Solar Tracking System Experimental Verification Based on GPS and Vision Sensor Fusion

Jeongjae Yoo and Yeonsik Kang
The Department of Automotive Engineering, Kookmin University, Seoul, Korea
Email: yoojj012@naver.com; ykang@kookmin.ac.kr

Bongsob Song
The Department of Mechanical Engineering, Ajou University, Korea
Email: bsong@ajou.ac.kr

Jinseop Song
Department of System Eng., Korea Institute of Machinery and Materials, Korea
Email: jssong@kimm.re.kr

***Abstract*—It is well known that solar tracking systems can increase solar panel efficiency by approximately 30 percent. However, because these systems require precise control, it is essential to develop tracking capabilities. In this paper, a solar tracking system using the fusion of astronomical estimates from GPS and vision-sensor image process outcomes is proposed. Using image processing outcomes, a decision-making process is also proposed to distinguish whether or not the current weather condition is sunny. Based on the outcomes, the solar tracking system determines whether to use image processing outcomes or astronomical estimates. The developed system is evaluated through experiments and the results are presented.**

***Index Terms*—alternative energy, solar panel, solar tracking, vision-based control**

I. Introduction

Because of recent concerns about air and water pollution and the depletion of natural resources such as fossil fuels, interest in renewable energy has been growing. As a result, solar energy as a sustainable energy source has been attracting the interest of engineers.

To improve solar energy efficiency, the development of an inexpensive and precise solar tracking system has been a popular research topic. In particular, concentrated photovoltaic (CPV) systems have shown better energy efficiency than conventional photovoltaic (PV) systems. However, because CPV systems use optics such as lenses or curved mirrors to concentrate sun light, it is important that their solar cells maintain a perpendicular angle to the sun to maximize efficiency. As a result, high precision tracking is required.

Existing tracking algorithms that use optical or illuminance sensors lack accuracy because they cannot distinguish between the presence and absence of sunlight.

In our study, we employ a vision camera image to track the position of the sun. Nowadays, camera sensors and their data processing units are much cheaper than before. In addition, compared to other types of optical sensors, camera images contain much more information, such as current weather conditions.

In this paper, we propose an algorithm that uses weather information, and a tracking method that depends on weather conditions.

II. Solar Tracking System

A. Hardware System Layout

Fixed, one-axis, and two-axis installation methods are typically used for photovoltaic power generation. The fixed installation method is the least effective because it is stationary regardless of the position of the sun. The one-axis method tracks the sun with only one shaft. The two-axis method, on the other hand, tracks the sun with two shafts; it is therefore more effective than the other two methods.

In our study, we use the two-axis system to track the sun. In addition, GPS and a camera sensor are installed to precisely track the horizontal and vertical angles of the sun.

The current time, as well as the latitude and longitude positions of the solar tracking system, can be acquired by GPS. Using that information, the current azimuth and altitude angles of the sun can be estimated by an astronomical formula. However, the current heading angle of the solar tracking system may not be correct, and it cannot be updated from the GPS measurement. Therefore, in our study the camera sensor is used to more accurately determine the position of the sun.

The center position of the sun is computed by image processing; the solar panel is maneuvered to locate the center position of the sun on the image center.

Fig. 1 is a conceptual diagram of the proposed solar tracking system. Figs. 2 and 3 are images of the solar tracking system developed in this study.

Manuscript received September 1, 2013; revised December 15, 2013.

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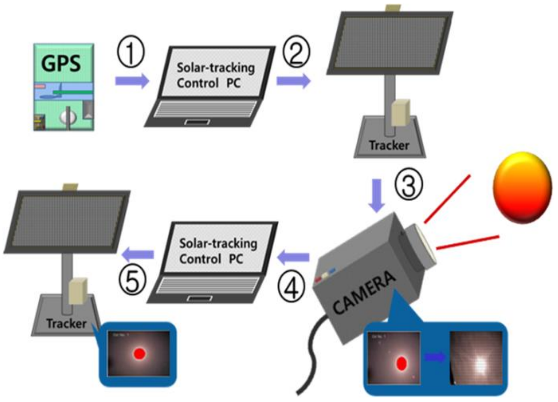
doi: 10.12720/joace.2.4.417-421



① Receive data from satellite using GPS.
② First correction angle of panel is produced.
③ Obtain coordinates of sun with image sensor.
④ Obtain weather information with image sensor.
⑤ Second correction angle of panel is produced.

