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Solar Position Measurement System Utilizing Solar Cell Array

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Abstract: This paper presents a novel approach for estimating the position of the sun by measuring the output voltage signals of two solar cell arrays orientated orthogonally to one another. Each array comprises a symmetrical arrangement of six cells inclined at angles of either 15°, 45° or 75° to the horizontal, respectively. As the position of the sun varies over the course of the day, a change is induced in the output voltage of each of the solar cells within the array. It is shown that the output voltage of any cell (V) varies as a linear function of the included angle between it and the solar cell with the maximum output voltage (V_{max}). A mathematical correlation is derived to express the relationship between the comparative output voltage of each solar cell (V/V_{max}) and the solar position. The sun's position is then computed by averaging the elevation angles derived from the comparative output voltages of all of the cells within the array. It is shown that both the zenith angle and the latitude angle of the sun can be accurately determined by deploying the measurement system such that one solar cell array is aligned in the East-West (E-W) direction while the other is orientated in the North-South (N-S) direction.

Keywords: Solar cell, solar collector, solar position algorithm.

1. INTRODUCTION

Solar energy systems have emerged as a viable source of renewable energy over the recent decades, and are widely used for a variety of industrial and domestic applications. At the heart of such applications lies the solar collector, designed to collect the solar energy and to convert it into either electrical power or thermal energy. Many previous studies have addressed the application of solar collectors in the development of solar energy technologies [1-3]. It has been shown that the energy absorbed by solar collectors can be increased by integrating them with a solar tracking system designed to compute the direction of the solar vector based on the location and time [4]. Using such tracking systems, the effectiveness of the solar collectors can be enhanced by adaptively adjusting their positions such that they are oriented toward the sun at all times [5-10]. Experimental studies have been performed to investigate the performance of various types of solar tracking system, including both open-loop and closed-loop type of schemes. McCluney proposed a optical solar tracking system consisting of a convex reflective sphere and a collimating lens designed to produce a collimated beam of solar radiation whose direction of propagation remained virtually constant over the daylight hours [11]. Meanwhile, Al-Naima and Yaghobian constructed a closed-loop type of solar tracking system comprising a two-axis equatorial mount and a microprocessor controller. The experimental results demonstrated that the proposed system outperformed a conventional one-axis tracking system [12].

Closed-loop systems based on photosensors have gradually emerged as the method of choice for realizing solar tracking systems. In such systems, the individual photosensors discriminate the sun's position and a comparative signal based on the output signals of each sensor is passed to a controller. The controller processes this signal and then issues appropriate instructions to the drive motors to actuate the tracking system in such a manner that its value falls to zero. Many researchers have employed the Maximum Power Point Tracking (MPPT) principle to accomplish the design and construction of solar tracking systems [13-16]. Kalogirou presented a solar tracking system with an accuracy of between 0.05^{o} and 0.2^{o} comprising three photosensors and three closed-loop control systems [13]. Helwa *et al.* compared a variety of sun tracking systems equipped with closed-loop control algorithms and concluded that two-axis trackers achieved a better performance than vertical-axis or tilted-axis systems [15]. Various researchers have proposed the use of numerical optimization schemes for the development of accurate solar tracking systems. Typical examples of such schemes include neural networks [17], fuzzy logic algorithms [18], adaptive neuro-fuzzy control schemes [19], optical vernier [20] and nonlinear compensation [21] measuring principles.

Various open-loop control systems have been proposed for measuring the solar orientation in recent years. For ex-

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ample, Blanco-Muriel *et al.* developed a solar tracking system which utilized open-loop controllers and a low-cost programmable logic controller (PLC) to compute the direction of the solar vector based on a knowledge of the system location and the local time [4]. Beshears *et al.* incorporated date, latitude, longitude and time zone information into the PLC program to improve the tracking system performance [22]. Recently, Georgiev *et al.* mounted three pyrheliometers within a solar orientation measurement system and used their output signals to calculate the solar position [23].

A review of the related literature reveals many different forms of solar sensor, including brightness sensors, artificial vision techniques, CCD devices, and so forth [7]. It has been shown that the solar energy values detected by these sensors can be used to compute the absorbed solar energy as a function of the time of day [24]. Of particular interest is the two-axis analog device, which measures the solar position relative to its optical axis based on the signal obtained from a quadrant silicon detector [25].

