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Improved Design of Automatic Solar Tracking System based on Integration of Accelerometer, Compass Sensor, and GPS

Nguyen Thi Hoa[1], Nguyen Canh Toan[2], Tran Van Hanh[3], Gian Quoc Anh[1], Tran Hieu[1], Hoang Thi Phuong[1] and Duc-Tan Tran[4,*]

[1]*Faculty of Electric-Electronic Engineering, Nam Dinh University of Technology Education, Nam Dinh 07100, Vietnam*
[2]*Vietnam Maritime University, Hai Phong, Vietnam*
[3]*Center of Engineering Practice, Nam Dinh University of Technology Education, Nam Dinh 07100, Vietnam*
[4]*Faculty of Electrical and Electronic Engineering, Phenikaa University, Hanoi 12116, Vietnam*

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Abstract: Nowadays, solar energy has been studied and applied widely. This study presents a design of a two-degree-of-freedom system that automatically controls the photovoltaic module's orientation according to the sun's apparent motion to improve energy efficiency. The system exploits the valuable information from the Global Positioning System (GPS) receiver, accelerometer, and compass sensor. It not only enhances energy efficiency significantly but also reduces the complexity of mechanical systems and controllers.

Keywords: Solar Tracking, Compass Sensor, Accelerometer, GPS, DoF (Degree of Freedom)

1. Introduction

Energy demand is increasing, and researchers are always looking for clean sources of energy. Solar energy is a plentiful and clean energy source that meets the above requirements and is converted into electricity supplied to electrical equipment. If 0.16% of the land on the earth is used for solar energy with 10% efficiency will provide 20 TW of electricity, double the earth's fossil fuel consumption [1]. The solar system's efficiency can be improved by increasing the received light radiation and maximizing the energy conversion of the photovoltaic (PV) panels. However, the movement of the earth during the day and season changes the radiation intensity and the incident angle of the sun's rays to photovoltaic (PV) panels located at a specified position. Keeping the PV panels perpendicular to the incident light beam in real-time is a solution to improving energy conversion efficiency. The system automatically follows the sun to compensate for the sun's apparent movement, keeping the incident light rays perpendicular to the PV panel surface, increasing collection efficiency by 10-100% in periods and different topographic conditions [1]. Several published studies focus on the following:

Passive solar tracking systems (mechanical) utilize the thermal expansion properties of matter [2]. The mechanical system usually consists of a pair of drives working in opposite directions to control PV direction. When they receive equal amounts of light, they are balanced. When the received light is not identical, the difference causes the system to move in a direction that maintains this dynamic equilibrium. Systems operating on this principle have a simpler construction than the active one but offer lower efficiency, limited accuracy, and do not work at low temperatures.

Active (electrical) solar tracking systems use photoelectric sensors or time control. For sensor-based systems, the sun's radiation direction obtained on the light sensor is used as the feedback signal to control the PV always to follow the sun [3]–[5]. Instead of directly looking for the sun's position, the system uses sensors to find the source of the sunlight. This system has a more precise grip [6] but has problems with weather conditions, such as cloudy weather, leading to inaccurate results. With diverse light sources, especially in urban areas with many tall buildings and glass doors, the system can confuse sunlight and reflect light, resulting in unstable operation. Moreover, the installation of sensors also requires engineers to calculate and align accurately.

Some solar tracking systems are designed with one or two-degree of freedom. (DoF). A 1-DoF system tracks the sun in North-South, the seasonal solar movement during the year, or East-West, solar movement during the day, is presented in the study [7], [8], while a two-order system followed the sun in both the elevation and direction angle [9], [10]. One DoF system has a straightforward struc-

E-mail address: hoaktnd@gmail.com, toannc@vimaru.edu.vn, tranvanhanhspktnd@gmail.com, gianquocanh@gmail.com, tranhieunute@gmail.com, hoangphuong.spktnd@gmail.com, tan.tranduc@phenikaa-uni.edu.vn

ture, so it is widely applied. However, the 2-DoF system has higher energy efficiency per unit area [11], [12]. A comparison among a fixed system, a 1-DoF system, and a DoF system was presented in [13]. The theoretical and experimental simulation results show that the 2-DoF system offer outstanding productivity.

