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A Cost-effective Microcontroller based Sensor for Dual Axis Solar Tracking

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Abstract. Energy crisis is one of the most important issues in today's world. Conventional energy resources are limited and are one of the primary reasons for pollution and global warming. The use of renewable energy is becoming increasingly popular. Solar energy is rapidly gaining ground as an important mean of expanding renewable energy use. Solar tracking is employed in order to maximize solar radiation collection by a photovoltaic panel. In this paper we present the design, fabrication, and testing of an active dual axis closed loop solar tracking sensor. The compactness of the design facilitates its easy mounting on any surface or place exposed to solar irradiance. The solar irradiance is detected by an Organic Photovoltaic Cell (OPV) which scans the sky for the maximum power point. Different modes of operation have been accommodated in a single generic mode which stops operation at night and facilitates night return of the panel(s) the sensor is connected to. This system is independent with respect to geographical location of the solar panel and diurnal as well as seasonal variations. This sensor can be effectively employed in efficient solar energy extraction for systems of any scale. The operation of the system is also independent with respect to the initial configuration and the starting conditions. The experimental testing shows agreement with true sun coordinates with a satisfactory degree of accuracy. This work can be extended to reduce the scan time of the sensor.

Key words

Solar sensor, dual axis, closed-loop tracking, microprocessor based, cost effective, organic PV.

1. Introduction

Energy is one of the primary factors affecting the socio-economic development of any nation. About 66 to 82 % of the total energy of the world comes from fossil fuels [1, 2]. Solar energy harvesting is becoming increasingly important as the costs and environmental impact of our non-renewable energy sources has become apparent. Solar radiation is one of the most important renewable sources of energy (others include waterpower, wind, biomass and geothermal energy). The source of solar radiation are ongoing nuclear fusion reactions in the sun's core and is practically inexhaustible, since the sun has a predicted life span of 5 billion more years [3]. The annual energy input of solar irradiation on the earth (5% Ultraviolet, 43% Visible and 52% Infrared) exceeds the world's yearly consumption by several thousand times [4]. Photovoltaic (PV) cell are one of the most promising devices to convert solar energy into electricity.

Nomenclature

α	Altitude angle (°)
β	Inclination angle (°)
γ_c	Surface azimuth angle (°)
γ_s	Solar azimuth angle (°)
δ	Solar declination angle (°)
θ	Incidence angle (°)
φ	Local latitude (°)
ω	Local hour angle (°)
FF	Fill Factor
PCE	Power conversion efficiency
V_{OC}	Open circuit voltage (V)
I_{SC}	Short circuit current (A)

As a result, solar photovoltaic systems have been in development since late 1800s when Charles Fritts built a 30 cm^2 cell from Selenium and Gold [5]. In, 1954, Chaplin et al demonstrated solar cells based on P-N junctions with an efficiency of 5-6 %. Recent research have reported a peak laboratory efficiency of around 46% under standard testing conditions[1] with an average efficiency of 10-25% [6].

The power output of a given photovoltaic cell depends on operating temperature, irradiance and incident angle of solar radiation [7]. Not much control can be achieved on the first two parameters for a given cell as they are primarily dependent on the geographical location. On the other hand, the output of PV cell can be substantially increased by a solar tracker, which makes sunlight to be incident normally (perpendicularly) to the PV cell. Although not essential it can boost the collected energy by 10-100% in different periods of day time and geographical locations [8]. Another study reports that single axis trackers improve efficiency by up to 40% [9]. Also, tests have shown that dual axis trackers improves efficiency by almost 50% (35 to 42% by East-West trackers and 5 to 8% by North-South) [10].

An ideal solar tracker should compensate for both, changes in altitude angle of the sun (during seasonal changes) and changes in azimuth angle of the sun; as pointed out by Clifford et al [7]. Additionally, there must be a provision of nocturnal return of the solar panel to align with the sunrise reducing energy losses in the early hours of sunshine.

Initial works in solar tracking were presented by Zerlaut et al [11] and Haywood et al [12] in the year 1976. More recent works employ hybrid tracking strategies employing algorithms to suit different illumination and geographical conditions as can be seen in [13, 14]. Tracking accuracy as high as 0.1° can be obtained through picture processing techniques as can be seen in [15].