Many algorithms have been presented for computing the solar position. For example, Reda and Andreas developed a step-by-step procedure for implementing an algorithm to calculate the zenith and azimuth angles of the sun [26]. Recently, Grena presented an algorithm for determining the solar position by considering the main effects that can affect the sun position like moon perturbation, nutation, difference between topocentric and geocentric coordinat [27]. The results revealed that the algorithm yielded highly accurate estimates of the solar position. However, the computational procedure was complex and time consuming.

In general, the solar tracking systems presented in the literature tend to suffer a number of drawbacks, including a bulky or complex structure, a high cost, excessive computational complexity, the requirement for large numerical databases for verification purposes, and so forth. Accordingly, the objective of the current study is to develop a low-cost, computationally efficient algorithm for estimating the solar position on a real-time basis. The proposed approach utilizes a static orthogonal arrangement of two linear photocell arrays. Each array comprises a symmetrical arrangement of six cells inclined at angles of either 15°, 45° or 75° to the horizontal direction, respectively. The output voltage (V) of each photocell depends on its position relative to that of the sun and varies as a linear function of the included angle between it and the solar cell with the maximum output voltage (V_{max}). The correlation between the solar position and the individual output voltages is calibrated and it is shown that the elevation angle of the sun can be accurately estimated by computing the comparative output voltage signal (V/V_{max}) of each of the solar cells within the array. By positioning the measurement system such that its two arrays are aligned with the East-West (E-W) and North-South (N-S) directions, respectively, the proposed system can accurately detect both the solar zenith angle and the solar azimuth angle.

2. SENSOR DESIGN AND ALGORITHM

2.1. Irradiation Absorbency

In general, the radiation incident on a surface originates from many different directions. However, the intensity of the absorbed radiation depends fundamentally on the position of the absorbing surface relative to that of the light source. Consider the case shown in Fig. (**1**), in which a solar cell whose surface is orientated normal to the direction $\bar{N}$ is irradiated by the sun located at a zenith angle of θ in the spherical coordinate system. In the solar measurement system proposed in the current study, the quantity q_θ of absorbed solar irradiation is transformed into an electrical voltage signal and is then recoded in a personal computer. The rate at which radiant energy incident in the θ direction is absorbed by the solar cell is given by

$$I_\theta = I\cos\theta\,, \tag{1}$$

where I is the radiant intensity when the surface of the solar cell is normal to the position of the sun. The total amount of radiation absorbed by the cell is given by

$$q_\theta = \int I_\theta dA = \int I\cos\theta dA\,, \tag{2}$$

where dA is the unit area of the solar cell [28]. (Note that the absorbed radiation has units of watts (W)).

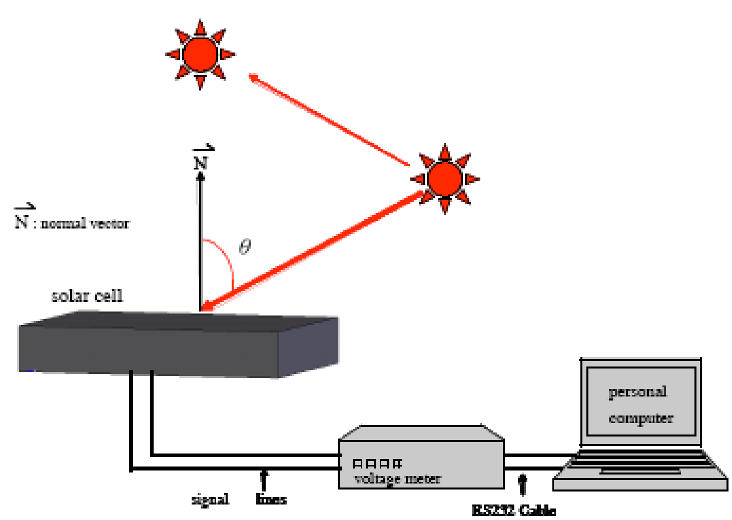

Fig. (1). Geometry of direct sunlight irradiation of solar sensor [31].