Some systems determine the solar position based on astronomical calculations to control the orientation of PV panel according to time [14]–[16]. The system uses the installation coordinates and time to calculate the sun's elevation and direction in real-time. The sun position is determined exactly regardless of weather conditions. However, sun-tracking, even on rainy, cloudy days consuming driving energy without gaining additional solar power, is useless. We can overcome this problem by switching the system in the horizontal direction to reduce energy consumption relative to the energy obtained [17] or by adding humidity and light sensors to decide whether to stick to the sun or not.

A similar tracking system was used for auto-positioning based on the solar orbit algorithm and astronomical equations to control the angle of elevation and direction [18]. The system has higher accuracy but a high cost and complex algorithm.

The open-loop control system uses either an encoder or stepper motor to determine the tilt and direction angles. Instead of directly determining the actual angle of tilt and direction, the system calculates indirectly through the engine's rotation angle and transmission. It requires the precise calculation of the ratio of communication between the engine and the mechanical system, and the powertrain is more complicated. On the other hand, it is difficult for the system to know the exact orientation angle if a slip occurs between the engine and transmission. This error will accumulate during the day until the system resets to the original state. During the installation, the system's initial position must be precisely aligned as the basis for the directional movement of the system. The feedback control system uses sensor feedback to determine the actual tilt and direction angle for control [3], [19]–[23]. This system has a simpler drive but is influenced by surrounding conditions such as magnetic material.

In this paper, we propose to build an automatic sun-holding control system with 2 DoF based on the calculation of the solar position relative to the position of the system on the ground. The proposed method uses the new technology of GPS positioning, accelerometer sensor, compass sensor with low power consumption and lower price. GPS module is used to get real-time information and the current system coordinates (i.e., longitude, latitude). Microcontroller chip reads information about coordinates, time to determine the sun position in real-time, calculate the time of sunrise and sunset in a day. On that basis, the microcontroller controls two stepper motors that change the direction and tilt angle so that PV is always perpendicular to the sun's rays.

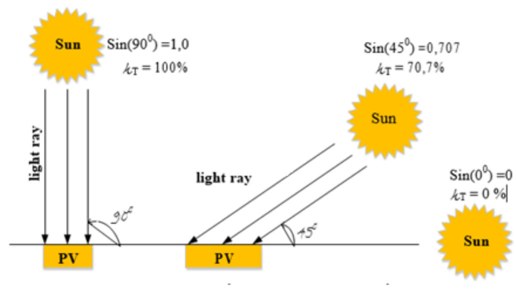

Figure 1. Performance of the PV with different incident angles

The proposed system has the following advantages: 1) Can be placed on a mobile device, changing the direction of motion, the system automatically locates and computes the sun's position to adjust the direction without impact from people; 2) Automatic sun tracking control with precise directional angle without requiring system directional alignment during installation; 3) Determining Sun orientation is not affected by light sources such as systems using light sensors; 4) Using very low energy consumption equipment, so the energy consumption for system control is low. In addition, to overcome the phenomenon that the system still sticks to the sun in unfavorable weather conditions (rain, cloudy), temperature and humidity sensors are used to support the system's operation decision.

The paper has four sections. After the introduction, we will present the hardware and software system's design in Section 2. The experiment results and evaluation of the proposed system are analyzed in Section 3. Finally, the conclusions are drawn in section 4.

2. Material and Methods

A. Hardware components

PV panel: the intensity of light radiation received on the PV module depends on the intensity of sunlight (see Figure 1). If the PV module is perpendicular to the sun's rays, the received power is maximum [14]. The tracking efficiency ratio in the direction of the sun (α) is determined by

$$\eta_T = 100.sin(\alpha)\% \quad (1)$$

Module GPS: GPS includes a network of 24 active satellites. At least seeing four satellites at one time can provide complete information about the location of the GPS receiver. Fastrax UP501alpha GPS module receives a GPS signal with a built-in antenna. The module communicates with user applications via serial port, using CMOS (Complementary Metal-Oxide-Semiconductor) voltage level or converting the level from CMOS to RS232.

