Research Article

Cubic Composite Sensor with Photodiodes for Tracking Solar Orientation

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A cubic composite solar sensor with photo diode is proposed for tracking the relative solar orientation. The proposed solar sensor composes of five photodiode detectors which are placed on the front, rear, left, right, and horizontal facets in a cubic body, respectively. The solar detectors placed on five facets can detect solar power of different facets. Based on the geometric coordinate transformation principle, the relationship equations of solar light orientation between measured powers with respect to various facets can be conducted. As a result, the solar orientation can be precisely achieved without needing any assistance of electronic compass and extra orientation angle corrector. Eventually, the relative solar light orientation, the elevation angle, and azimuth angle of the solar light can be measured precisely.

1. Introduction

Recently, the renewable energy has drawn great attention due to energy shortage. Many renewable energy researches are focused on solar power system [1–4]. For the solar system, a precise sensor is indispensable to tracking the sunlight orientation. Many studies have been focusing on solar tracking technique. However, there still exist some drawbacks on solar light tracking apparatus. Solar light tracker can, in general, be classified into mechanical and electronic category [5, 6]. Mechanical solar tracker experiences much fault probability and maintenance cost, electronic solar tracker depends highly on electronic compass accompanied by perpetual calendar, and precise perpetual calendar heavily relies on complicated computation through the usage of internet, thus leading to inconvenience in application [7, 8]. Therefore, to develop an electronic solar light tracker, without needing electronic compass and perpetual calendar, is essential to researchers and solar power applications.

An electronic solar light tracker can only be realized through the application of photo detecting devices. There are many photo devices such as photodiode, photo transistor, and resistive CdS components. The CdS components are passive components and usually cannot play the key role in a precise measurement. In this paper, the active photodiodes with wide

measuring range and fast response and low dark current are applied as a solar sensor to measure the solar orientation.

The solar light orientation information should consist of the relative elevation angle and azimuth angle between solar source and photo detector. For collecting lights from all possible orientations, this paper employed five photodiodes to compose a cubic structure photo detector in the absence of electronic compass and perpetual calendar to accomplish an electronic solar light orientation tracking system. The composite sensor is composed of five photo diode detectors placed on five different facets: left, right, front, rear, and horizontal facets, to constitute a cubic structure solar light detector. By placing five detectors on five different facets, the sunlight orientation can be derived by geometric coordinate transformation technique.

There exists discrepancy in collecting power amounts for photo detectors on different facets. Moreover, the incident light on the photo diode comprises not only direct solar light but also diffuse light and scattered light [8]. The diffuse and scattered light power is also generally called undisciplined light power, denoted by P_U . Therefore, the received solar power should be categorized precisely into power of direct incident solar light P_D and power of undisciplined incident solar light P_U . Through the geometric transformation analysis and accurate evaluation formula, each collecting solar power

FIGURE 1: Photo diode applied circuit for detecting solar power.

on different facets can be divided into direct incident solar power P_D and undisciplined incident solar power P_U , to accomplish the calculation of solar light orientation and solar polar powers on all facets.

In this paper, a novel light orientation sensor is proposed to track the solar orientation effectively. No expensive electronic components and no perpetual calendar are required. By appropriate computation based on different solar power quantities collected from five sensors, the sunlight direction can be determined. Also, the solar light orientation and power can easily be attained.

2. Optimal Shunt Resistor Matching and Selection

The ideal photo diode should generate an active current source which is proportional to the incident solar light. The total current through the photodiode is the sum of the dark current and the photo active current, so the dark current must be minimized to maximize the sensitivity of the device. In order to obtain the correct photo voltage, an appropriate shunt resistor R_P should be shunted across the output terminals. The application circuit is shown in Figure 1 with external shunt resistor R_P ; the photo voltage is generated at the two ends of the photo diode. The dark current has essential effects on the output voltage. Therefore, a calibration process for the shunt resistor R_P is required.

