JPE 13-6-15

http://dx.doi.org/10.6113/JPE.2013.13.6.1051
ISSN(Print): 1598-2092 / ISSN(Online): 2093-4718

A Study of an Implementable Sun Tracking Algorithm for Portable Systems

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Abstract

This paper proposes an implementable sun tracking algorithm for portable systems powered by alternative energy sources. The proposed system uses a 2-axis tilt sensor and a 3-axis magnetic sensor to measure the orientation and posture of the system, according to a horizon coordinates system, and compensate for tilt effects. Then, through an astronomical calculation, using the present time and position information obtained from GPS sensors, the azimuth and altitude of the sun in that location is calculated and converted to portable sun tracking system coordinates and used to control the A- and C-axes of the system.

Key words: Alternative energy, Astronomical calculation, Portable systems, Sun tracking, Tilt effects

I. INTRODUCTION

Photovoltaic systems are receiving a great deal of attention as an environmentally friendly alternative energy source. Aided by government demonstration projects, the applicable scope of photovoltaic systems tends to be expanding gradually from small-scale systems for homes and buildings to large-scale systems for power generation networks.

Increasing the efficiency of photovoltaic systems requires a sun tracking algorithm which can ensure that the solar cells face normal to the sun. Along with maximum power point tracking (MPPT) [1]-[4] this improves the efficiency of the solar cells and power conditioning system.

The efficiency of solar cells and power conditioning systems has been consistently improved by developments in technology. The efficiency of a photovoltaic system is determined largely by the angle of incidence of sunlight on the solar cells. The sunflower type sun tracking algorithm generally used for fixed installations relies on alignment with the horizontal system of coordinates. When the azimuth and altitude of the sun are calculated for a given point in time, the system tracks the sun, using a 2-axis control method with a pan and tilt drive. Since the sun tracking algorithm is aligned with the horizontal coordinates, it can control the array simply. The pan drive adjusts the array to the corresponding azimuth and the tilt drive compensates for the altitude angle. This general sun tracking method is shown in Table I.

On the other hand, photovoltaic systems are expected to be applied for use in portable applications as well as existing fixed installations. To use photovoltaic systems as a power source for automobiles, ships, and portable devices, as well as portable battery chargers, the system must be lightweight and be able to produce as much electric power as possible for use as an energy source. However, in portable systems it is difficult to track the sun with a simple method like that used in fixed systems, because the current position changes continuously and the sun tracking algorithm is not lined up with the horizontal coordinates of the current location. In a fixed system algorithm, it is necessary to know the position and direction of motion of the sun and its tilt angle with respect to the horizontal plane.

This paper proposes a sun tracking algorithm for portable applications, which tracks the sun both by measurements and astronomical calculations. The sun tracking algorithm measures the tilt angle made with respect to the horizontal plane, its posture (direction and position), and the current time in real time with a tilt sensor, a geo-magnetic sensor, and a GPS. Fig. 1 shows a flow diagram of the algorithm for portable applications.

Manuscript received May 6, 2013; revised Sep. 9, 2013
Recommended for publication by Associate Editor Young-Seok Jung.
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TABLE I
CLASSIFICATION OF SUN TRACKING METHODS

Tracking Method	- Tracking Signal Generating method	-Advantages	-Disadvantages
Natural Type	- Tracking without electric circuit/driving motor	- Simple structure - Low repair and maintenance costs	- Impossible to track accurately
Program Method	- Calculating the sun position - Driving the solar cell module to the calculated position	- Possible to track accurately - Possible to track consistently	- Complex structure - Accuracy needed for initial installation
Sensor Method	- Uses a sun position sensor - The sensor signal drives the motor	- Simple structure	- Can malfunction due to reflected sunlight
Combined Program and Sensor Method	- Combination of the program and sensor method	- Offsets the disadvantages of the program and sensor method - Tracks accurately	- Complex structure