Acceleration sensor: This kind of sensor has a wide application [24]–[26]. ADXL345 provides the output data with 13-bit resolution and can communicate peripheral in

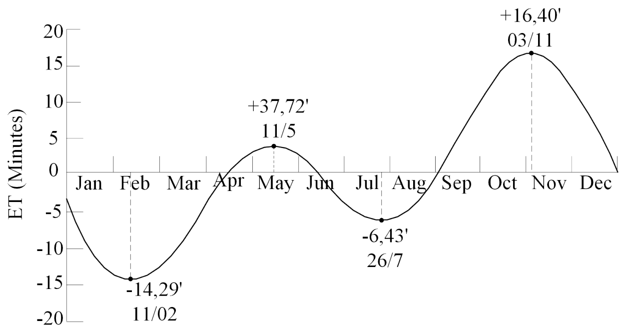

Figure 2. The equation of time (ET) vs. time

I2C (Inter-Integrated Circuit) or SPI (Serial Peripheral Interface) standard. The ADXL345 uses the twos-complement data format (positive numbers vary in the range 0-0FFF, negative numbers change in the range FFFF-F000). In the 13-bit mode, the least significant bit represents 2.9 mg. We use this sensor to compute the tilt angle of the solar panels.

Digital compass sensor HMC5883L: is a 3-dimensional sensor packed in an integrated circuit (IC) and uses Earth's magnetic fields to determind direction. The sensor has a digital interface using standard I2C communication. Inside the HMC5883L is a built-in 12-bit resolution ADC (Analog-to-Digital Converter) that allows an angle accuracy of up to 1 degree. We use this sensor to compute the direction angle of the solar panels.

B. Calculation of the sun's direction at the observation location

To receive solar energy optimally, it must predict the sun's position relative to the receiver. The difference between average solar time and the local one is presented in Figure 2. It is known as the *equation of time* (ET).

ET is calculated using the following expression [27]:

$$ET = 9,87sin(2B) - 7,53cos(B) - 1,5sin(B)\ (minutes) \quad (2)$$

where $B = \frac{360(d-81)}{365}$ $(degrees)$, d is the number of days in a year, starting from January 1, given in Table I.

To locate the sun from a point on the ground, we need to determine the sun's date, time, and location relative to the observation point on the surface. The the sun's position from an observation point on the earth's surface is determined using several parameters such as local solar time (LST), angle of deviation (δ), hour angle (H), and latitude (φ) of the sun. The relationship between LST and local time (LT) is represented by [27]:

$$LST = LT + \frac{TC}{60}\ (hours) \quad (3)$$

where TC is *a time correction* factor

$$TC = 4.(longitude - LSTM) + ET\ \ (minutes) \quad (4)$$

TABLE I. Number of days by month in the year

Month	Day number, d
January	d
February	d+31
March	d+59
April	d+90
May	d+120
June	d+151
July	d+181
August	d+212
September	d+243
October	d+273
November	d+304
December	d+334

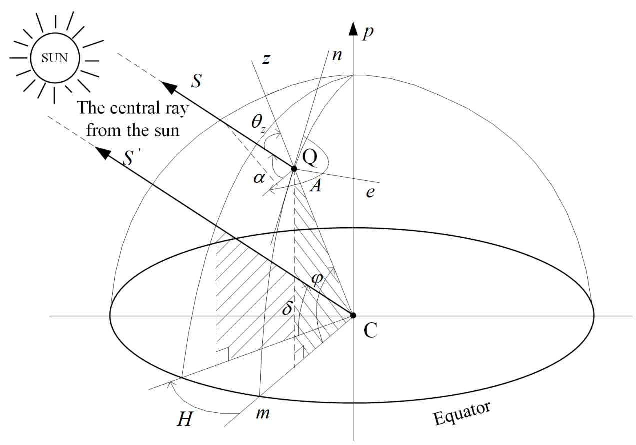

Figure 3. The coordinate system combined with sun rays parallel vector S, S'

where *longitude* is the longitude of the observations, *LSTM* is the Local Standard Time Meridian. The hour angle H is calculated using the following expression [27]:

$$H = 15^{\circ}.(LST - 12)\ (degrees) \quad (5)$$

The declination angle (δ) is computed as

$$\delta = sin^{-1}[sin(23,45^{\circ}).sin(\frac{360}{365}(d-81))]\ (degrees) \quad (6)$$

Determine the position of the sun from an observation point on the earth's surface which is determined through the parameters of elevation angle (α), and azimuth (A).