Poulek et al. designed a single axis solar tracker based on an arrangement of solar cells connected directly to a reversible DC motor. In their work, solar cells, both sense and provide energy for tracking. Sensing/driving solar cells are balanced to each other and differential signal is used to overcome friction and aerodynamic drag. The area of the auxiliary solar panel of the tracker is about 2% of the area of the moved solar collectors while collectable energy surplus is up to 40%. With slight modifications this system can be used for space panel tracking in addition to terrestrial applications but requires a set of bifacial solar cells per panel to be tracked [16, 17].

Roth et al. designed and constructed a two-axis (one axis from east to west and the other for elevation) sun following device with the use of a pyrheliometer as a measuring instrument. The device works in two modes viz clock mode and sun mode. In the clock mode, the tracker computes the position of the sun based on the date/time information in its clock. Panel position errors are measured during the day and stored for later analysis. The data gathered during the day is analyzed, and a new improved set of parameters for the installation errors is computed. This data is used in the next day to compute more accurate positions of the sun. In the sun mode, the tracker uses the theoretical data of the sun position to control the panel position. If the intensity drops below a certain level, it falls temporarily back to the clock mode [14, 18].

Rizk et al. designed a solar tracker employing a new principle of using small solar cells to function as self-adjusting light sensors. The set-up provided an indication of their relative angle to the sun by detecting the voltage output. A power increase of 30% was obtained by using this strategy [19].

Based on their functioning principle, Sun trackers can be classified into three types: passive, microprocessor and electro-optically controlled units [20].

Passive trackers rely on the differential expansion of substances exposed to different amount of irradiance. They are based on thermo-sensitive substances that adjust the position of the receiving panel in accordance with the position of the sun. Freon and bimetallic strips are the commonly used substances. These systems are simple, without any electronic controls or motors. Some of the drawbacks of these systems is the possible involvement of poisonous substances, slow response and absence of nocturnal return mechanism. A novel passive tracker can be found in [7]; some other interesting passive tracker designs can be found in [21-23]

Microprocessor based trackers rely on calculations of the Sun's position through mathematical relations such as

$$\alpha = \sin^{-1}(\cos\varphi \times \cos\delta \times \cos\omega + \sin\varphi \times \sin\delta) \tag{1}$$

$$\gamma = \cos^{-1}\left(\frac{\sin\alpha \times \sin\varphi - \sin\delta}{\cos\alpha \times \sin\varphi}\right) \tag{2}$$

The latest type of trackers are those which use both microprocessors and electro-optic sensors (LDRs and CCDs) for their operation [10-12, 16-18, 24-33].

[1] 1000 W/m^2 solar intensity, 25 °C ambient temperature and an air mass of 1.5 (elevation of 42°)

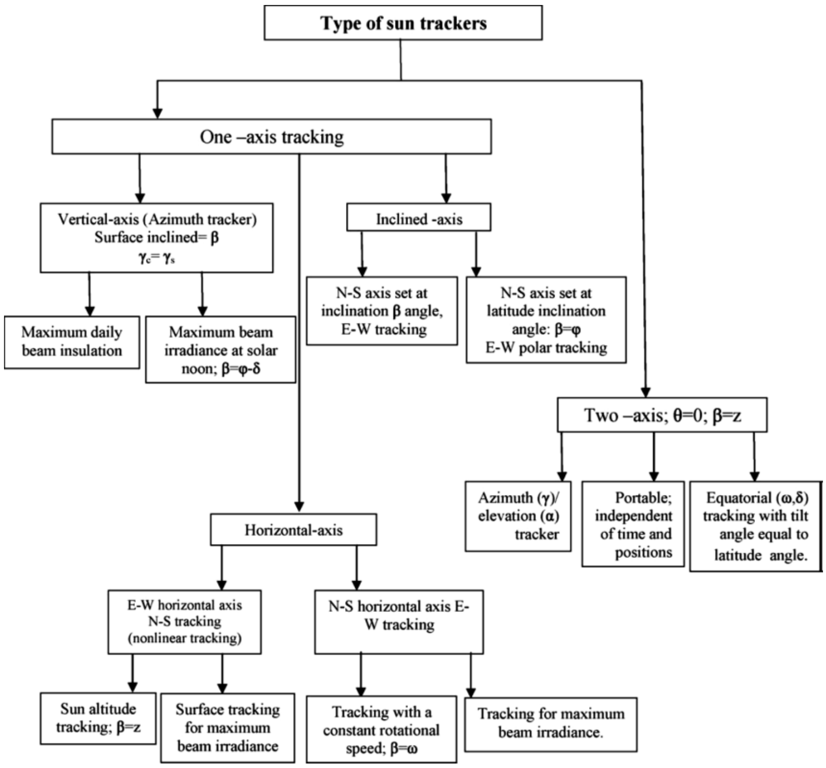

Figure 1. Types of solar trackers [8].