The values of the output load resistor R_P . The adopted photo detector in this paper is produced by Hamamatsu Inc. with model code S1087-01. The parameters of the shunt resistor are assorted at 10 Ω , 100 Ω , 220 Ω , 510 Ω , 1 k Ω , and 2 k Ω .

The solar power is defined as P_{solar} , the output voltage is defined as V_{out} , and S is defined as the sensitivity of the detector. In regard to an ideal photo power detector, S should be kept with a constant quantity to maintain the linear relationship between sensing power and sensor output voltage as follows.

$$P_{\text{solar}} = \frac{V_{\text{out}}}{S}. \quad (1)$$

By shunting appropriate resistor R_P in the output terminal, the solar power can be measured as shown in Figure 2, in case that ill condition occurs. The resistor value cannot be used to convert the current into voltage correctly. As shown in Figure 2, during the lower solar power period in the morning

FIGURE 2: Optimal resistor matching and selection.

or evening periods, the solar power is roughly proportional to the photo current with resistor ranging from 100 Ω to 220 Ω . However, the output power is slightly lower than the standard value during midday with direct sunlight. When the value is above 2 k Ω , the solar power curve lies under the standard curve. When the resistor value is between 510 Ω and 1 k Ω , the output curve is inspected to be better fitting the theoretical solar power.

Since the photo diode has nonlinear equivalent characteristics as shown in Figure 2, an appropriate output resistor is required to be selected. When the sunlight is in either weak condition or strong condition, the solar power curve displays nonlinear phenomenon. When the value falls between 510 Ω ~1 k Ω , the curve has the best coincident condition with the standard curve. Considering that the identical solar power would generate identical output voltage, larger resistance will require less output current. Therefore, 1 k Ω resistor is selected to shunt with photo detector to enhance the linearity and precision of the proposed circuit.

In order to obtain the precise voltage conversion, an OPAMP circuit is designed to ensure the precise voltage gain for the five detectors. The calibration circuit of the detector is shown in Figure 3. The 0.01 μF capacitor is connected across shunt resistor R_P to eliminate noise.

3. Geometric Coordinate Transformation and Formulation

As designated in Figure 4, photo-detecting device is located at origin of the horizontal plane of 3D coordinate. The polar coordinate representation of position of light source is designated as (r, ϕ, α) which results in the Cartesian

FIGURE 3: Detector calibration circuit.

FIGURE 4: Geometric coordinate system.

coordinate and polar coordinate transformation relationship expressed as follows:

$$\begin{aligned} x &= r \sin \phi \cos \alpha, \\ y &= r \sin \phi \sin \alpha, \\ z &= r \cos \phi, \end{aligned} \quad (2)$$

where ϕ is the light incident angle, α is the azimuth angle, and r is the distance between light source and photo diode detector. Then, the elevation angle ϕ_h can be described as

$$\phi_h = 90^\circ - \phi. \quad (3)$$

The orientation of sunlight is defined as elevation angle ϕ_h and azimuth angle α that means the orientation of the sunlight can be specified by formulation using the two angles: ϕ_h and α .

For a 3D coordinate system, the rear direction is defined as the X direction, the right direction is defined as the Y

FIGURE 5: θ rotation along the X-, Y-, and Z-axis.

direction, and the normal vector direction of X-Y horizontal plane is defined as the Z direction, as indicated in Figure 4. The solar light incident angle ϕ can also be defined as the angle between the sunlight and the normal vector direction of horizontal plane. Thus, the horizontal detector collects direct light power P_{HD} which can be expressed as

$$P_{HD} = P_D \cos \phi. \quad (4)$$

The collected direct light power P_{HD} of horizontal detector is the multiplication of solar direct radiation power and cosine of incident angle ϕ . Incident angle ϕ is defined as the angle between the normal vector of each facet with its corresponding incident light. Thus, when the horizontal detector rotates an angle θ along X, Y, and Z axis, the associated incident angles of all facets will change accordingly. Figure 5 illustrates the rotational coordinate transformation by rotating along Z-axis with an angle θ_z or along X-axis with θ_x or along Y-axis with θ_y . By doing so, the original coordinate (x, y, z) is transformed to a new coordinate $(x1, y1, z1)$, and the expression can be written as follows.