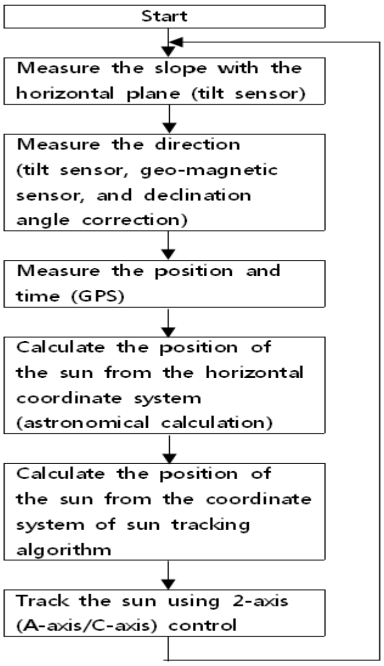

Fig. 1. Portable sun tracking system flow chart.

II. STRUCTURE OF THE SUN TRACKING ALGORITHM

The sun tracker shown in Fig. 2 consists of solar cells, a rotating mechanical part and the mounting. The mounting is installed with the tilt sensor, GPS sensor, and geo-magnetic sensor. The tilt sensor and geo-magnetic sensor are aligned in the direction shown in the figure. The rotating mechanical part provides 2-axis control of the A-axis (the rotating angle in the direction of the x-axis: α) and the C-axis (the rotating angle in the direction of the z-axis: γ). It tracks so that the surface of the solar cell always faces the sun. The solar cells and mounting are aligned in parallel from the home position and have the relation of α=γ =0 that is, the rotation angle of the A- and C-axes.

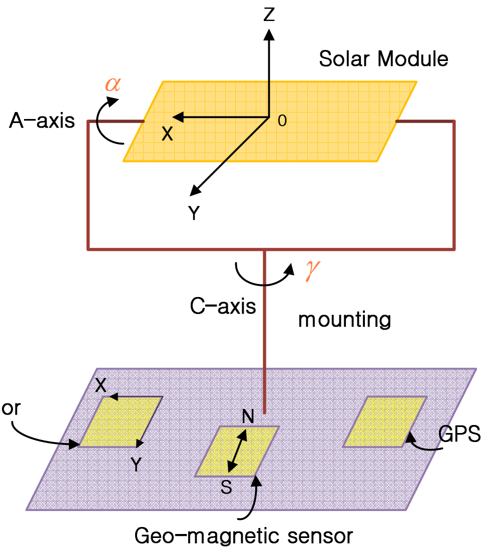

Fig. 2. Structure of the sun tracker.

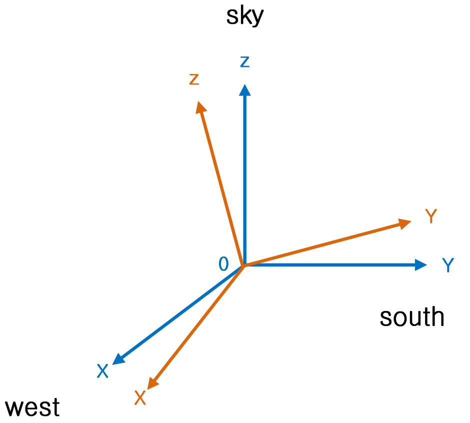

Fig. 3. Sun tracking system and horizontal coordinates.

Fig. 3 shows the coordinate system of the sun tracking algorithm and the horizontal coordinate system.

The xyz axes in the horizontal coordinate system refer to a coordinate system that shows the location of the sun based on the horizontal plane of the current position. In this paper, the y-, x-, and z-axes indicate the respective directions to the south, west and sky. The xyz axes in the coordinate system of the sun tracking algorithm show the correlation with the axes as a rotation of the coordinate system. Rotate the xyz axis about the Z-axis as much as γ when the xyz axis is aligned with the XYZ axis. When rotating as much as β about the Y-axis after rotating as much as α about the X-axis, the relation that converts one point P in the xyz coordinate system into the xyz coordinates can be expressed as in Expression (1) and the transform matrix ${}^{XYZ}_{xyz}T$ can be expressed as in Expression (2). Here, the lower left subscript of T indicates that the coordinate system to be transformed, and the upper left subscript shows the coordinate system upon transformation [5].

$$P(X,Y,Z)={}^{XYZ}_{xyz}TP(x,y,z) \tag{1}$$

$${}^{XYZ}_{xyz}T=B(\alpha)A(\beta)C(\gamma) \tag{2}$$

Here,

$$A(\alpha)=\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} \tag{3}$$

$$B(\beta)=\begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix}$$

$$C(\gamma)=\begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 1 & 1 \end{bmatrix}$$

III. SENSOR SIGNAL PROCESSING

This section describes the sensor used in the sun tracking algorithm for portable applications and its signal processing method.

