Design of an Automated System to Optimize the Capture of Solar Energy in Photovoltaic Panels

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Abstracts: This article presents the design of an automated solar tracker system to increase the efficiency of low-cost photovoltaic panels. The proposed meetings follow the sun's movement across the sky at any time of the day using two axes, which perform an azimuthal activity and estimate the solar height. The axes are controlled by a program that uses an astronomical model implemented within a Raspberry Pi module. The program receives the date and time data through the Wi-Fi network and the geographic coordinates through a GPS module for updating the position of the solar tracker in real time. The proposed design can be applied to most commercial photovoltaic panels with maximum measurements of 2m x 1.05m x 4 cm.

Keywords: Optimization of Solar, Energy Capture, Solar Tracker, Solar Energy System, Photovoltaic Panels.

1. INTRODUCTION

The use of renewable energies is increasing worldwide due to environmental concerns, with solar energy having achieved more significant development due to its abundance, sustainability, and free cost. Peru has favorable weather conditions for generating electricity by capturing solar energy using photovoltaic panels [1].

The more efficient solar energy capture in photovoltaic panels can be achieved by improving the amount of sunlight directly hitting the panels [2]. In photovoltaic systems, the solar panels are coupled to solar tracker devices formed by a fixed and mobile part, whose purpose is to augment the solar uptake. The goal is that the solar panels remain as perpendicular as possible to the sun's rays, which is achieved by using an astronomical program that uses a series of equations that predict the sun's position at all times and is controlled by a microcontroller [3].

According to [4], they reported an increase in solar energy uptake between 12.7 % and 26.1 % in a 4-day evaluation when they added a solar tracking structure controlled by an Arduino module to the photovoltaic panels. On the other hand, [5,6] investigated experimentally the operation of solar trackers in different operating conditions according to the position of the sun day by day and compared with the virtual application program Sun Earth Tools to know the margin of error, which allowed a better understanding of the way solar trackers work.

2. MATERIEL AND METHODS

The proposed system is made up of two parts. The electronic part consists of a Raspberry Pi module with its respective astronomical prediction program, the power circuit interface to supply the necessary energy to the motors in two tracking axes, and a GPS module to calculate the coordinates at all times of the solar tracker. The mechanical part comprises motors, encoders, casters, shafts, pinions, and supports.

2.1. Autonomous Mechanism of Solar Tracker

For the design of the structure, it was required to control the movement in two axes to support the system, horizontally to achieve the positioning of the azimuth angle from 0 to 359 degrees from the magnetic north and vertically to achieve the positioning of the angle of the solar height from 0 to 90 degrees. Two stepper motors were used for the movements. To obtain the azimuth angle Az and the solar height h, an astronomical algorithm was used, which requires the following parameters as the date, time, and the geographical coordinates of latitude and longitude provided by a GPS global positioning module that will give us this data in NMA format (Figure 1).

Its main features are:

- Pre-engineered aluminum structure.
- Support axle and steel moving axle.
- Encoder AFM60E-S4AK004096
- Stepper motor PRIMOPAL PHB57S56-430, Nema 23 de 1.1Nm, 1.8°/passed, axis 6.35mm, 56mm long, 3 Amper, bipolar, 4 cables, 690 gr.
- Driver Allegro A4988.

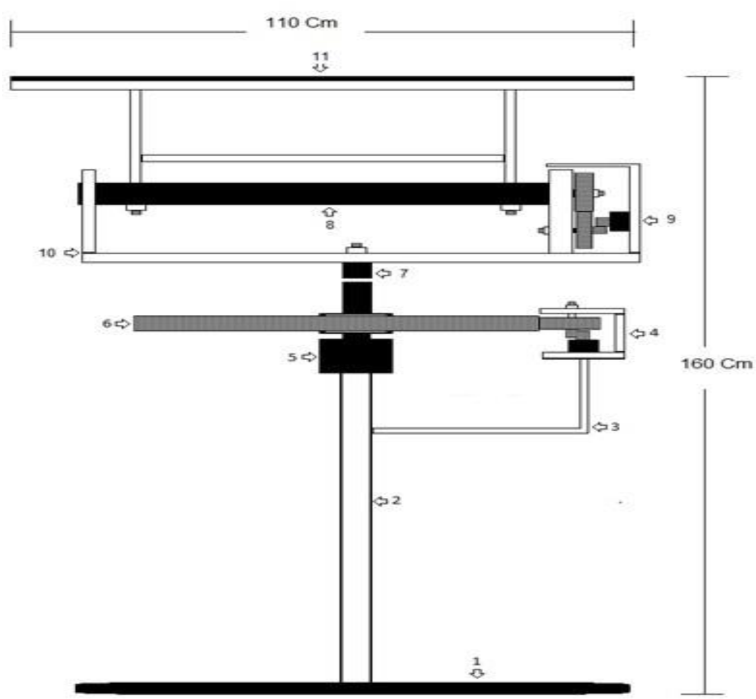

Figure 1. Full mechanism of solar tracker

In the upper mechanism, as shown in Figure 2, the following components are indicated:

- Number 11, the photovoltaic panel's metal support base is fixed to the vertical circular movement cylinder axis.
- Number 10, U-shaped metal support base.
- Number 9, fixing area of the stepper motor and the upper encoder.

- Number 8, cylindrical shaft fixed by fixed slides to the right-side sprocket.
- Number 7, the mobile axis of support to the upper mechanism.

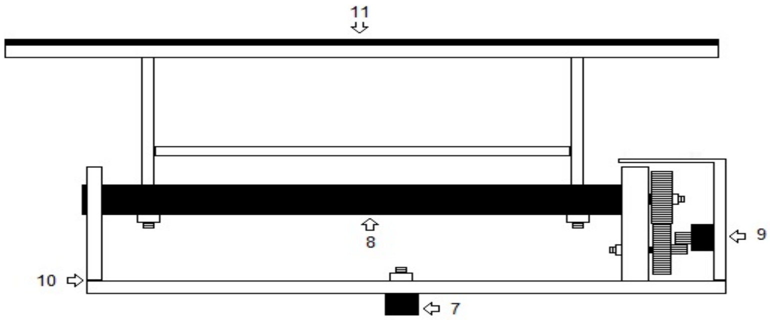

Figure 2. Top mechanism of the solar tracker

- Next, in Figure 3, the components of the lower mechanism are shown:
- Number 6, toothed wheel fixed to the horizontal turning.
- Number 5, main rotation horizontal circular.
- Number 4, Fixing the area of the steeper motor and encoder.
- Number 3, metallic angle of support of the stepper motor and lower encoder.
- Number 2 is the central fixed axis that supports the entire mechanism.
- Number 1, metal base that supports the entire upper and lower mechanism.

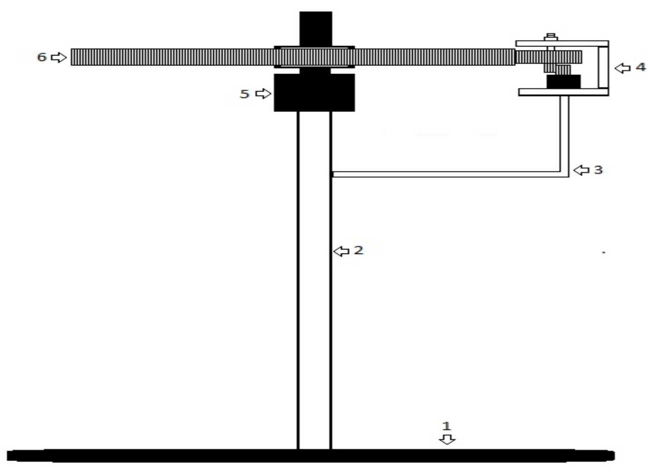

Figure 3. Top Mechanism of the Solar Tracker

2.2. Calculations

To direct the system in the correct solar position that changes in time, the program must calculate the azimuth angle and the elevation angle at solar noon, the two critical tips for the rotation of the two motors [7]. These angles are calculated using accurate solar time, which is not the same as the standard local time; there-fore, it is necessary to convert from the usual local time obtained from the GPS to accurate solar time [8].

Calculation of the decline:

$$\delta = 23.45\text{sen}\ (360((284 + j)/365)) \quad (1)$$

Where: j = number of the day of the year from January 1 = 1 to December 31 = 365.

Calculation of the part-time hour angle:

$$\cos\omega 0 = -\tan\delta \tan L \quad (2)$$

Where: L = latitude

Calculation of the duration of the day:

$$D = 2\omega 0/15 \quad (3)$$

Calculation of ortho and sunset time:

$$t_{ortho} = 12 - D/2 \quad (4)$$

$$t_{sunset} = 12 + D/2 \quad (5)$$

Calculation of the Solar Height in each hour:

$$\text{Sen}h = \text{sen}L\,\text{sen}\delta + \cos L \cos H \cos\delta \quad (6)$$

Where: h = Hourly angle, which is calculated for each hour knowing that noon is worth 0º and the sun goes 15º in each hour so that at 11 in the morning, it will be worth - 15º at 10 a.m. -30º and so on. The same thing would happen in the afternoon, but with a positive sign, the hour angle being + 15º at 13 o'clock, + 30º at 2 o'clock, and so on.