- (1) By rotating θ_z along z-axis, $x1$, $y1$, and $z1$ can be obtained as follows

$$\begin{aligned} \begin{bmatrix} x1 \\ y1 \\ z1 \end{bmatrix} &= \begin{bmatrix} \cos \theta_z & -\sin \theta_z & 0 \\ \sin \theta_z & \cos \theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \\ &= r \begin{bmatrix} \sin \phi \cos \alpha \cos \theta_z - \sin \phi \sin \alpha \sin \theta_z \\ \sin \phi \cos \alpha \sin \theta_z + \sin \phi \sin \alpha \cos \theta_z \\ \cos \phi \end{bmatrix}. \end{aligned} \quad (5)$$

In (5), new coordinate $z1$ is identical with the original coordinate z . The angle between incident solar light and normal vector of detector plane of new coordinate still remains ϕ ; the projection on normal vector direction is $r \cos \phi$. Therefore, regardless of the rotating angle θ_z , the incident of solar light keeps unchanged, that is, ϕ .

- (2) By rotating θ_x along x -axis, $x1$, $y1$, and $z1$ can be obtained as

$$\begin{bmatrix} x1 \\ y1 \\ z1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_x & -\sin \theta_x \\ 0 & \sin \theta_x & \cos \theta_x \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad (6)$$

$$= r \begin{bmatrix} \sin \phi \cos \alpha \\ \sin \phi \sin \alpha \cos \theta_x - \cos \phi \sin \theta_x \\ \sin \phi \sin \alpha \sin \theta_x + \cos \phi \sin \theta_x \end{bmatrix}.$$

The projection component of solar light on the normal vector of new coordinate plane $z1$ deviates a significant quantity from the original projection value z , so does the incident angle.

- (3) By rotating θ_y along y -axis, $x1$, $y1$, and $z1$ can be obtained as

$$\begin{bmatrix} x1 \\ y1 \\ z1 \end{bmatrix} = \begin{bmatrix} \cos \theta_y & 0 & \sin \theta_y \\ 0 & 1 & 0 \\ -\sin \theta_y & 0 & \cos \theta_y \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad (7)$$

$$= r \begin{bmatrix} \sin \phi \cos \alpha \cos \theta_y + \cos \phi \sin \theta_y \\ \sin \phi \sin \alpha \\ -\sin \phi \cos \alpha \sin \theta_y + \cos \phi \cos \theta_y \end{bmatrix}.$$

Like that of rotation along X -axis, the projection of incident light on normal vector of new coordinate plane $z1$ deviates noticeably from original one, z . It implies that incident angle changes with rotation angle θ_y .

After installing five detectors on five different facets, the cubic composite sensor is shown in Figure 6. Aside from the horizontal facet detector, the other four detectors can be looked upon as those coordinates transformed from the horizontal one by rotating either along X -axis or Y -axis with $\pm 90^\circ$. The coordinate transformation can be derived in the following section.

4. Cubic Composite Sensor

The relationship between direct incident solar power P_D , undisciplined power P_U , the light incident angle ϕ , and the azimuth angle α can be discussed in this section. Since the five detectors are located on five different facets of a cubic box, the coordinate transformation relationships between five facets will be discussed below.

- (1) The horizontal (H) detector is located on the facet which $\theta_x = 0^\circ$ along z -axis. Therefore, the transformed orientation coordinate of the sunlight and corresponding collecting power can be derived as

$$\begin{bmatrix} x1 \\ y1 \\ z1 \end{bmatrix} = r \begin{bmatrix} \sin \phi \cos \alpha \cos 0^\circ - \sin \phi \sin \alpha \sin 0^\circ \\ \sin \phi \cos \alpha \sin 0^\circ + \sin \phi \sin \alpha \cos 0^\circ \\ \cos \phi \end{bmatrix} \quad (8)$$

$$= r \begin{bmatrix} \sin \phi \cos \alpha \\ \sin \phi \sin \alpha \\ \cos \phi \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}.$$

FIGURE 6: Cubic sensors model in a 3D coordinate system.

