 800
16 MoveMotor(direction, steps)
17 currentPosition ← maxPosition
18 else
19 currentPosition ← 3
```

In line 9, the variable `highlight` is initially set to `TRUE`. In lines 10 to 11, the algorithm checks whether the difference between the highest value and the other sensor values is significant. If not, `highlight` is set to `FALSE`. In line 12, if `highlight` is `TRUE` and `maxPosition` is different from the `currentPosition`, the system calculates the direction and number of steps, and performs the movement using the `MoveMotor` function. Finally, if there is no `highlight`, line 17 sets the current position to 3 (central position), keeping the system in a neutral position when there is no clearly dominant light. Poor results were obtained using only the LDR sensors and the stepper motor.



Thus, in the fourth stage, it was decided to add an MPU6050 gyroscope, as shown in Figure 4. It began to be used to identify the system's current angle when powered on and to correct the position to the center (0°) before starting operation. This made the system more robust and reliable, especially after shutdowns or successive reboots. The code was modified so that the stepper motor would rotate based on the degrees provided by the gyroscope.

Figure 4. Implemented algorithm with gyroscope

```
1  angleX ← gyroAngleX
2  angleY ← gyroAngleY
3  angleZ ← gyroAngleZ
4  display("X:", angleX)
5  display("Y:", angleY)
6  display("Z:", angleZ)
7  if NOT centered then
8      if |angleZ| < 3 then
9          currentAngle ← 0
10         currentPosition ← 3
11         centered ← TRUE
12         display("Centered at 0° (position 3)")
13     else
14         if angleZ > 0 then
15             direction ← UP
16         else
17             direction ← DOWN
18         steps ← |angleZ| × stepsPerDegree
19         rotateMotor(direction, steps)
20         currentAngle ← 0
21         currentPosition ← 3
22         resetGyroscope()
23         centered ← TRUE
24         display("Realigned to center")
```

During the centering stage, the algorithm reads the three angles (X, Y, and Z), but the alignment check is based on the Z angle (rotation around the vertical axis). If this value is close to 0° (with a margin of $\pm 3^\circ$), the system considers the panel to be already centered, setting the current position as the center (position 3).

If the panel is out of alignment, the system calculates the direction of movement based on the angle's sign (positive or negative) and determines the number of steps required for the motor, proportional to the value read. The stepper motor then performs the movement, repositioning the panel until it reaches the center. After realignment, the system resets the gyroscope parameters to ensure stability in future readings.

This procedure ensures that, even if the system is powered on in an incorrect position, it can automatically adjust to the initial reference position before starting the tracking operation.



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After the tests based on proportional movement by steps, an improvement was implemented in the system with the addition of the MPU6050 gyroscope sensor. The aim was to replace the fixed-step logic with one based on actual tilt angles, providing greater accuracy and autonomy to the solar tracking system. It is necessary to indicate where the gyroscope was installed.

The system started recognizing the central position (position 3) as the 0° angle and, from there, calculates how many degrees it needs to move to reach the new desired position. A practical calibration was established to determine the number of steps per degree, allowing the stepper motor to perform displacements proportional to the calculated angle. This calibration enabled, for example, that if the system was tilted at -30° , it could automatically rotate back to 0° before starting the sweep with the LDR sensors.

During testing, the system was powered on in different positions and angles to verify if it could automatically realign to the center. The behavior was monitored via serial communication, which displayed the detected angle and the motor's movement direction in real time, facilitating the practical validation of the system's operation.

4 RESULTS AND DISCUSSION

After completing the development and calibration stages of the system, the data collection phase for performance analysis began. Current and voltage measurements of the solar panel were taken every 30 minutes over two consecutive days, both with the panel in a fixed position and with the tracking system in operation. For each time interval, the average between the two days was calculated in order to obtain a more accurate representation of the energy behavior, minimizing variations caused by weather conditions or other external factors.

Table 1 presents the average values obtained with the panel in a fixed position, while Table 2 shows the corresponding average values for the panel using the tracking system.