A. Tilt Sensor

When the sun tracking system is positioned at a certain point, it measures the extent that the mountings are tilted in terms of the horizontal plane of the point. As shown in Fig. 4, the outputs θ_x and θ_y of the tilt sensor installed in the mounting are aligned with the x- and y-axes of the coordinate system of the sun tracking algorithm, and they show the angle between the z-axis of the horizontal coordinate system and the x-axis and y-axis of the coordinate system of the sun tracking algorithm. As shown in Expression (4), the tilt sensor outputs θ_x and θ_y can be expressed as the inner product from the unit vector α_z of the z-axis of the horizontal coordinate system and the unit vector α_x of the x-axis, respectively, as viewed from the XYZ axis of the horizontal coordinate system and the unit vector α_y of the y–axis. G in Fig. 4 represents the gravitational direction.

$$\cos\theta_x = \alpha_z \bullet {}^{XYZ}\alpha_x \tag{4}$$

$$\cos\theta_y = \alpha_z \bullet {}^{XYZ}\alpha_y$$

When defining the rotational sequence as Euler's angles, where the xy plane of the coordinate system of the sun tracking algorithm being aligned on the XY plane of the horizontal coordinate system is tilted by the rotation of β_0 about the Y-axis after the rotation of α_0 about the X-axis of the horizontal coordinate system as in Fig. 4, the unit vector α_x of the x-axis and α_y of the y-axis could be expressed as in Expression (5).

$${}^{XYZ}\alpha_x = B(\beta_0)A(\alpha_0)\begin{bmatrix}1 & 0 & 0\end{bmatrix}^T \tag{5}$$

$${}^{XYZ}\alpha_y = B(\beta_0)A(\alpha_0)\begin{bmatrix}0 & 1 & 0\end{bmatrix}^T$$

Here, the upper subscript T represents the transposed matrix. Hence, by arranging Expressions (3)-(5), Expression (6) is obtained.

$$\cos\theta_x = -\sin\beta_0 \tag{6}$$

$$\cos\theta_y = \cos\beta_0 \sin\alpha_0$$

Here, θ_x and θ_y hold values in the range of [0, π].

Finding the solution of Expression (7), the following is obtained:

$$\alpha_0 = \sin^{-1}\left(\frac{\cos\theta_y}{\cos\beta_0}\right) \tag{7}$$

$$\beta_0 = \theta_x - \frac{\pi}{2}$$

Here, α_0 and β_0 hold values in the range of $[-\frac{\pi}{2},\frac{\pi}{2}]$. The values α_0 and β_0 obtained from Expression (7) are used in correcting the tilt of the sun tracking algorithm. They are also used in correcting the output of the geo-magnetic sensor for the tilt of the geo-magnetic sensor installed on the mounting of the sun tracker.

B. GPS Sensor

By receiving signals from a satellite system, the GPS provides the time, latitude, longitude, and speed in the NMEA (National Marine Electronics Association) format. If the current position (latitude/longitude) and time are known, the azimuth and altitude angle of the sun can be calculated through astronomic calculation. This paper used an astronomic calculation method that has an accuracy of 0.01° for 100 years from 1950 to 2050.

C. Geo-magnetic Sensor

While the latitude and longitude information of the current point can be obtained from the GPS sensor, it is not possible to get direction information. Hence, this paper tries to obtain the direction information—which way the sun is heading at the current point. The geo-magnetic sensor measures the magnetic north of the earth. The angle between true north and the magnetic north is referred to as the declination angle. If the declination of the current location is known, the direction of true north can be found by correcting the declination angle from the magnetic north found by the geo-magnetic sensor. The declination differs by region. In Korea, the magnetic north is in the range of 6-8° to the west from true north.