Calculation of the azimuth of each hour:

$$\text{Cos}az = (\text{Sen}l\,\text{sen}h - \text{Sen}\delta)/\text{Cos}l\cos h \quad (7)$$

2.3. Control Application

For the location of the stepper motors on the vertical and horizontal axes, a Python script has been developed to perform the necessary calculations, which provides the essential pulses required by the system to guide the mechanism that supports the photovoltaic panels. The panels rotate to the sun's current position by determining the solar height and the respective azimuthal angle.

The information with the new position is sent to the power circuit that amplifies the current sent by the Raspberry Pi (value of 25 mA) to 250 mA. The motors guide the movement of the photovoltaic panels so that the incidence of the sunlight is perpendicular to these at any time of the day, from sunrise to sunset [8], as shown in Figure 4.

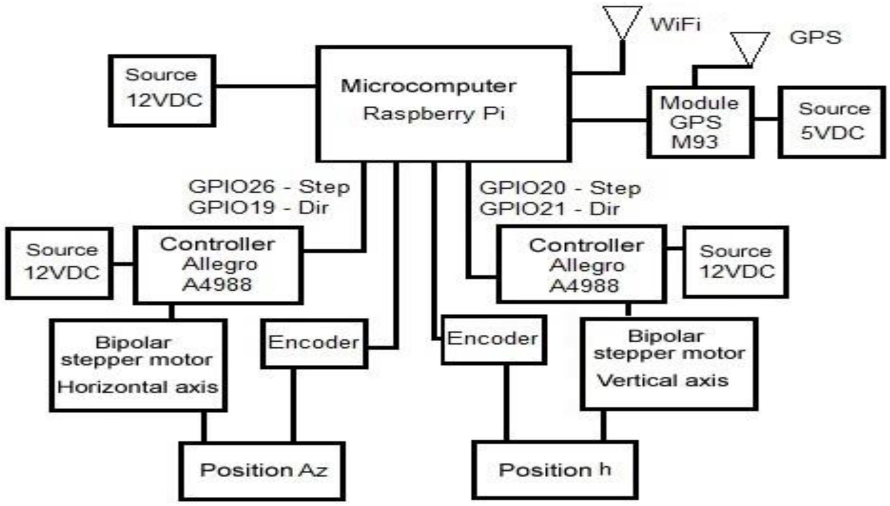

Figure 4. Block diagram of the control system and data acquisition

In Figure 5a and 5b, a section of the Python program that corresponds to the stepper motor control that controls the movement of the mechanical system on the vertical axis is presented.

```
gpio.setup(21, gpio.OUT)
gpio.setup(20, gpio.OUT)
gpio.setup(19, gpio.OUT)
gpio.setup(26, gpio.OUT)
#————————————————————————————————
#Step 4: Set the direction of rotation
# and the output to true for the left and false for the rightif direction == 'left':
gpio.output(19, True) elif direction == 'right':
gpio.output(19, False)
#— — — — — — — — — — — — — — — — — — — — — — — — — — —
#Step 5:
# Set the step counter and speed control variables
StepCounter = 0
WaitTime = 0.000001
#— — — — — — — — — — — — — — — — — — — — — — — — — — —
#Step 6: start main loop
while StepCounter < steps:
# turning on and off the  gpio |
#tells the controller to take a step
gpio.output(26, True)
gpio.output(26, False)
StepCounter += 1
# Wait before taking the next step
#this controls the speed of rotationtime.sleep(WaitTime)
   #————————————————————————————————
```

Figure 5a. Python program that controls the mechanical movement of the vertical axis

```
import sys
import RPi.GPIO as gpio
#https://pypi.python.org/pypi/RPi.GPIO#more info import time
#Step 1:
# read the address and number of steps
# if the steps are 0 exit
try:
direction = sys.argv[1]
steps = int(float(sys.argv[2]))
except:
steps = 0
#Step 2:
# Print in which direction and how many steps you haveprint("You told me to turn %s %s steps.")%
(direction, steps)
#——————————————————————————————————
#Step 3: Set up GPIOs
gpio.setmode(gpio.BCM) #GPIO21 = Direction
#GPIO20 = Step
#GPIO19 = Direction
#GPIO26 = Step
```

Figure 5b. Python Program That Controls the Mechanical Movement of the Vertical Axis

2.4. Control Application

We sought to design an algorithm that balances precision and ease of calculation. For this, the algorithm proposed by the U.S. Naval Observatory [9] offers some approximate formulas for the analysis of fundamental parameters of the astronomical positions with a precision of 1 arcmin or 1/60, which is sufficient for the requirements of the design of the project [10], as shown in Table 1.