Consider the vector in the Qnez coordinate system at the point of view, then use the mathematics of displacement on the earth's center with another coordinate system located at the earth's center (see Figure 3). The vector S is defined as follows [27]:

$$S = kS_n + jS_e + iS_z \quad (7)$$

where i, j, k are unit vectors along the z, e, n axes.

$$\begin{bmatrix} S_z \\ S_e \\ S_n \end{bmatrix} = \begin{bmatrix} cos(\varphi) & 0 & sin(\varphi) \\ 0 & 1 & 0 \\ -sin(\varphi) & 0 & cos(\varphi) \end{bmatrix} \begin{bmatrix} S'_m \\ S'_e \\ S'_p \end{bmatrix} \quad (8)$$

From expression (8) has:

$$S_z = S'_m cos(\varphi) + S'_p sin(\varphi) \quad (9)$$

$$S_e = S'_e \quad (10)$$

$$S_n = S'_p cos(\varphi) - S'_m sin(\varphi) \quad (11)$$

$$sin(\alpha) = sin(\delta).sin(\varphi) + cos(\delta).cos(H).cos(\varphi) \quad (12)$$

$$cos(\alpha).sin(A) = -cos(\delta).sin(H) + cos(\delta).cos(H) \quad (13)$$

$$cos(\alpha).cos(A) = sin(\delta).cos(\varphi) - cos(\delta).cos(H).sin(\varphi) \quad (14)$$

From equation (12), we have the angle of the sun's direction towards the observer latitude (place), hour angle (time), and the deviation of the sun (date) as follows:

$$\alpha = sin^{-1}[sin(\delta).sin(\varphi) + cos(\delta).cos(H).cos(\varphi)] \ (degrees) \quad (15)$$

From the equation (14) we determine the solar azimuth:

$$A = cos^{-1}[\frac{sin(\delta).cos(\varphi) - cos(\delta).cos(H).sin(\varphi)}{cos(\alpha)}] \ (degrees) \quad (16)$$

Sun azimuth angle is measured from the north due to the clockwise direction. In which:
- If LST<12 (or sin H<0), the azimuth is A
- If LST>12 (or sin H>0), the azimuth is $360 - A$

From the two expressions (15), (16), calculate the direction angle, solar azimuth, and other parameters as following:
- Calculate the time of sunrise and sunset

$$sunrise = 12 - \frac{1}{15^\circ} cos^{-1}(\frac{-sin(\varphi).sin(\delta)}{cos(\varphi).cos(\delta)}) - \frac{TC}{60} \ (hours) \quad (17)$$

$$sunset = 12 + \frac{1}{15^\circ} cos^{-1}(\frac{-sin(\varphi).sin(\delta)}{cos(\varphi).cos(\delta)}) - \frac{TC}{60} \ (hours) \quad (18)$$

or it can be written as follows

$$sunrise = 12 - \frac{1}{15^\circ} cos^{-1}(-tan(\varphi).tan(\delta)) - \frac{TC}{60} \ (hours) \quad (19)$$

$$sunset = 12 + \frac{1}{15^\circ} cos^{-1}(-tan(\varphi).tan(\delta)) - \frac{TC}{60} \ (hours) \quad (20)$$

C. Improved design of a solar tracking system

Figure 4 shows the proposed automatic controls system. The calculation determines the sun's location based on information about the time and the system's coordinates. After processing data, determining the sun's location in the azimuth and elevation angle, the system controls the panel perpendicular to the sun. Actual azimuth and elevation are reflected from the direction and tilt sensors. The system compares the desired angle and the actual angle to make the control decision. The solar tracking control model includes the control part (processing unit) and actuator (the mechanical and motor attached to the PV panel). In the following, the most important modules are described.