2.2. Validity Test

The literature contains many solar irradiation geometry models for solar devices [4, 6, 18, 29-31]. In the present study, a spherical coordinate system is used to model the geometrical relationship between the sun and each sensor in the sensing array. Changes in the solar position are then estimated by processing the corresponding changes in the output voltage signals of the various sensors. To confirm the validity of the proposed approach, a single solar cell (SC-5848, SINONAR, Taiwan) with dimensions of 57.8 x 48.2 x 2.0 mm (*L* x *W* x *T*) was positioned in the horizontal plane and connected to a voltage meter (3136A, Escort, Taiwan). The variation in the output voltage signal was then recorded as the zenith angle of the sun changed over the course of the day. Note that as shown in Fig. (**1**), the zenith angle, θ, was defined as the angle between the incident rays of the sun and the normal direction of the horizontal solar cell, and thus varied from -90^o at sunrise to +90^o at sunset.

Fig. (**2**) illustrates the variation in the output voltage of the solar cell with the zenith angle of the sun under three different solar solar irradiation conditions, i.e. 35 - 90 W/m^2, 90 – 150 W/m^2 and 150 – 200 W/m^2, respectively. It can be seen that the output voltage increases linearly over the zenith angle ranges of -90^o to +90^o, respectively, but saturates between zenith angles of -15^o and +15^o. (Note that this saturation effect is consistent with that reported in [3]).

2.3. System Design

Fig. (**3**) presents a photograph of one of the two linear photocell arrays used in the present study to measure the position of the sun. As shown, a compass is mounted in the central region of the array such that its position relative to the North, South, East and West coordinates can be easily determined. The array comprises a symmetrical arrangement of six photocells arranged such that their normal directions to the horizontal plane are equal to 15^o, 45^o, 75^o, 105^o, 135^o, and 165^o, respectively. Note that the angular displacement between the normal directions of adjacent photocells is deliberately specified as 30^o to exploit the saturation range of 30^o (from -15^o to 15^o) when the sun is positioned at or close to the normal direction of the solar cell (see Fig. **2**). During daytime, the zenith angle of the sun can therefore be crudely estimated as lying within $\pm$15^o of the normal direction of the solar cell with the maximum output voltage. In practice, all of the sensors within the array will absorb a certain amount of solar radiation, not only the sensor facing the sun. The exact amount of absorbed energy varies in accordance with the position of the sensor relative to that of the sun (see Eq. 2). Therefore, as described in the following section, a more precise evaluation of the solar position can be obtained by comparing the voltage signals generated by each of the non-facing cells within the array to that of the facing sensor.

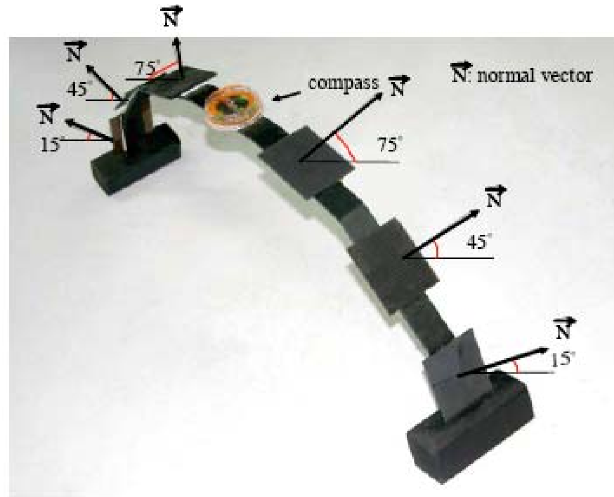

Fig. (3). Photograph of linear array comprising symmetrical deployment of six solar cells.