The normal vector of horizontal plane $z1$ is the same with the original normal vector z ; the incident angle is kept unchanged, that is, $\phi_H = \phi$,

$$\phi_H = \phi, \quad (9)$$

$$P_H = P_D \cos \phi + P_{UH} = P_D \cos \phi_H + P_{UH}. \quad (10)$$

The collected power P_H on the horizontal detector can be expressed as (10). Wherein, P_D is the maximum direct incident solar power and P_{UH} is the power caused by light diffusion and scattering.

- (2) The right sensor is located on facet which $\theta_x = 90^\circ$ along x -axis. Therefore, the orientation of the sunlight can be derived as

$$\begin{bmatrix} x1 \\ y1 \\ z1 \end{bmatrix} = r \begin{bmatrix} \sin \phi \cos \alpha \\ \sin \phi \sin \alpha \cos 90^\circ - \cos \phi \sin 90^\circ \\ \sin \phi \sin \alpha \sin 90^\circ + \cos \phi \cos 90^\circ \end{bmatrix} \quad (11)$$

$$= r \begin{bmatrix} \sin \phi \cos \alpha \\ -\cos \phi \\ \sin \phi \sin \alpha \end{bmatrix} = \begin{bmatrix} x \\ -z \\ y \end{bmatrix}.$$

As shown in (11), right facet detector is equivalent to rotating horizontal facet by $\theta_x = 90^\circ$. The normal vector of right plane is directed toward Z -axis which is the positive Y -axis direction of horizontal facet. The light incident angle ϕ_R is related to original incident

angle ϕ by (12). Next, the collected power on the right facet detector P_R is written as

$$\phi_R = \cos^{-1}(\sin \phi \sin \alpha), \quad (12)$$

$$P_R = P_D \sin \phi \sin \alpha + P_{UR} = P_D \cos \phi_R + P_{UR}, \quad (13)$$

where P_{UR} is the undisciplined light power collected by right detector.

- (3) The left sensor is located on facet which $\theta_x = -90^\circ$ along x -axis. Therefore, the orientation of the sunlight can be derived as

$$\begin{aligned} \begin{bmatrix} x1 \\ y1 \\ z1 \end{bmatrix} &= r \begin{bmatrix} \sin \phi \cos \alpha \\ \sin \phi \sin \alpha \cos(-90^\circ) - \cos \phi \sin(-90^\circ) \\ \sin \phi \sin \alpha \sin(-90^\circ) + \cos \phi \cos(-90^\circ) \end{bmatrix} \\ &= r \begin{bmatrix} \sin \phi \cos \alpha \\ \cos \phi \\ -\sin \phi \sin \alpha \end{bmatrix} = \begin{bmatrix} x \\ z \\ -y \end{bmatrix}. \end{aligned} \quad (14)$$

As shown in (14), left facet detector is equivalent to rotating horizontal facet by $\theta_x = -90^\circ$. The normal vector of left plane is directed toward the negative Y -axis direction of horizontal facet. The light incident angle ϕ_L is related to original incident angle ϕ by (15). More, the collected power on the right facet detector P_L is written as

$$\phi_L = \cos^{-1}(-\sin \phi \sin \alpha), \quad (15)$$

$$P_L = -P_D \sin \phi \cos \alpha + P_{UL} = P_D \cos \phi_L + P_{UL}, \quad (16)$$

where P_{UL} is the undisciplined light power collected by left detector.