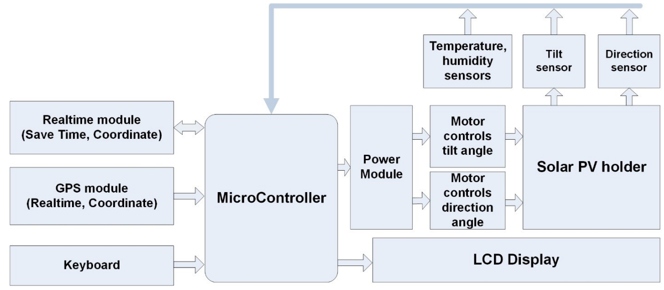

Figure 4. Block diagram of the solar tracking system

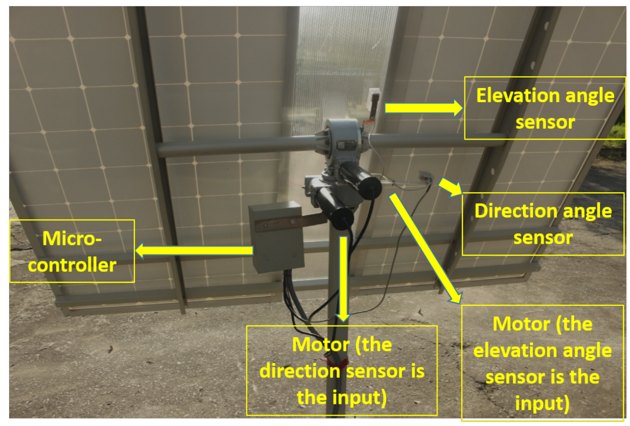

Figure 5. Photo of the power motor module

Real-time IC module: The real-time IC DS1307 contains information about time (i.e., hour, minute, second, day, month, year) and location information of the system. DS1307 has RAM to save location information obtained from GPS. It connects with the microcontroller via standard I2C communication. The IC uses an external battery to store information, so even if the system loses power, this information is still kept. Time and location information obtained from the GPS module will be recorded to the DS1307 by the microcontroller. If the GPS module temporarily cannot obtain satellites' data, the system uses the information stored in the real-time module to determine sun position.

Power module: It interfaces the microcontroller with the two stepper motors that control the tilt and direction movements (see Figure 5). The module is designed based on ICs L297 and L298

Main program: The system's main program is a closed, repetitive cycle and is performed according to the steps shown in Figure 6.