3. RESULTS AND DISCUSSION

When the linear array shown in Fig. (**3**) is deployed in sunlight conditions, the output signal from one of the solar cells will correspond to the saturated voltage value shown in Fig. (**2**) since the sun will inevitably be positioned within $\pm$15^o of the normal direction of one of the six solar cells. In this study, the output voltage of this cell is designated as V_{max}. From Fig. (**1**) and Eq. (**2**), it can be seen that the ratio between V_{max} and the output voltage of any of the other five sensors within the array varies as a function of the included angle between their respective normal directions. Fig. (**4**) shows the variation in the output voltage of an arbitrary cell as the cosine value of the included angle between it and the solar cell with the maximum output voltage increases from 0 to 1. The results clearly show that the correlation between the measured output voltage and the included angle varies as a function of the solar irradiation intensity. Since in practice, the solar irradiation intensity can not be controlled, it is necessary to normalize this correlation in some manner.

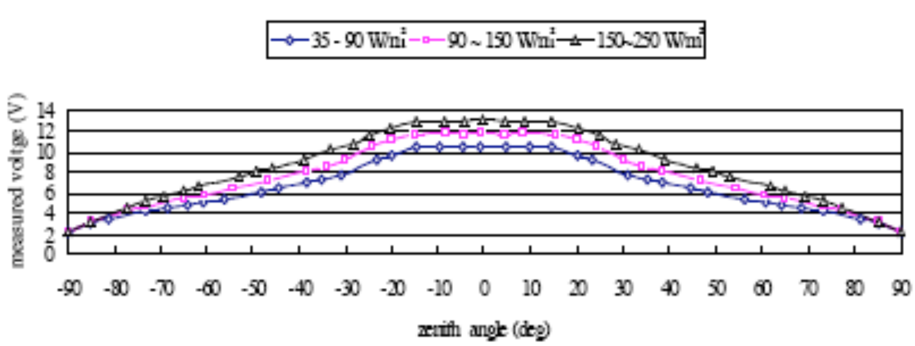

Fig. (2). Variation of measured output voltage with solar zenith angle.

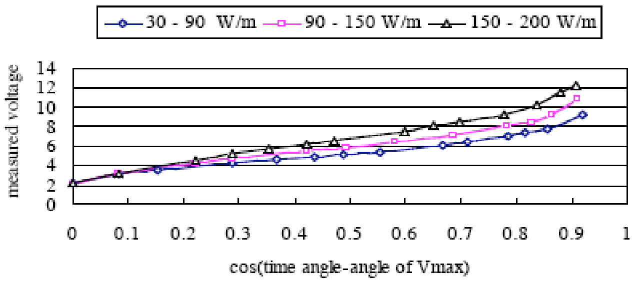

Fig. (4). Variation of output voltage of arbitrary photo cell with cosine value of included angle between it and solar cell associated with V_{max}.

In the current study, this is achieved simply by dividing the output voltage, *V*, of any photocell in the array by the maximum voltage output within the array, V_{max}, to obtain a normalized value between 0 and 1. Fig. (**5**) illustrates the results obtained for the variation of V/V_{max} with the included angle between an arbitrary solar cell and the cell with the maximum output voltage under three different solar irradiation conditions. It can be seen that an approximately linear correlation is obtained. From a process of linear regression, it can be shown that the relationship between V/V_{max} and the zenith angle of the sun, θ, is given by

$$V_\theta / V_{\max} = 0.7276\cos(\theta - 90^o) + 0.1679 \tag{3}$$

The correlation coefficient is found to be r^2 = 0.9433. Therefore, it can be inferred that the relationship given in Eq. (3) is valid for any solar irradiation in the range of 35 – 200 W/m^2.

Fig. (**6**) presents a flowchart showing the proposed algorithm for estimating the zenith angle of the sun. The process commences by acquiring the output voltage signals from all six cells in the array. The maximum voltage output V_{max} is identified and the sun's position is crudely estimated to be located within $\pm 15^o$ of the normal direction of the corresponding solar cell. The output voltages of the other five solar cells are then divided by V_{max} and substituted into Eq. (3) in order to determine the corresponding value of the zenith angle, θ. The calculated angles are checked to verify