A more generic classification classifies them as one-axis and two-axis devices as illustrated in Figure 1. A detailed account of different solar tracking systems can be found in reviews [8, 34].

In this article, a novel optoelectronic closed-loop dual-axis solar tracking sensor is designed with the help of an OPV which can be readily implemented in a wide range of sun tracking scenarios. A prototype sensor was constructed and evaluated for various performance parameters. Section 2 of this article describes the objectives of the study, Section 3 covers the solar tracking system description in detail, Section 4 shines light on the algorithm used followed by experimental results in Section 5. Section 6 presents the concluding remarks.

2. Objectives

Keeping in mind the increase in efficiency that can be obtained and the characteristics of an ideal tracker. This solar tracking sensor is designed as a low cost and effective alternative to currently available complex, expensive, patented and proprietary systems. It is intended to serve as an additional incentive in adoption of solar harvesting techniques especially when access to technology and capital is limited.

3. Solar Tracker System Description

3.1 Mechanical Structure

The solar tracking sensor weighs around 200 g and has overall dimension of 200 × 200 × 200 mm. The compactness of the proposed system enables it to be mounted conveniently with minimal use of space. It consists of a frame, two controlling motors and an OPV Cell which acts as the sensor. The prototype was fabricated from acrylic sheets of 3 mm thickness. The frame is designed such that free 180° rotational movement of the OPV is allowed with respect to both horizontal and vertical axis when operated by the servo motors. The tracking sensor is designed to pinpoint both the azimuth and elevation angles facilitating tracking.

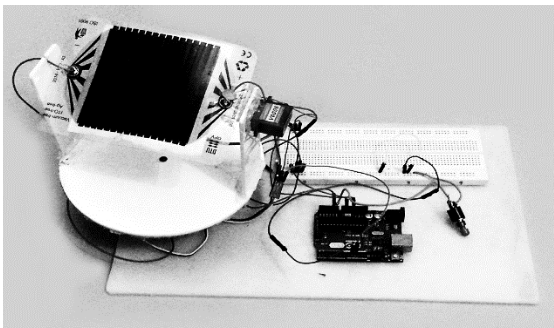

Figure 2. Prototype of the sensor.

Figure 2 shows the actual working model (prototype) of the sensor constructed using above mentioned apparatus.

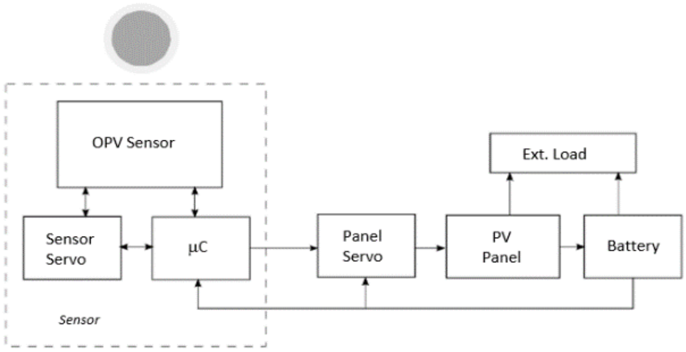

Figure 6. Schematic diagram of the tracker system.

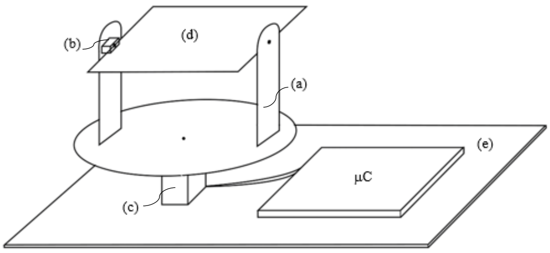

Figure 3. Construction of the sensor.

3.2 *Electrical System*

The mechanical and electrical systems are combined to form the solar tracking system. The block diagram consists of mainly electrical components as shown in Figure 6.

The construction of the solar sensor is shown in Figure 3. The setup consists of two servo motors (b) and (c), one of which (b) is mounted on the frame (a) to facilitate East-West movement of the Organic Photovoltaic (OPV) Cell (d) which acts as a primary sensing devise. Servo (c) is mounted at the base which facilitates the North-South movement of the OPV cell. The OPV cell is connected to the fork shaped frame such that it can rotate about the horizontal axis when moved by the servo (b) and vertical axis when moved by the servo (c). The tracking algorithm of the sensor is controlled by a microcontroller (e).