- (4) The front sensor is located on facet which $\theta_y = 90^\circ$ along y -axis. Therefore, the orientation of the sunlight can be derived as

$$\begin{aligned} \begin{bmatrix} x1 \\ y1 \\ z1 \end{bmatrix} &= r \begin{bmatrix} \sin \phi \cos \alpha \cos 90^\circ + \cos \phi \sin 90^\circ \\ \sin \phi \sin \alpha \\ -\sin \phi \cos \alpha \sin 90^\circ + \cos \phi \cos 90^\circ \end{bmatrix} \\ &= r \begin{bmatrix} \cos \phi \\ \sin \phi \sin \alpha \\ -\sin \phi \cos \alpha \end{bmatrix} = \begin{bmatrix} z \\ y \\ -x \end{bmatrix}. \end{aligned} \quad (17)$$

As expressed in (16), front facet detector is equivalent to rotating horizontal facet by $\theta_y = 90^\circ$. The normal vector of front plane is directed toward the negative X -axis direction of horizontal facet. The light incident angle ϕ_F is related to original incident angle ϕ by (18). Next, the collected power on the front facet detector P_F is written as

$$\phi_F = \cos^{-1}(-\sin \phi \cos \alpha), \quad (18)$$

$$P_F = -P_D \sin \phi \cos \alpha + P_{UF} = P_D \cos \phi_F + P_{UF}, \quad (19)$$

where P_{UF} is the undisciplined light power collected by front detector.

- (5) The rear sensor is located on facet which $\theta_y = -90^\circ$ along y -axis. Therefore, the orientation of the sunlight can be derived as

$$\begin{aligned} \begin{bmatrix} x1 \\ y1 \\ z1 \end{bmatrix} &= r \begin{bmatrix} \sin \phi \cos \alpha \cos(-90^\circ) + \cos \phi \sin(-90^\circ) \\ \sin \phi \sin \alpha \\ -\sin \phi \cos \alpha \sin(-90^\circ) + \cos \phi \cos(-90^\circ) \end{bmatrix} \\ &= r \begin{bmatrix} -\cos \phi \\ \sin \phi \sin \alpha \\ \sin \phi \cos \alpha \end{bmatrix} = \begin{bmatrix} -z \\ y \\ x \end{bmatrix}. \end{aligned} \quad (20)$$

As shown in (20), rear facet detector is equivalent to rotating horizontal facet by $\theta_y = -90^\circ$. The normal vector of rear plane is directed toward the positive X -axis direction of horizontal facet. The light incident angle ϕ_{Re} is related to original incident angle ϕ by (21). Next, the collected power on the rear facet detector P_{Re} is written as

$$\phi_{Re} = \cos^{-1}(\sin \phi \cos \alpha), \quad (21)$$

$$P_{Re} = P_D \sin \phi \cos \alpha + P_{URe} = P_D \cos \phi_{Re} + P_{URe}, \quad (22)$$

where P_{URe} is the undisciplined light power collected by rear detector.

Figure 6 defines incident quadrant of the solar light. The assessing criteria of incident quadrant are based on the collecting light power of five facets P_H , P_R , P_L , P_F , and P_{Re} , respectively. By comparing the quantities of the collecting light power, the criteria are described as follows.

- (1) When the $P_R > P_L$ and $P_F > P_{Re}$, the sunlight comes from the first quadrant.
- (2) When the $P_L > P_R$ and $P_F > P_{Re}$, the sunlight comes from the second quadrant.
- (3) When the $P_L > P_R$ and $P_{Re} > P_F$, the sunlight comes from the third quadrant.
- (4) When the $P_R > P_L$ and $P_{Re} > P_F$, the sunlight comes from the fourth quadrant.

Once the solar light incident quadrant is determined, the solar power orientation and power information can be obtained by substituting (8) in to (22). When the sunlight is incident to the fourth quadrant, the relationships of ϕ_F , ϕ_R , α , and P_D can be conducted from (12) to (15) to arrive at (23) as follows:

$$\begin{aligned} P_D \cos \phi_{Re} &= P_D \sin \phi \cos \alpha, \\ P_D \cos \phi_R &= P_D \sin \phi \sin \alpha. \end{aligned} \quad (23)$$

Since the incident light falls on the fourth quadrant, the direct light cannot reach front and left facets. The collecting solar power can merely come from the undisciplined light power. Consequently, the undisciplined light power of (23)

TABLE 1: Solar power with respect to five detectors (unit: (W/m²)).