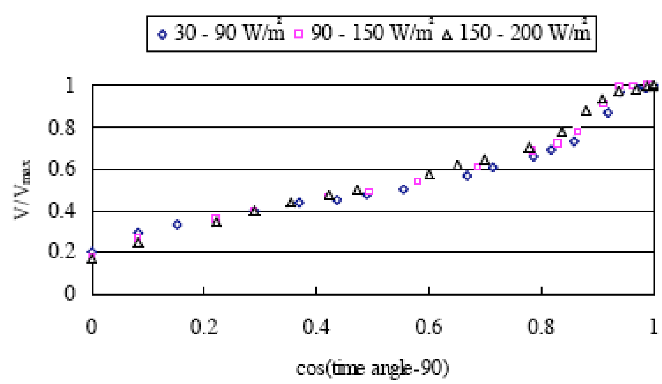

Fig. (5). Variation of ratio of output voltage of arbitrary photo cell to V_{max} with cosine value of included angle between arbitrary solar cell and solar cell associated with V_{max}.

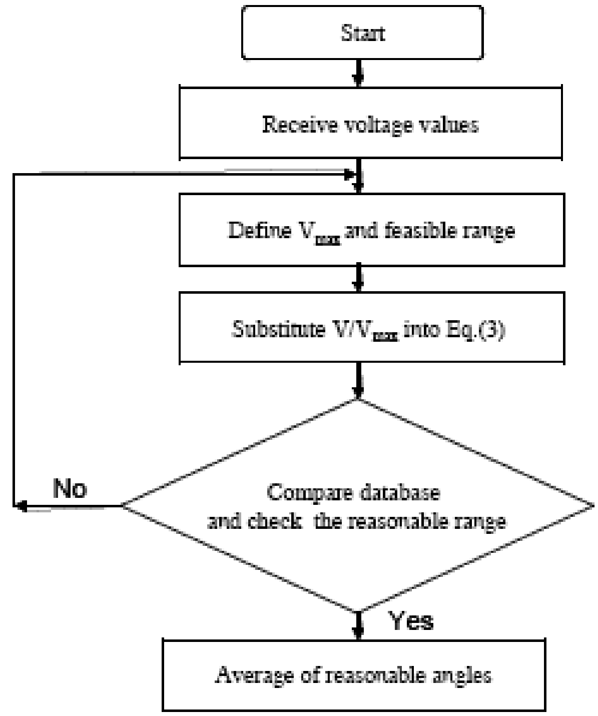

Fig. (6). Block diagram of proposed solar position algorithm.

that they fall within a reasonable range of the solar cell with maximum voltage output. Finally, the average of all the reasonable angles is computed to determine an accurate estimation of the zenith angle.

As shown in Figs. (**7**) and (**8**), by deploying the two sensing arrays in the measurement system such that they are aligned with the East-West (E-W) and North-South (N-S) directions, respectively, both the zenith angle and the azimuth angle can be simultaneously measured. Fig. (**9**) shows the comparison of predicted angles with the actual angles with a correlation coefficient of 0.9433 (r^2) in the study.

5. CONCLUSIONS

This study has presented a novel low-cost, computationally straightforward solar position algorithm comprising two linear solar cell arrays. The algorithm is capable of obtaining

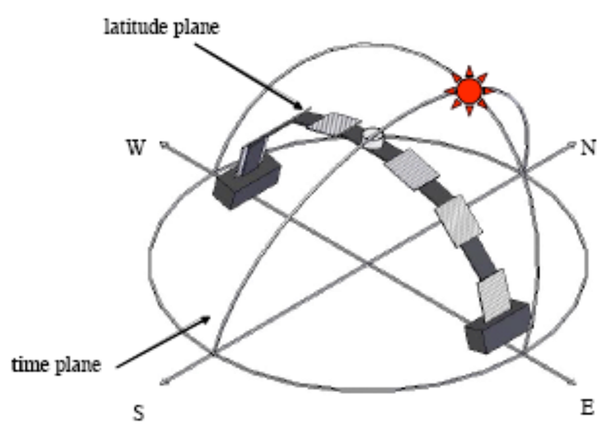

Fig. (7). Schematic representation showing solar cell array orientated in East-West direction.