Abundance, fast manufacture, and low cost are what ideally epitomize organic and polymer photovoltaics and is therefore a choice of sensor in this tracking device. These cells are indium-tin oxide (ITO)-free and have been shown to exceed 10 000 hours of lifetime under standard outdoor exposure conditions. The normal operation temperature range is from - 80 °C to 120 °C and the sensor used in the prototype weighs around 5 g. The I-V response of the OPV is shown in Figure 4 and Figure 5 shows an actual photograph of the sensor used in the prototype (Figure 2) [35].

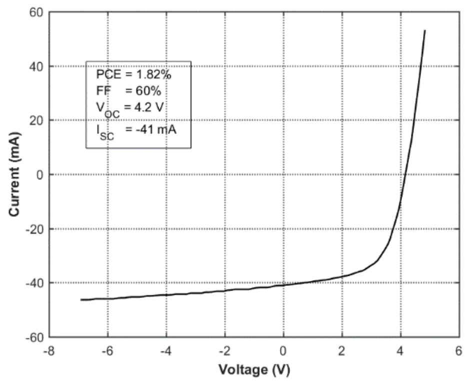

Figure 4. I-V curve of the OPV.

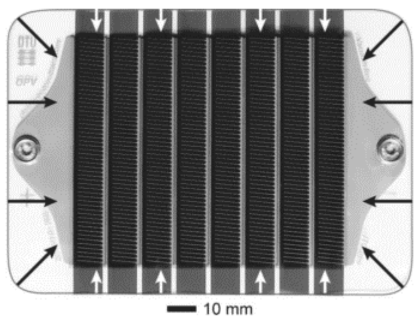

Figure 5. OPV module as sensor.

The driving mechanism of the OPV for executing its tracking cycle includes two servo motors. A smaller servo (TowerPro SG90) is used to rotate the sensor in East-West tracking while a bigger motor (Futaba S3003) is used to turn the fork frame. The controller uses the PWM (Pulse Width Modulation) signal to drive the servo motor at a controlled speed correspond to a maximum voltage of 6 V. The duration or width of the pulse determines the angle of the shaft's rotation.

An open source microcontroller board Arduino Uno (Figure 7) was used to control the servo motors and analyze the OPV output. The Uno is a microcontroller board based on the ATmega328P. The analog voltage provided by the OPV is converted into digital signal for processing. As the input-output pins of the microcontroller can operate between 0-5V, a simple voltage divider circuit was constructed to input the voltage from the OPV (0 to 10 V) to the microcontroller. The Arduino IDE is used to program the microcontroller. The C++ program can be written and compiled in the IDE before uploading into the Uno board.

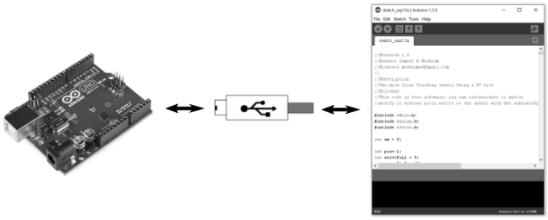

Figure 7. Process of programming the microcontroller.

The power required to drive the two servo motors and the microcontroller was taken from a USB port of a personal computer. It can also be taken from the solar energy produced by the panels to which the sensor caters or any other external direct voltage source.

4. Algorithm

The sensor first scans for local Maximum Power Point (MPP) in the horizon i.e. rotating the OPV about the vertical axis (Figure 8) and sets at azimuth angle corresponding to MPP.

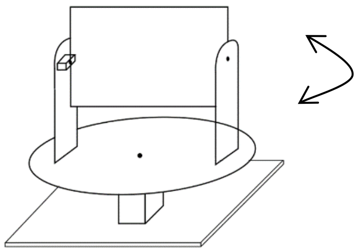

Figure 8. Scan for MPP in North-South direction.

Next, it scans for local MPP in the East-West direction rotating the OPV about the horizontal axis (Figure 9) and sets at altitude angle corresponding to MPP.

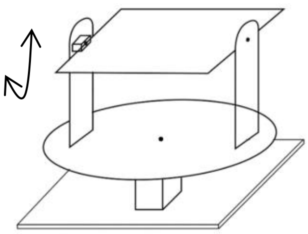

Figure 9. Scan for MPP in East-West direction.

The global MPP is obtained by taking into consideration both the local MPPs. Once the final position of the sensor corresponding to global (overall) MPP is calculated the sensor sets the panels it is connected to at the calculated positions till the next scan or search cycle begins. Each scan cycle is of around 20 second duration with one cycle being performed at an interval of 30 minutes.