When the output of a geo-magnetic sensor, aligned and installed on the coordinate system of the sun tracking algorithm, is converted into the horizontal coordinate system, Expression (8) is obtained.

$$\begin{aligned}&\begin{bmatrix}H_X & H_Y & H_Z\end{bmatrix}^T \\ &= B(\beta_0)A(\alpha_0)\begin{bmatrix}H_x & H_y & H_z\end{bmatrix}^T \qquad (8)\end{aligned}$$

Fig. 5 shows the output of the geo-magnetic sensor viewed from the horizontal coordinate system. Since the elements H_X and H_Y need to be known to get the direction information, as shown in the figure, Expression (9) can be obtained by finding these elements and using Expression (8).

$$\begin{aligned}H_X &= H_x\cos\beta_0 + H_y\sin\beta_0\sin\alpha_0 + H_z\sin\beta_0\cos\alpha_0 \\ H_Y &= H_Y\cos\alpha_0 - H_Z\sin\alpha_0 \qquad (9)\end{aligned}$$

Accordingly, the rotation angle δ_0 about magnetic north for the sun tracking algorithm becomes as Expression (10), and the rotation angle γ_0 about true north can be arranged as Expression (11), which corrected the declination angle from δ_0.

$$\delta_0 = \frac{3\pi}{2} - a\tan(H_Y, H_X) \qquad (10)$$

$$\gamma_0 = \delta_0 - Declination\ Angle \qquad (11)$$

A 2-axis geo-magnetic sensor can be used instead of a 3-axis geo-magnetic sensor. In this case, the inclination angle is needed—the angle made by the terrestrial magnetism of the surface of the earth. In the case of Korea, the inclination angle has a distribution of 48-55°.

When the sun tracking algorithm for portable applications is in a random position, from the sensor information above, it can be seen that the current posture is rotated by γ_0 about the Z-axis of the horizontal coordinate system and by β_0 about the Y-axis after rotating by α_0 about the X-axis. Accordingly, the transform matrix that converts one point of the coordinate system of the sun tracking algorithm into the horizontal coordinate system is expressed as Expression (12) using Expression (2).

$${}^{XYZ}_{xyz}T = A(\alpha_0)B(\beta_0)C(\gamma_0) \qquad (12)$$

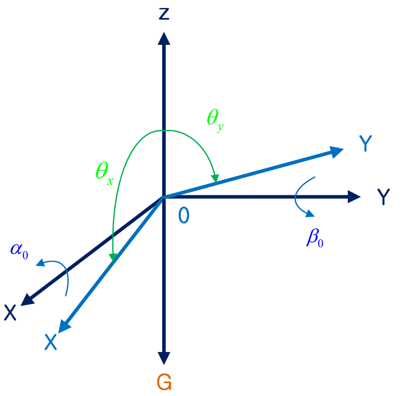

Fig. 4. Gravitational direction.

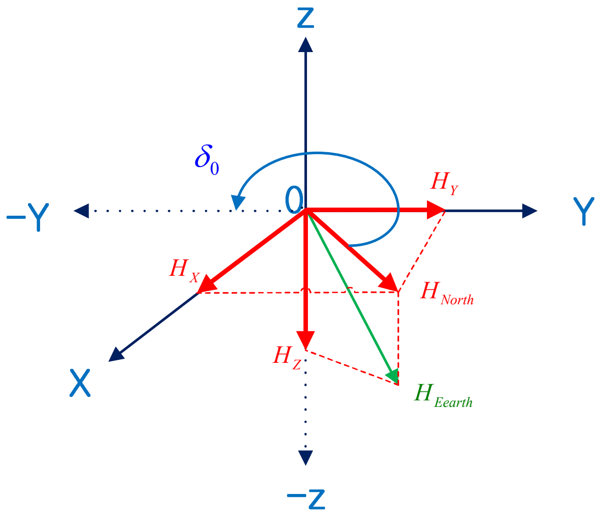

Fig. 5. Magnetic sensor output.