Figure 1. Conceptual diagram of the proposed solar tracking system.

Figure 2. Solar tracking system prototype.

Figure 3. Sensor module and two-axis servo module components.

B. *Astronomical Tracking Method*

The azimuth and altitude angles of the sun are calculated by the celestial formula below. The planet position is updated every minute to minimize unnecessary power consumption [1] and [2]. The algorithm inputs for calculating planetary positions are latitude, longitude, and time, which can be acquired from the solar tracker GPS.

The number of days is defined as d and is obtained using (1), [3] and [4].

$$\begin{aligned} d &= 367 \times Y \\ &- (7 \times (Y + ((M+9)/12)))/4 \\ &+ (275 \times M)/9 + D - 730530 \end{aligned} \tag{1}$$

In (1), Y, M, and d represent the year, month, and day, respectively, which are obtained by GPS. Eccentricity (e), angle from ascending node to perihelion (w), mean anomaly (M), mean longitude (L), eccentric anomaly (E), and declination (a) are defined by (2), (3), (4), (5), (6), and (7).

$$e = 0.016709 - (1.151 \times 10^{-9} \times d) \tag{2}$$

$$w = 282.9404 + (4.70935 \times 10^{-5} \times d) \tag{3}$$

$$M = 356.0470 + (0.9856002585 \times d) \tag{4}$$

$$L = M + w \tag{5}$$

$$E = M + \left[\left(\frac{180}{\pi} \right) \times e \times \sin(M) \times (1 + e \times \cos(M)) \right] \tag{6}$$

$$\alpha = 23.4393 - (3.563 \times 10^{-7} \times d) \tag{7}$$

The x and y rectangular coordinates for ecliptic coordinates are obtained using (8) and (9). True anomaly (v) is obtained using (10). Celestial longitude (l) and distance (r) for calculating celestial longitude are obtained using (11) and (12) [5], [6] and [7].

$$x = \cos(E) - e \tag{8}$$

$$y = \sin(E) \times \sqrt{1 - e^2} \tag{9}$$

$$v = \tan^{-1} \frac{y}{x} \tag{10}$$

$$r = \sqrt{x^2 + y^2} \tag{11}$$

$$l = v + w \tag{12}$$

The perpendicular ecliptic coordinates are transformed to an equator coordinate system using (13),[8].

$$\begin{aligned} x_{equat} &= r \times \cos(l) \\ y_{equat} &= (r \times \cos(l)) \times \cos(\alpha) \\ z_{equat} &= (r \times \cos(l)) \times \sin(\alpha) \end{aligned} \tag{13}$$

The right ascension (RA) and declination (De) of the sun is obtained using (14) and (15).

$$RA = \tan^{-1} \left(\frac{y_{equat}}{x_{equat}} \right) \tag{14}$$

$$De = \tan^{-1} \left(\frac{z_{equat}}{\sqrt{x_{equat}^2 + y_{equat}^2}} \right) \tag{15}$$

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Greenwich Mean Sidereal Time (GMST) and sidereal time (SIDTIME) are defined by (16) and (17). The hour angle (ha) is obtained using (18).

$$GMST = L/15 + 12 \tag{16}$$

$$SIDTIME = GMST + UT + LON/15 \tag{17}$$

$$ha = SIDTIME - RA \tag{18}$$

The z-axis transformation in the direction of the zenith is defined by (19), (20), and (21). In (19), (20), and (21), lat represents the latitude of the tracker.

$$x_{hor} = (\cos(ha) \times \cos(De) \times \sin(lat)) - (\sin(De) \times \cos(lat)) \tag{19}$$

$$y_{hor} = \sin(ha) \times \cos(De) \tag{20}$$

$$z_{hor} = (\cos(ha) \times \cos(De) \times \cos(lat)) - (\sin(De) \times \sin(lat)) \tag{21}$$

Finally, the azimuth and altitude of the sun are obtained using (22) and (23).

$$azimuth = \left(\tan^{-1} \frac{y_{hor}}{x_{hor}}\right) - 180 \tag{22}$$

$$altitude = \sin^{-1}(z_{hor}) \tag{23}$$

C. Solar Image Tracking

The conventional solar image tracking method using an optical sensor is inefficient because it often mistakes the sun for light scattered by clouds or other obstacles. Therefore, it is desirable to find the widest range for the location of the sun through pixels separated by color.