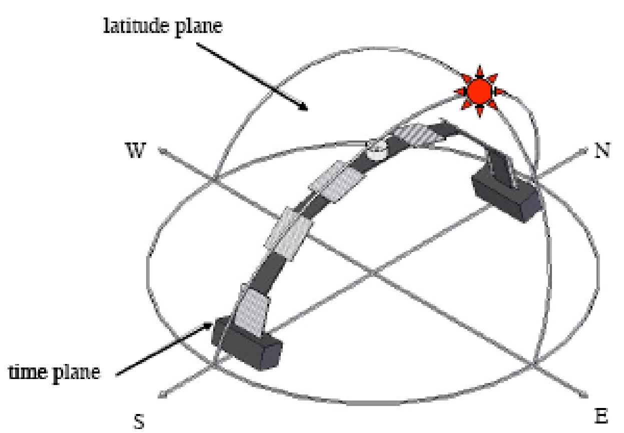

Fig. (8). Schematic representation showing solar cell array orientated in North-South direction.

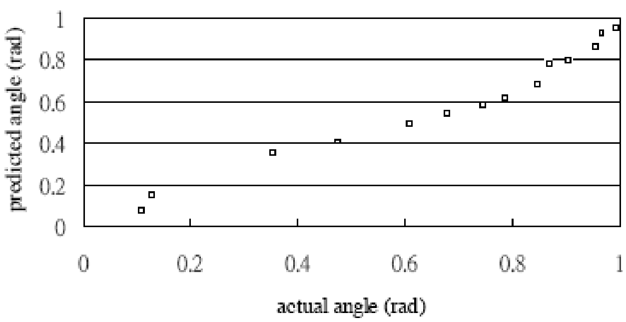

Fig. (9). Comparison of predicted angles with actual angles.

precise real-time estimates of the time and latitude angles of the sun under a wide range of solar irradiation conditions (any daylight condition) and therefore represents an ideal solution for control systems designed to adaptively adjust the orientation of the solar cell collectors within a solar system in order to enhance their absorption of solar radiation.

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REFERENCES

[1] B. Raasakka, "Solar Skylight Apparatus", *Renewable Energy*, vol. 12, pp. 117, 1997.

[2] S. Bari, "Optimum Slope Angle and Orientation of Solar Collectors for Different Periods of Possible Utilization", *Energy Conversion & Management*, vol. 41, pp. 855-60, 2000.

[3] T. Tesfamichael and E. Wäckelgård, "Angular Solar Absorbance and Incident Angle Modifier of Selective Absorbers for Solar Thermal Collectors", *Solar Energy*, vol. 68, pp. 335-41, 2000.

[4] M. Blanco-Muriel, D. C. Alarcón-Padilla, T. López-Moratalla and M. Lara-Coira, "Computing the Solar Vector", *Solar Energy*, vol. 70, pp. 431-41, 2001.

[5] K. A. Akhmedyarov, B. A. Bazarov, B. Ishankuliev, K. E. Karshenas and G. Schaimerdangulyev, "Economic Efficiency of the FV-500 Solar Photoelectric Station with Automatic Tracking of the Sun", *Applied Solar Energy*, vol. 22, pp. 44-7, 1986.

[6] M. A. Hj, M. Yakup and A. Q. Malik, "Optimum Tilt Angle and Orientation for Solar Collector in Brunei Darussala", *Renewable Energy*, vol. 24, pp. 223-34, 2001.

[7] M. Berenguel, F. R. Rubio, A. Valverde, P. J. Lara, M. R. Arahal, E. F. Camacho and M. López, "An Artificial Vision-based Control System for Automatic Heliostat Positioning Offset Correction in a Central Receiver Solar Power Plant", *Solar Energy*, vol. 76, pp. 563-75, 2004.

[8] A. Al-Mohamad, "Efficiency Improvements of Photo-voltaic Panels Using a Sun-tracking System", *Applied Energy*, vol. 79, pp. 345-54, 2004.

[9] S. Abdallah, "The Effect of Using Sun Tracking Systems on the Voltage-current Characteristics and Power Generation of Flat Plate Photovoltaics", *Energy Conversion and Management*, vol. 45, pp. 1671-9, 2004.

[10] S. Shanmugan and W. Christraj, "The Tracking of the Sun for Solar Paraboloidal Dish Concentrators", *Journal of Solar Energy Engineering*, vol. 127, pp. 159-60, 2005.