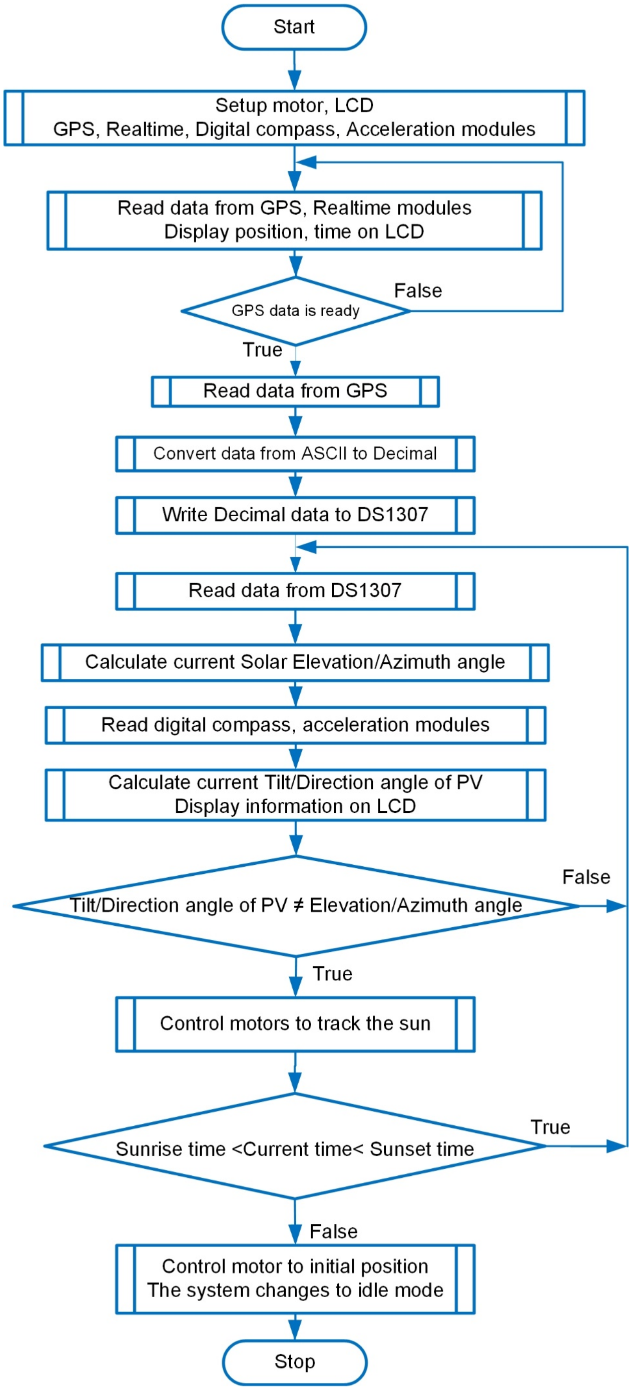

Figure 6. Algorithm flowchart of the main program

- When the system is started, the program initializes, sets the system parameters, I/O ports, and the devices' initial status.
- Perform reading data from the GPS module. There are two possibilities: 1) GPS is not receiving information from satellites; 2) GPS has received satellite signals, determined the time, and calculated the system's position.
  In case 1, the microcontroller read data from the real-time module (IC Realtime DS1307); if this IC already has the location information saved during the previous operation, the system temporarily takes it to estimate the sun's location. If the real-time module's position information is not available, the microcontroller waits until the GPS module receives the correct information.
  In case 2, the microcontroller write the updated data from GPS to the real-time module.
  This solution helps the system avoid the temporary disorientation phenomenon. If the GPS module does not receive accurate information from the GPS, the system still has data saved in the real-time module for regular calculation operation.
- After obtaining the necessary information about the time and location, the microcontroller calculates the instantaneous angles of elevation, azimuth, sunrise time, and sunset time.
- Read data from the accelerometer and digital compass sensor to calculate the actual system tilt and direction angle.
- Comparing the calculated angles of elevation and direction with the actual angles of the PV panel, the microcontroller drives the motors to reach the desired angles if there is a difference.
- The system will not resume sun tracking and return the engine to the morning position if the actual time is out of the time range from sunrise to sunset. If the weather condition is not good enough, the system also stops tracking for the moment to reduce control energy.

3. Experiment results and discussions

To assess the correctness of the elevation and azimuth angles of the system, we calibrate the measured modules using a ruler with a length of 20 cm perpendicular to the photovoltaic panel's surface mounted a graduated plane (see Figure 7). At times during the day, the shade length and the angle of the ruler's shade are measured. The experimental results show that the elevation angle error is in the range of ±2 degrees, the error of the azimuth angle is in the range ±3 degrees.

To evaluate the solar system's performance, we conducted experiments to compare the obtained power of the

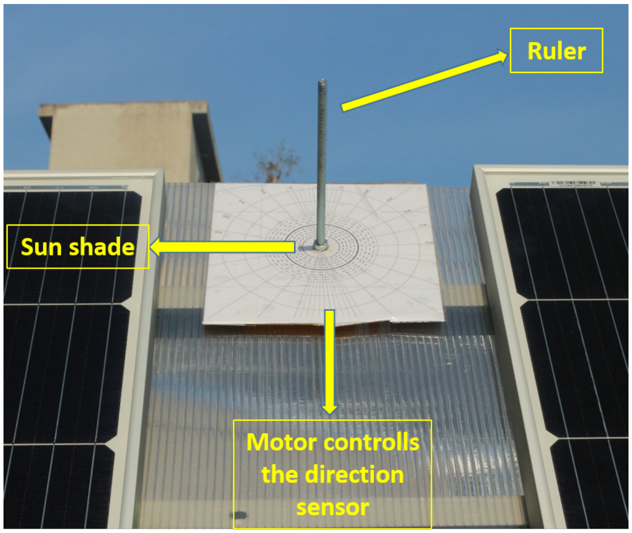

Figure 7. Calibration of direction sensor

photovoltaic panels mounted on the solar tracking system and the fixed system. Two PV panels with the same parameters in which one board is mounted on the solar tracking system and the other were on the fixed system. We place the fixed PV panel in a North-South direction and tilt at 17.80° to achieve high performance at the trial position. Power resistors are used to dissipate the energy obtained from each PV panel while measuring the current and voltage across these resistors. The value of the resistor is 60 Ω with a capacity of 20 W. Based on the received current and voltage, we calculate the panels' capacity at a measurement time. A monitoring system continuously measures the current and voltage across two dissipated resistors of the two PV panels. It sends the data back to the computer for storage via software on the computer. CoolTerm software is used to communicate with a computer via COM port, routinely recording data received, saving data as .xls files. Data is collected every 15 minutes, including the following parameters: measurement time (hours, minutes), current, the voltage on each dissipated resistance of the two panels. Data is measured continuously from sunrise to sunset.

The experiment was conducted at Nam Dinh city, Vietnam, at coordinates of 20,44948 degrees north latitude, 106,183258 degrees east longitude, from October 30, 2019, to November 6, 2019 (see Figure 8). The temperature of the day did not exceed 28°C. During this time of the year, the sun is low compare with the horizon; light intensity is not strong. Measurement time starts from 7:30 to 16:30 daily. After this period, the output power of both the fixed and solar tracking systems is negligible. Calculate the average of the results at the same time between days. Figure 9 and Figure 10 show the measurement results between the two systems. The measurement interval between two consecutive measurements is 15 minutes.