Although astronomical estimates from the celestial formula are expected to provide an accurate position of the sun, the actual solar panel could be facing away from the normal direction of the sun because of the tracking system's current heading-angle measurement error.

Therefore, we propose a more precise tracking method using an image sensor. Fig. 4 shows the position of the sun obtained by an image sensor after tracking with astronomical estimates. The objective of tracking is then to locate the sun at the center of the image.

In Fig. 4, the x and y coordinates represent horizontal and vertical distances, respectively. In Fig. 5, A and L represent the distance to the center and the image sensor focal length, respectively. The lateral angle correction using the image sensor is defined as (24). The longitudinal angle correction is calculated in the same way.

$$\theta = \tan^{-1} \frac{h}{L} \tag{24}$$

Fig. 6 shows the angle error of the tracker. Although the tracker is controlled through astronomical estimates until t = 1700, the tracker has an angle error. After t = 1700, it is evident that the angle error decreases because of the second correction made with solar image tracking.

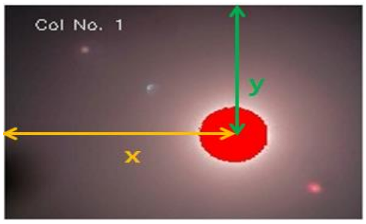

Figure 4. Position of sun acquired by image sensor before second correction.

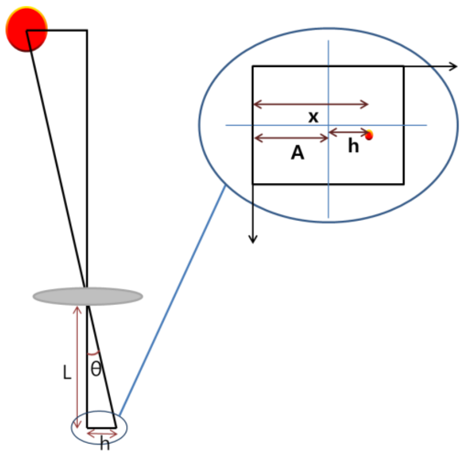

Figure 5. Corrected position of sun acquired by image sensor.

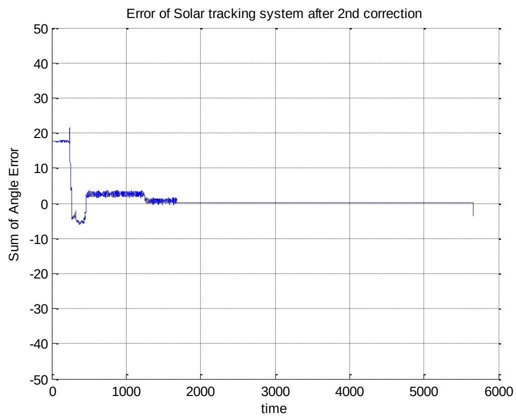

Figure 6. Sum of solar tracking horizontal and vertical angle errors.

III. Experimental Result

Using the tracking method that fuses astronomical estimates and the solar image, the solar tracker panel can maintain its position facing the normal direction of sunlight.

However, when the weather is cloudy, controlling the tracker by solar image is not desirable because it is difficult to locate the sun using the solar image. In such a case, it is better to employ only astronomical estimates instead of their fusion with image processing.

The remaining issue is how to develop a solar tracking system that can autonomously determine if the weather is sunny or cloudy. To address this issue, we propose the algorithm shown in Fig. 7. Using the solar image and

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algorithm, we can fundamentally determine whether it is sunny.

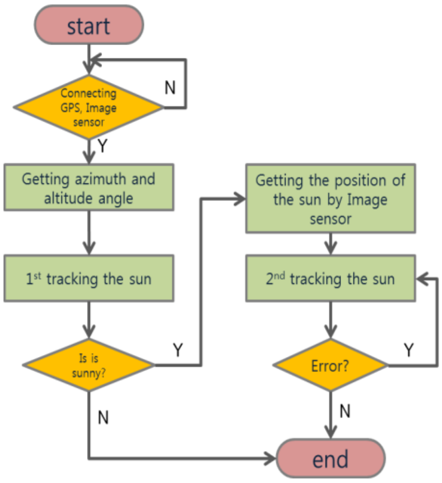


Figure 7. Solar tracking system flowchart.