IV. SUN TRACKING CONTROL

If the altitude angle and calculated latitude of the sun are θ and ϕ, respectively, the unit vector ${}^{XYZ}S$ looking at the sun from the horizontal coordinate system, as shown in Fig. 6, can be expressed as Expression (13).

$${}^{XYZ}S = \begin{bmatrix}S_X \\ S_Y \\ S_Z\end{bmatrix} = \begin{bmatrix}\cos\left(\frac{3\pi}{2} - \phi\right)\cos\theta \\ \sin\left(\frac{3\pi}{2} - \phi\right)\cos\theta \\ \sin\theta\end{bmatrix} \qquad (13)$$

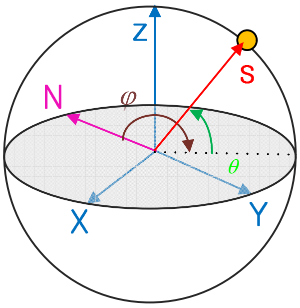

Fig. 6. Position of Sun.

If both sides of Expression (13) are multiplied by the inverse transform matrix of Expression (12) , the unit vector ${}^{XYZ}S$, when viewing the sun from the coordinate system of the sun tracking algorithm, can be expressed as Expression (14).

$$ {}^{XYZ}S = \left({}^{XYZ}_{xyz}S\right)^{-1}\, {}^{XYZ}S = \begin{bmatrix} S_X \\ S_Y \\ S_Z \end{bmatrix} \tag{14}$$

Here, the inverse transformation matrix is identical to the transposed matrix of the transformation matrix [5].

$$\left({}^{XYZ}_{xyz}T\right)^{-1} = {}^{XYZ}_{xyz}T^{T} \tag{15}$$

Now, in order for the solar cell of the sun tracking algorithm to face the solar cells toward the sun, the unit normal vector of the solar cell face, viewed from the coordinate system of the sun tracking algorithm, must be matched with Expression (14) when, having rotated the A-axis as much as α, after rotating the C-axis as much as γ in the home position of the sun tracking algorithm. The unit normal vector u_z of the solar cell face in the home position is matched to the Z-axis of the coordinate system of the sun tracking algorithm. In other words:

$$U_Z = [0 \quad 0 \quad 1]^T \tag{16}$$

Thus, Expression (17) is obtained.

$$C(\gamma)A(\alpha)U_Z = {}^{XYZ}S \tag{17}$$

Arranging Expression (17) using Expressions (3), (14), and (16), the results of Expressions (18)-(20) are obtained.

$$\sin\gamma \sin\alpha = S_X \tag{18}$$

$$-\cos\gamma \sin\alpha = S_y \tag{19}$$

$$\cos\alpha = S_z \tag{20}$$

Calculating Expressions (18)-(20) produces the two values $(\gamma_1, \alpha_1), (\gamma_2, \alpha_2)$ in Expression (21).

$$\gamma_1 = \eta - \frac{\pi}{2} \tag{21}$$

$$\alpha_1 = -\cos^{-1} s_z$$

or

$$\gamma_1 = \eta + \frac{\pi}{2}$$

$$\alpha_1 = \cos^{-1} s_z$$

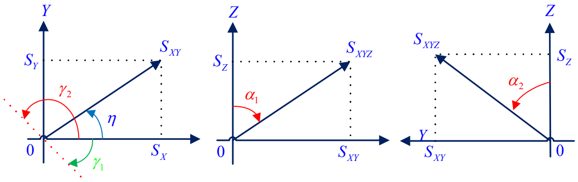

Fig. 7. Sun position in sun tracking system coordinates.