Table 1. Most Common Photovoltaic Panel Brands and Sizes

Solar Panel Brand	Average dimensions of the solar panel
Canadian Solar	1.95m x 0.90m x 3cm
LG	1.70m x 1m x 4cm
Panasonic	1.60m x 1.05m x 4cm
Agudo	1.60m x 1m x 4cm
SolarWorld	2m x 1m x 3cm
Yingli Solar	1.65m x 1m x 4cm

To obtain the solar coordinates, the following twelve-step procedure is followed (Figure 6 shows its flow chart):

1) Start the System.
2) Load astronomical application developed in Python.
3) Declare variables and initialize the entire system.
4) Configure the GPIO pins of the Raspberry Pi microcomputer.
5) Put power on the GPS module and wait 5 minutes to perform an accurate data reading: $GPRMC,081836, A,3751.65, S,14507.36, E,000.0,360.0,130998,011.3, E*62.
6) Once the data read by the GPS Module has been checked with the system's location, date, and time, decoding the NMA frame read from the GPS module proceeds.
7) The first time the entire mechanical system is in the initial position, the data Az and h are calculated with the abovementioned equations.
8) The sun's position is obtained for the moment required in the elliptic coordinate system.
9) The obtained position is converted to the equatorial coordinate system.
10) The obtained data is converted to the horizontal coordinate system, correcting the coordinates for the time zone.
11) Encoders and feedback to the system with the final rotated degree read the axes' position.