Table 1 - Table of data from the fixed panel system

Hr	I _{pn} (mA)	V _p (V)	E _{pn} (Wh)
9:00	106,2	41,65	2,211615
9:30	105,45	41,30	2,1775425
10:00	103,7	40,95	2,1232575
10:30	105,45	41,15	2,1696375
11:00	104,5	40,95	2,1396375
11:30	99,3	38,95	1,9338675
12:00	101,75	41,00	2,085875
12:30	103,3	41,35	2,1357275
13:00	105,85	41,25	2,18315625
13:30	104,1	41,20	2,14446
14:00	104,1	40,55	2,1106275
14:30	103,75	40,55	2,1035312
15:00	104,5	40,80	2,1318
15:30	104,2	40,65	2,117865
16:00	101,95	39,65	2,02115875



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17:00	86,3	33,15	1,4304225
		Total	34,6520687

Table 2 - Table of data from the moving panel system

Hr	Ipn(mA)	Vp(V)	Epn(Wh)
9:00	107,05	41,7	2,2319925
9:30	104	40,9	2,1268
10:00	103,95	40,9	2,1257775
10:30	102,9	40,05	2,0605725
11:00	102,3	40,05	2,0485575
11:30	102	40,05	2,04255
12:00	103,75	40,95	2,12428125
12:30	103,75	40,5	2,1009375
13:00	104,9	41,2	2,16094
13:30	104,05	41,55	2,16163875
14:00	104,3	41,6	2,16944
14:30	104,3	40,85	2,1303275
15:00	105,05	41,25	2,16665625
15:30	105,35	41,4	2,180745
16:00	104	40,7	2,1164
16:30	103,9	40,75	2,1169625
17:00	102,9	40,25	2,0708625
		Total	36,13544125

The measurements presented in Tables 1 and 2 were carried out under identical weather conditions, aiming to show the difference between the fixed and the mobile systems. Table II displays the average results of the solar tracking system, whose dynamic movement is automatically controlled based on the light intensity detected by the sensors, as described in Section III – Methodology. The comparison between both scenarios allows the evaluation of the efficiency gain provided by the automated system in relation to the conventional fixed model.

In addition to the current and voltage measurements taken every 30 minutes, Equation (1)

$$E_{pn} = V_p \times I_{pn} \times t \quad (1)$$

For the calculation of the generated energy E_{pn} (in Wh), where V_p is the voltage (in V), I_{pn} is the current (in A), and t is the measurement time (in hours), considered as 0.5 hours (30 minutes). Based on this, the average energy values were obtained for each time slot throughout the mentioned period, which were highlighted in the tables along with their respective measured times (Hr).

For a more accurate assessment of the automated system's performance, the energy consumption of the control components during the operating period (from 9 a.m. to 5 p.m.) was also considered. The stepper motor consumes 0.57 A at 21 V while idle, whereas the Arduino consumes 0.04 A at 8 V. During movement (on average three times per day, each lasting approximately 5 seconds), the



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motor reaches 1.86 A and the Arduino reaches 0.07 A, totaling 98.32 Wh in idle mode and 0.16534 Wh in motion, resulting in a daily consumption of 98.49 Wh.

5 CONCLUSIONS

The system was able to successfully recentralize itself, with an average deviation of less than 3° and an average realignment time of approximately 3 seconds. This ensured greater robustness in operation, reducing the margin of error in cases of manual repositioning or accidental restart. In addition, experimental measurements were carried out comparing the performance between a fixed panel and another with automated tracking, both oriented to the north and tilted at 15°. The results showed that the tracking panel generated approximately 4.29% more energy than the fixed panel. However, when considering the energy consumption of the system itself, composed of the stepper motor and the microcontroller, it was observed that the system becomes unfeasible in energy terms for the motor and the number of panels used. For future versions, it is proposed to implement strategies such as automatic motor shutdown during inactivity and the use of more panels.

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