Here:

$$\eta = a\tan 2(S_y, S_x) \tag{22}$$

Fig. 7(a) shows the view of ${}^{XYZ}S$ from the Z-axis of the coordinate system of the sun tracking algorithm. S_{xy} reflected on the xy plane makes an angle of η in Expression (22) with the X-axis. To look at the sun by rotating the Z-axis, the solar cell face needs to be rotated about the z-axis so that the x-axis becomes perpendicular to S_{xy}. As shown in the figure, there are two methods (γ_1, γ_2). Fig. 7(b) and 7(c) show the views from the X-axis after rotating the Z-axis as much as γ_1 and γ_2, respectively. When rotating the X-axis as much as α_1 or α_2 for each of these, the solar cells face the sun. To select one of the solutions, the one that produces the smaller movement from the current position while considering the limitations in the mechanical structure corresponding to the control range of α and γ is chosen.

V. EXPERIMENTAL RESULTS AND REVIEW

For one location in Seoul (latitude: 126.9833°E, longitude: 37.5667°N), Table II shows the results for the seasonal time of sunset/culmination/sunrise and the change range of the azimuth angle and altitude angle in the year 2009 through astronomical calculations.

As shown in Table II, the azimuth angle of the sun change to bilateral symmetry around the south (azimuth angle of 180°) and the altitude angle of the sun reach their maximum with the southing of the sun. In the case of a fixed PV generation system, it is normal to install the unit around an azimuth angle of 180° and an altitude angle of 32° so that the daily average PV generation is at its maximum. A fixed 1-axis control solar tracking algorithm controls the azimuth angle while fixing the altitude angle. However, a fixed 2-axis control system maximizes the PV generation by controlling both the altitude and the azimuth. For a fixed installation, it is possible to track the sun accurately through a simple astronomical calculation, since the installation can be done by aligning it to the horizontal coordinate system of that point. However, for a portable type system, the PV generation can be kept to its maximum only after measuring the posture with the method suggested in this paper, since the posture of the sun tracking algorithm changes continuously.

PV generation is determined by the cosine of the angle made

TABLE II
SUN POSITION FOR SEOUL IN 2009

Date	Sunrise	Southing	Sunset	Range of Azimuth Angle (°)	Range of Altitude Angle (°)
Spring Equinox (3/20)	06:36	12:40	18:44	89.6 ~270.7	0~52.3
Summer Solstice (6/21)	05:11	12:34	19:57	59.1 ~300.9	0~75.9
Fall Equinox (9/23)	06:20	12:24	18:28	89.3 ~270.4	0~52.3
Winter Solstice (12/22)	07:44	12:31	17:18	119.5 ~240.7	0~29.0

between the normal of the solar cell face and the sunlight. For example, for a fixed installation, the PV generation during southing at the summer solstice is no more than 72% from cos(75.9°E-32°E)=0.72. On the other hand, when the sun tracking algorithm proposed in this paper is used, a PV generation of 100% can theoretically be maintained.

Table III shows the calculated locations of the sun on a given date for the region suggested previously, using astronomical calculation. Table IV shows the calculations of α_0, β_0 and γ_0 from the sensor output, according to the posture of the sun tracking algorithm for portable applications under the same conditions, and α and γ, the controlled outputs for the sun tracking. In Case-1, $\alpha_0 = \beta_0 = \gamma_0 = 0$ when the sun tracking system is aligned with the horizontal coordinate system. From this, it can be expected that the controlled output from Table III is either -38.39° or 141.11° for γ, and α should be ±59.09°. This result is identical to the calculation in Table IV. For Case-2, the controlled output γ was either -67.08° or 112.92° and the respective results for α were ±78.60° when α_0=-35.26°, β_0=30°, and γ_0=54.74° since the sun tracking algorithm is not aligned with the horizontal coordinate system.

Fig. 8 shows a prototype of the sun tracking algorithm made in this study. This paper performed a shadow test to evaluate the sun tracking performance of the proposed system. The shadow test is a method that calculates the accuracy of sun tracking by installing a rod (10 cm) in the normal direction of the solar cell face and measuring the length of the shadow. In Case-2, under the conditions of Table IV, the result of about 1.4 cm were obtained—the PV generation in this case is 99% from cos(atan(0.14))=0.99. If the cause of the error is analyzed, the largest part of the error occurs due to the geo-magnetic sensor. Since the geo-magnetic sensor measures magnetic north rather than true north, true north must be determined using the declination angle information of the region. In addition, since the geo-magnetic sensor is heavily influenced by the surrounding environment, this might cause an error. Additionally, an alignment error from the sensor installation, or an error in the processing of the mechanical part could be the cause.