5. Performance Testing and Experimental Results

In order to validate the accuracy for the sensor it was necessary to compare the experimental results with that obtained through mathematical formulae *(1)* and *(2)* and the Sun Position/Angle Calculators [36, 37]. To obtain this data, simple experiments were performed with the setup as shown in Figure 10 in the month of January 2016. Tests were made at Latitude: 18.9803578, Longitude: 72.8148362 at an altitude of 52 meters above sea level with average temperature of 34 °C on a sunny day.

Tracking accuracy of the sensor throughout the day was determined in terms of Azimuth and Altitude angles and was plotted against solar time (Figure 11, 12, 13). A comparative analysis of true and observed values versus solar time showed a maximum deviation of ± 4°.

Figure 10. Experimental Setup for performance testing.

The sensor was also tested under three different illumination conditions – a sunny day, a cloudy day and an overcast day to establish its performance in different climatic conditions (Figure 14).

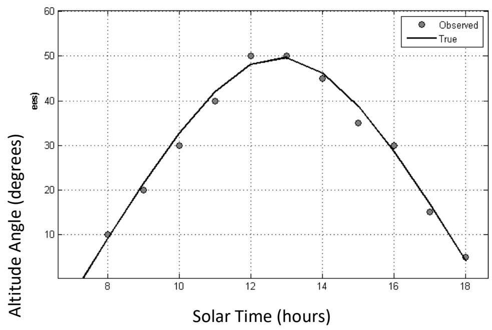

Figure 11. Altitude angle (observed and true) v. solar time.

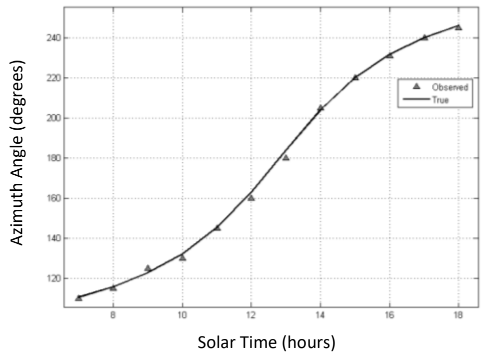

Figure 12. Azimuth angle (observed and true) v. solar time.

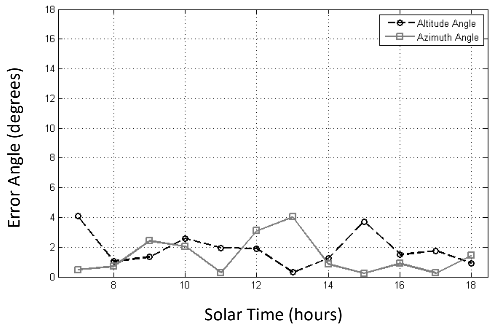

Figure 13. Error in azimuth and altitude angles.

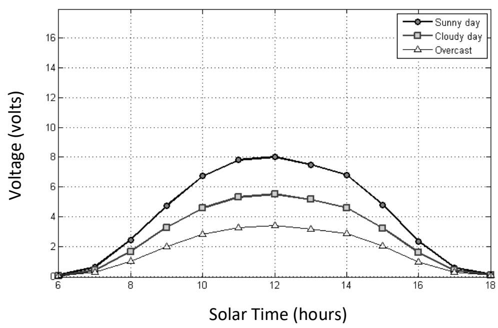

Figure 14. Performance in different climatic conditions.

The coordinates obtained from the solar sensor were compared with standard Sun position calculators [36, 37] for verification and validation purpose.

6. Conclusions

The proposed design of the sensor was demonstrated to be a low cost ($ 30), simple to construct, simple to use and easily maintainable. This system was designed with a view that it can be constructed and be made operational by anyone with basic understanding of circuits. It also employed commonly available materials and easy fabrication techniques. The sensor implemented an Organic Photovoltaic Cell (OPV) which is Indium Tin Oxide (ITO) free and is environmentally friendly as compared to its Silicon counterparts. With 180° tracking angle it can even work in regions above polar circle (Russia, Canada, Alaska, Scandinavia) with good accuracy. Experiments conducted showed maximum deviation of ±4° from true values of observed azimuth and altitude angles. Future works for the study may include testing the production intent set-up for its durability when subjected to various environmental conditions, reducing the scan cycle time, performing Life Cycle Assessment (LCA) and Life Cycle Cost assessment (LCC) analysis.

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