Time	Facet					Light incident quadrant
	P_R	P_{Re}	P_L	P_F	P_H	
08:00	454.7	105.1	92.4	164.1	220.2	I
09:00	526.7	135.3	113.3	170.9	390.2	I
10:00	467.0	128.9	120.4	172.5	552.8	I
11:00	439.9	136.4	127.4	149.0	703.0	I
12:00	267.5	130.0	121.1	118.6	815.9	IV
13:00	91.1	111.9	103.7	92.6	953.9	III
14:00	141.4	147.8	317.3	112.7	860.4	III
15:00	143.3	136.7	452.9	148.8	691.6	II
16:00	168.6	158.4	511.5	198.2	582.9	II

can be roughly substituted by collected power quantity of adjacent facets. In other words, the direct solar light falling on the fourth quadrant comes from right and rear directions; the undisciplined light power on the rear facet P_{URe} is approximated by left facet light power P_L ; the undisciplined light power on the right facet P_{UR} is approximated by front facet light power P_F .

From (23), the α angle can be derived as follows

$$\frac{P_{RD}}{P_{ReD}} = \frac{P_D \sin \phi \sin \alpha}{P_D \sin \phi \cos \alpha} = \frac{\sin \alpha}{\cos \alpha} = \tan \alpha \implies \alpha = \tan^{-1} \frac{P_{RD}}{P_{ReD}}. \quad (24)$$

From (10) and (22), the ϕ angle can be derived as follows

$$\frac{P_{ReD}}{P_{HD}} = \frac{\sin \phi \cos \alpha}{\cos \phi} = \tan \phi \cos \alpha \implies \phi = \tan^{-1} \frac{P_{ReD}}{P_{HD} \cos \alpha}. \quad (25)$$

After the ϕ angle is decided, the P_D can be derived as

$$P_D = \frac{P_{HD}}{\cos \phi}. \quad (26)$$

The incident quadrant of incident light is changing with time. Similar derivation can be used to obtain the solar light orientation and power information.

5. Experimental Results

In order to verify the formulation, an experimental measurement was performed on June 02, 2013. Table 1 lists the collecting solar power of all facet detectors on the hour.

In Table 1, to take data at 12:00 A.M. as an example, the cubic sensor receives the incident light from the fourth quadrant, the detectors on the right, rear, and horizontal facets can absorb power of direct incident solar light P_D . However, the left and front facets can only absorb power of undisciplined incident solar light P_U . Therefore, the collecting solar power on the left detector P_L is near the undisciplined power P_{UL} . Also, the collecting solar power on the front detector P_F can be approximated by the undisciplined power P_{UF} . The collected undisciplined power on the horizontal

TABLE 2: Undisciplined incident solar light power with respect to five detectors (unit: (W/m²)).

Time	Facet					Light incident quadrant
	P_{UR}	P_{URe}	P_{UL}	P_{UF}	P_{UH}	
08:00	105.1	105.1	92.4	92.4	98.7	I
09:00	135.3	135.3	113.3	113.3	124.3	I
10:00	128.9	128.9	120.4	120.4	125.7	I
11:00	136.4	136.4	127.4	127.4	131.8	I
12:00	118.6	121.1	121.1	118.6	119.9	IV
13:00	91.1	91.1	92.6	92.6	91.8	III
14:00	141.4	141.4	112.7	112.7	127.1	III
15:00	143.3	136.7	136.7	143.3	140.0	II
16:00	168.6	158.4	158.4	168.6	163.5	II

TABLE 3: Direct incident solar light power with respect to five detectors (unit: (W/m²)).