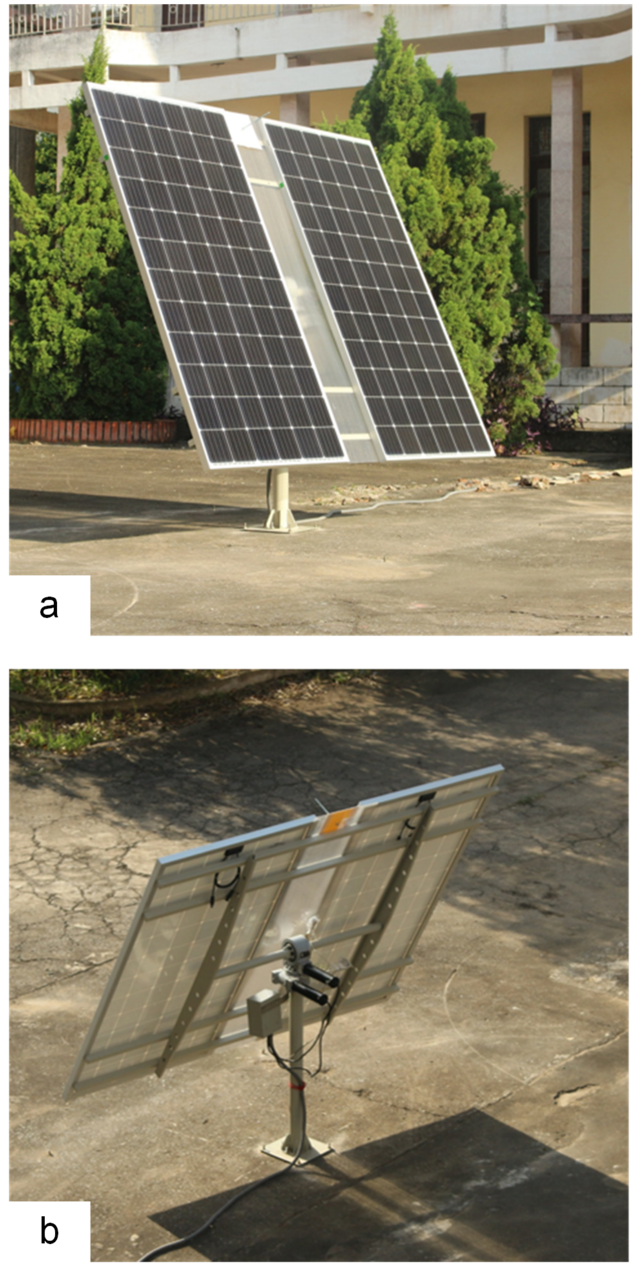

Figure 8. Photos of two solar panels on the front (a) and back (b) sides

In Figure 10, we would like to compare the output power ratio between fixed pannel and solar tracking pannels. The ratio is calculated by dividing the power of fixed pannel to tracking pannel in terms of time.

$$P_{ratio} = \frac{P_{OF}}{P_{OT}}.100\% \qquad (21)$$

P_{ratio} is the ratio between output power between fixed PV and solar tracking PV.
P_{OF} is the output power of fixed PV