TABLE III
EXAMPLE OF ASTRONOMICAL CALCULATION

Item	Description
Latitude	126.9833°E
Longitude	37.5667°N
Date	2009.10.26.14:30:00
Azimuth Angle	218.89°
Altitude Angle	30.91°

TABLE IV
EXAMPLE OF SUN TRACKING RESULTS

<table>
<tr><td rowspan="4">case 1</td><td colspan="2">α_0</td><td colspan="2">β_0</td><td colspan="2">γ_0</td></tr>
<tr><td colspan="2">0°</td><td colspan="2">0°</td><td colspan="2">0°</td></tr>
<tr><td colspan="3">α</td><td colspan="3">γ</td></tr>
<tr><td colspan="3">-59.09°/59.09°</td><td colspan="3">-38.89°/141.11°</td></tr>
<tr><td rowspan="4">case 2</td><td colspan="2">α_0</td><td colspan="2">β_0</td><td colspan="2">γ_0</td></tr>
<tr><td colspan="2">-35.26°</td><td colspan="2">30.00°</td><td colspan="2">54.74°</td></tr>
<tr><td colspan="3">α</td><td colspan="3">γ</td></tr>
<tr><td colspan="3">-78.60°/78.60°</td><td colspan="3">-67.08°/112.92°</td></tr>
</table>

Fig. 8. Picture of the prototype model.

VI. CONCLUSIONS

In the future, it is expected that photovoltaic systems will be applied in fields such as for leisure and large ships, as they move from the existing fixed types to portable types. To use a photovoltaic system as the power source of an automobile, ship and portable devices, as well as for portable battery chargers, the system must be lightweight and able to produce as much electric power as possible. In portable systems, it is difficult to track the sun with a simple method like the ones used in fixed systems, since the current position changes continuously and the sun tracking algorithm is not aligned with the horizontal coordinate system of the current location. It is necessary to know the position and direction of the sun tracking algorithm for the current movement, and also to understand the tilt angle with respect to the horizontal plane.

In this paper, a sun tracking algorithm is presented for portable applications that can improve photovoltaic efficiency by tracking the sun in an arbitrary position in relation to a portable PV generation system. A prototype was developed for testing. In the future, the practicality of this proposal will be demonstrated by implementing an actual system with 2-axis control of the sun tracking system so that the solar cell face could look at the sun perpendicularly, based on the calculations of the azimuth angle and altitude angle of the sun from the horizontal coordinate system. This will be accomplished through astronomical calculations that measure the posture of the sun tracking system in terms of the horizontal coordinate system with a tilt and geo-magnetic sensors, using the rotation of coordinate system, and by acquiring current position and time information from the GPS sensor.

ACKNOWLEDGMENT

This work was supported in part by MEST & DGIST(13-BD-01) and also the present research has been conducted by the Research Grant of Kwangwoon University in 2013.

REFERENCES

[1] M. Kim, “Study on the making and application of portable small-sized tracking solar battery module,” F*inal Report of Korea Energy Management Corporation*, 2001.

[2] R. Zogbi and D. Laplaze, “Design and construction of a sun tracker,” *Solar Energy*, Vol. 33, No. 3/4, pp. 369-372, 1984.

[3] P. Baltas, M. Tortoreli, and P. E. Russell, “Evaluation of power output for the fixed and step tracking photovoltaic arrays,” *Solar Energy*, Vol. 37. No. 2, pp. 147-163, 1986.

[4] D. M. Mosher, R. E. Boese, and R. J. Soukup, “The advantage of sun tracking for planar silicon solar cells,” *Solar Energy*, Vol. 19, No. 1, pp. 91-97, 1977.

[5] John J. Craig, *Introduction to Robotics Mechanics and Control*, 2nd ed., Addison-Wesley Publishing Company, Inc., 1986.

[6] Keith Burnett, Position of the Sun, http://www.stargazing.net/kepler/sun.html

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