[11] R. McCluney, "Passive Optical Solar Tracking System", *Applied Optics*, vol. 22, pp. 3433-9, 1983.

[12] F. M. Al-Naima and N. A. Yaghobian, "Design and Construction of a Solar Tracking System", *Solar and Wind Technology*, vol. 7, pp. 611-7, 1990.

[13] S. A. Kalogirou, "Design and Construction of a One-axis Sun-tracking System", *Solar Energy*, vol. 57, pp. 465-69, 1996.

[14] J. V. Patil, J. K. Nayak and V. P. Sundersingh, "Design, Fabrication and Preliminary Testing of a Two-axes Solar Tracking System", *RERIC International Energy Journal*, vol. 19, pp. 15-23, 1997.

[15] N. H. Helwa, A. B. G. Bahgat, A. M. R. El Shafee and E. T. El Shenawy, "Maximum Collectable Solar Energy by Different Solar Tracking Systems", *Energy Sources*, vol. 22, pp. 23-4, 2000.

[16] J. Li, W. Lu, X. He and H. Yu, "Mechanical Design of an Intelligent Automatic Solar-tracking Device", *Acta Energiae Solaris Sinica*, vol. 24, pp. 330-4, 2003.

[17] D. G. Brown and K. W. Stone, "High Accuracy/Low Cost Tracking System for Solar Concentrators Using a Neural Network", in Proceedings of 28th Intersociety Energy Conversion Engineering Conference, 1993.

[18] H. A. Yousef, "Design and Implementation of a Fuzzy Logic Computer-controlled Sun Tracking System", in Proceedings of IEEE International Symposium on Industrial Electronics, 1999.

[19] M. Alata, M. A. Al-Nimr and Y. Qaroush, "Developing a Multipurpose Sun Tracking System Using Fuzzy Control", *Energy Conversion and Management*, vol. 46, pp. 1229-45, 2005.

[20] F. Chen, J. Feng and Z. Hong, "Digital Sun Sensor Based on the Optical Vernier Measuring Principle", *Measurement Science and Technology*, vol. 17, pp. 2494-8, 2006.

[21] F. Chen and J. Feng, "Analogue Sun Sensor Based on the Optical Nonlinear Compensation Measuring Principle", *Measurement Science and Technology*, vol. 18, pp. 2111-5, 2007.

[22] D. L. Beshears, G. J. Capps, D. D. Earl, J. K. Jordan, L. C. Maxey, J. D. Muhs and T. M. Leonard, "Tracking Systems Evaluation for the Hybrid Lighting System", in Proceedings of International Solar Energy Conference, 2003.

[23] A. Georgiev, P. Roth and A. Olivares, "Sun Following System Adjustment at the UTFSM", *Energy Conversion and Management*, vol. 45, pp. 1795-806, 2004.

[24] J. Wen and T. F. Smith, "Absorption of Solar Energy in a Room", *Solar Energy*, vol. 72, pp. 283-97, 2002.

[25] G. Falbel, J. Puig-Suari and A. Peczalski, "Sun Oriented and Powered, 3 axis and Spin Stabilized Cubesats", in Proceedings of IEEE Aerospace Conference, 2002, pp. 9-16.

[26] I. Reda and A. Andreas, "Solar Position Algorithm for Solar Radiation Applications", *Solar Energy*, vol. 76, 577-89, 2004.

[27] R. Grena, "An Algorithm for the Computation of the Solar Position", *Solar Energy*, vol. 82, pp. 462-70, 2008.

[28] F. P. Incropera and D. P. De Witt, *Fundamental of Heat and Mass Transfer*, USA: John Wiley & Sons Inc, 1985.

[29] J. Duffie and W. Beckman, *Solar Engineering of Thermal Processe,* USA: Wiley Interscience, 1991.

[30] W. Lorenz, "Design Guidelines for a Glazing with a Seasonally Dependent Solar Transmittance", *Solar Energy*, vol. 63, pp. 79-96, 1998.

[31] C. M. Chiang, C. Y. Lee, W. J. Hwang and P. C. Chou, "Solar Orientation Measurement System with Integrated Solar Cells", *Open Construction and Building Technology Journal*, vol. 2, pp. 302-8, 2008.

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