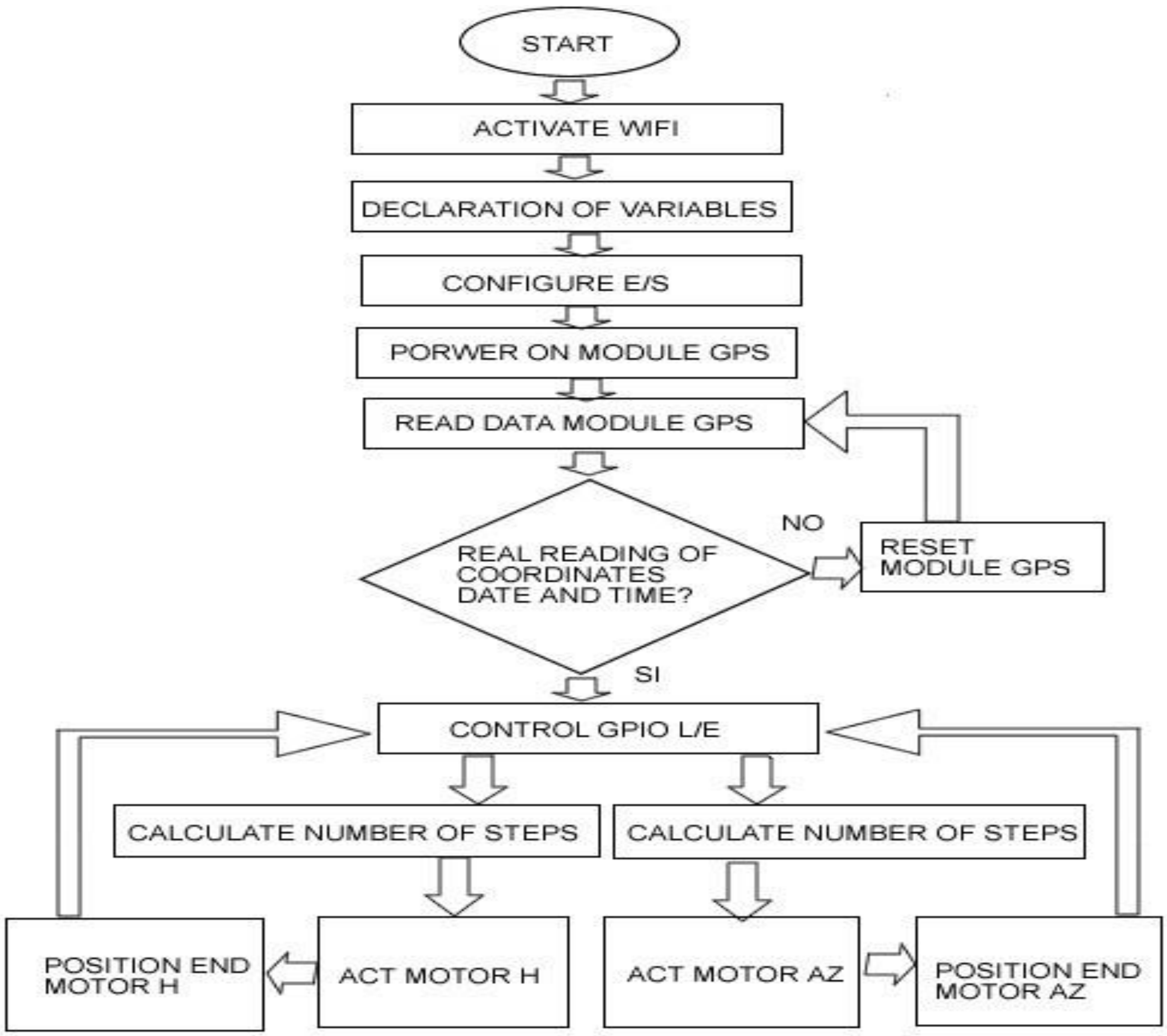

Figure 6. Flowchart of The Solar Tracker Program

CONCLUSIONS

In the present study, we have reached the following conclusions:

In the design of the solar tracking mechanism, which is responsible for positioning the photovoltaic panel according to the coordinates processed by the control algorithm, the weight of the entire structure resting on the two axes with their respective bearings has to be taken into account to allow for movement of the shaft without friction or wear problem between parts.

The control system design put forward in this work to optimize the uptake of the sun's energy must use a guiding system. Solar position angles and time intervals were calculated in real-time, thus obtaining the desired position of the system at any time of the day, with minimum error for the two displacement axes.

The system's design allows us to obtain a general perspective of the operation of the solar tracker for photovoltaic commercial panels with maximum measurements of 2m x 1.05m x 4cm. For the implementation of the project, this design can be used to guarantee a trouble-free operation.

REFERENCES

[1] Vazquez L, Zúñiga B. Proyecto de prefactibilidad para la implementación de energía solar fotovoltaica y térmica en el campamento Minero

Comihuasa. 2016; 1:196.

[2] Machado Toranzo N, Lussón Cervantes A, Leysdian Oro Carralero L, Bonzon Henríquez J, Escalona Costa O. Seguidor Solar, optimizando el aprovechamiento de la energía solar. Sol. tracker, Optim. of improvement of Sol. energy. 2015;36(2):190–199.

[3] Gómez S. Monitorización en tiempo real de seguidores solares fotovoltaicos en doble eje. 2016;144.

[4] Calderón JSG, Cruz PMR. Prototipo de sistema fotovoltaico con seguimiento solar de bajo costo. Pist. Educ. 2016;(120):911–922.

[5] Cárdenas JA, Hernández EJ. Diseño e implementación de un seguidor solar empleando un controlador PID con modo deslizante. 2014.

[6] Maiga A, Maiga A. Theoretical Comparative Energy Efficiency Analysis of Dual Axis Solar Tracking Systems. Energy Power Eng. 2021 Dec;13(12):448–482. https://doi.org/10.4236/EPE.2021.1312031.

[7] Thungsuk N, et al. Performance Analysis of Solar Tracking Systems by Five-Position Angles with a Single Axis and Dual Axis. Energies. 2023 Aug;16(16):5869. https://doi.org/10.3390/en16165869.

[8] Lemus A. Diseño y construcción de un sistema seguidor de sol con Modelo Astronómico. Rev. inge@uan. 2011;2(3):21–23.

[9] "Topocentric Configuration of Major Solar System Bodies." https://aa.usno.navy.mil/data/ssconf (accessed Aug. 27, 2023).

[10] Al-Ezzi AS, Ansari MNM. Photovoltaic Solar Cells: A Review. Appl. Syst. Innov. 2022 Jul;5(4):67. https://doi.org/10.3390/asi5040067.

DOI: https://doi.org/10.15379/ijmst.v10i2.3145