Time	Facet					Light incident quadrant
	P_{RD}	P_{ReD}	P_{LD}	P_{FD}	P_{HD}	
08:00	349.6	0	0	71.7	121.5	I
09:00	391.4	0	0	57.6	265.9	I
10:00	338.1	0	0	52.1	427.1	I
11:00	303.5	0	0	21.6	571.2	I
12:00	148.9	8.9	0	0	696.0	IV
13:00	0	20.8	11.1	0	862.1	III
14:00	0	6.4	204.6	0	733.3	III
15:00	0	0	316.2	5.5	551.6	II
16:00	0	0	353.1	29.6	419.4	II

detector equals around the average of these two quantities. Besides, any detector, with direct incident solar power, possesses collected undisciplined solar power which is similar with the power collecting environment of adjacent facet detector. Thus, the collected undisciplined solar power can be substituted by collecting solar power on adjacent facet detector. It means that P_{URe} equals P_L and P_{UR} equals P_{UF} . Table 2 lists the undisciplined powers of each facet on the hour. Table 3 lists the direct incident solar power of each detector which is obtained by deducting undisciplined power from measured power. Therefore, the listed quantities in Table 1 are equal to the summation of those corresponding entities in Tables 2 and 3.

Based on the direct incident solar light power on five facets listed in Table 3, the orientation angles at different times can be evaluated. Taking the measured power at 12:00 A.M. on the selected day as an example, the azimuth angle and elevation angle are calculated and obtained as follows.

According to (24), it arrives at α :

$$\alpha = \tan^{-1} \frac{P_{RD}}{P_{ReD}} = \tan^{-1} \frac{148.9}{8.9} = 86.58^\circ. \quad (27)$$

TABLE 4: Azimuth angles comparison between theoretical and computed values.

Time	Theoretical azimuth angles α	Computed azimuth angles α	Error
08:00	105.14°	101.59°	3.55°
09:00	100.82°	98.37°	2.45°
10:00	96.72°	98.76°	−2.04°
11:00	92.30°	94.07°	−1.77°
12:00	85.55°	86.58°	−1.03°
13:00	331.06°	331.91°	−0.85°
14:00	273.15°	271.79°	1.36°
15:00	267.02°	269.00°	−1.98°
16:00	262.70°	265.21°	−2.51°

TABLE 5: Elevation angles comparison between theoretical and computed values.

Time	Theoretical elevation angles ϕ_h	Computed elevation angles ϕ_h	Error
08:00	22.61°	18.80°	3.81°
09:00	36.00°	33.91°	2.09°
10:00	49.57°	51.31°	−1.74°
11:00	63.25°	61.96°	1.29°
12:00	76.98°	77.90°	−0.92°
13:00	88.14°	88.43°	−0.29°
14:00	75.20°	74.40°	0.80°
15:00	61.48°	60.17°	1.31°
16:00	47.81°	49.81°	−2.00°

Using (25), incident angle ϕ can be obtained as

$$\phi = \tan^{-1} \frac{P_{RD}}{P_{HD} \sin \alpha} = 12.1^\circ. \quad (28)$$

Elevation angle is the complimentary angle of incident angle; thus,

$$\phi_h = 90 - \phi = 77.9^\circ. \quad (29)$$

The theoretical azimuth angle and the computed azimuth angle are shown in Table 4, and the theoretical elevation angle and the computed elevation angle are shown in Table 5, respectively. Theoretical azimuth angles and elevation angles are obtained from perpetual calendar.

In this paper, the light diffusion factor is neglected and not taken into the formulation. Only simple constant offset value is used to present the diffusion power. In Tables 4 and 5, the elevation angles and azimuth angles are quoted and calculated. In Table 4, by comparing the theoretical azimuth angles and computed azimuth angles, the errors are kept below 3.55°. In Table 5, by comparing the theoretical elevation angles and the computed elevation angles, the errors are also kept below 3.81° which is within acceptable range.

6. Conclusion

This paper has successfully proposed a cubic composite sensor with five sensors placing on five different facets. By coordinate transformation and detailed formulation, the azimuth angles and elevation angles for different sunlight orientations can be derived. Accordingly the sunlight orientation can be determined. No electronic compass and CdS resistors are required in the mechanism. Results show that the proposed method has precise solar tracking performance. This proves the validity of the proposed formulation to estimate the sunlight orientation and solar power. Besides, the solar light power can also be measured and provide valuable information for the solar tracking system.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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