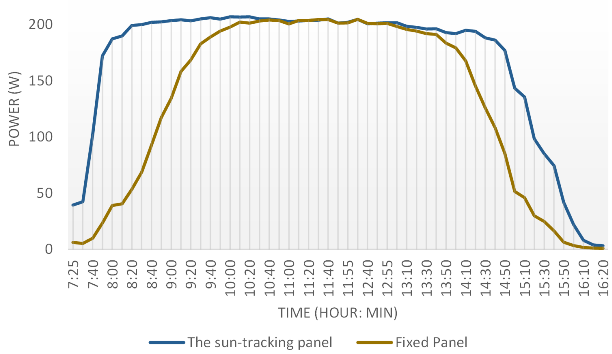

Figure 9. Power obtained on two panels over time

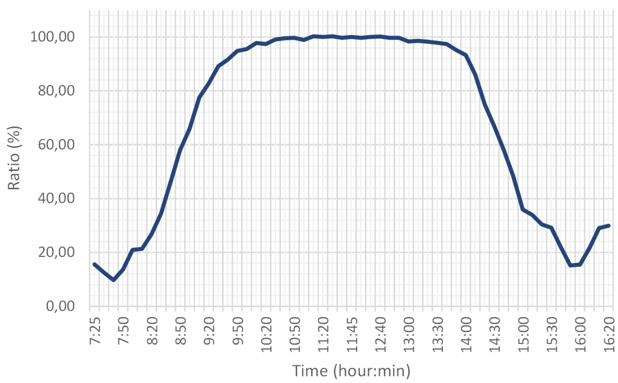

Figure 10. The ratio of the power between fixed and tracking panels

P_{OT} is the output power of solar tracking PV

It can be seen that by using the accelerometer, compass sensor, and GPS, the power efficiency is improved significantly and reduces the complexity of mechanical systems and controllers. Using the method of counting the motor's step requires the calibration of the initial position and the design of the complex mechanical system.

4. Conclusion

We proposed a 2 DoF solar auto-tracking system using the sun position equation with the accuracy and calculation of mass under the speed of the microcontroller. The elevation angle and azimuth are frequently updated. The microcontroller controls two rotating motors concerning the calculated tilt and direction angles. Feedback from the accelerometer and digital compass is used to compute the panel's actual tilt and direction angles. The proposed system overcomes the disadvantages of a sensor-based solar tracking system by exploiting the estimation equation of the sun's position. Comparisons with a fixed system, the solar tracking system shows evident efficiency before 10 am and after 2 pm.

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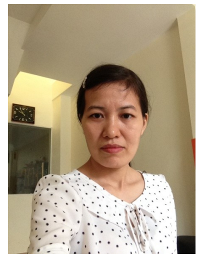

Nguyen Thi Hoa is currently a lecturer at the Faculty of Electric - Electronic Engineering, Nam Dinh University of Technology Education. She received her Engineering degree in Telecommunications Engineering from Hanoi University of Transport and Communications in 2001 and M.S. degree in Electronic technic from Hanoi Military technical Academy in 2007. Her research is interested in the fields of applied electronics and power electronics.

Nguyen Canh Toan received the IT.E degrees in Information Technology from Vietnam Maritime University, Vietnam in 1999, the M.E. degree in Network Monitoring from Asian Institute of Technology in 2002, and the Ph.D. degree in Optimize Networks from Ryazan State Radio Engineering University in 2010. Since 1999, he has been with Vietnam Maritime University, where hi is currently working as the Deputy Head of Academic Affairs. his research interests include Network Security, machine learning, artificial intelligence.

Tran Van Hanh was born in 1982. He received the degree Electrical and Electronics Engineering from Ho Chi Minh City University of Technology and Education in 2007 and an M.S. degree in Electronics Engineering from Military Technical Academy in 2013. His current research work focuses on power electronics and applied electronics.

Gian Quoc-Anh received the B.S. degree in Physics from VNU, Hanoi - the University of Science in 2003 and an M.S. degree in Electronics and Telecommunication technology from VNU, Hanoi -University of Engineering and Technology (UET) in 2010. He is currently working towards a Ph.D. degree in Electronic Engineering at VNU-UET. His research interests are applications of digital signal processing and embedded systems. He is the author and co-author of 10 papers about the embedded systems and WSN.

Tran Hieu was born in 1978. He received the M.S. Degree in Automation and Engineering Control from the Military Technical Academy in 2006. His research interests are SCADA, microprocessor, applied electronics.

Hoang Thi Phuong holds a Ph.D. in Electronic Engineering from Military Technical Academy in 2017, a Master of Degree in 2006, and a Bachelor of Science Degree in Telecommunication Electronics from the University of Transport and Communications in 2000. Her current research work focuses on digital processing and microprocessor.

Duc-Tan Tran is an Associate professor and Vice Dean of the Faculty of Electrical and Electronic Engineering, Phenikaa University. He has published over 150 research papers. His publications received the ”Best Paper Award” at the 9th International Conference on Multimedia and Ubiquitous Engineering (MUE-15) and International Conference on Green and Human Information Technology (ICGHIT-2015). He was the award recipient for the excellent young researcher from Vietnam National University in 2008, Hanoi, and the third prize in the contest ”Vietnamese Talents” in 2008. His main research interests include the representation, processing, analysis, and communication of information embedded in signals and datasets. He serves as a TP Co-chair, technical committee program member, track chair, session chair, and reviewer of many international conferences and journals