Fig. 8 and Fig. 10 represent weather information obtained by the image sensor; they show that the position of the sun changed over time. Fig. 9 and Fig. 11 show the actual positions of the sun over time for sunny and cloudy weather, respectively.

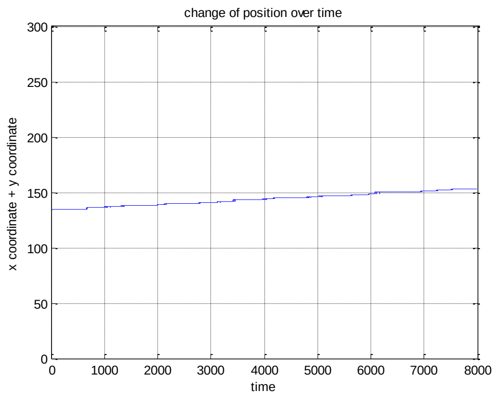


Figure 8. Change of sun position over time on a sunny day.

Figure 9. Solar movement during the experiment when it is sunny.

The y-axes in Fig. 8 and Fig. 10 are the summation of the x- and y-coordinate distances of the sun. Fig. 8 shows the summation of the x- and y-coordinate distances when it is sunny; the position of the sun moves continuously over time. On the other hand, Fig. 10 shows the same result when it is cloudy. Although the sun's position may at times be obtained, its path is discontinuous and unpredictable. The primary reason for such a path perception is that clouds partially obscure the sun. Thus, image processing results are heavily affected by the movement of clouds, which is fast compared to the movement of the sun. As a result, the image processing results show an unstable and unsmooth path.

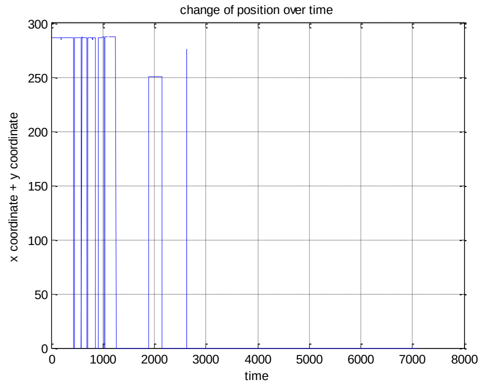
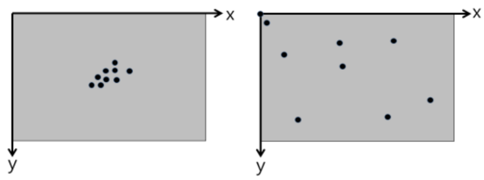


Figure 10. Change of sun position over time on a cloudy day.

Figure 11. The sky during the experiment when it is cloudy.



(a) (b)

Figure 12. (a) Example of sun positions obtained by image sensor when sunny; (b) Example of sun positions obtained by image sensor when cloudy.

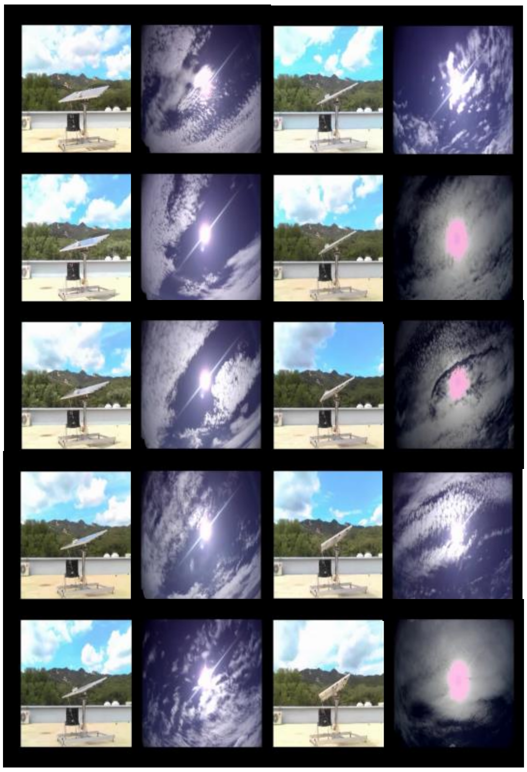


Figure 13. Images of the solar tracker tracing the sun, and solar images taken by the camera sensor fixed on the solar panel.

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In this paper, we have proposed a method for determining whether it is sunny. In this method, the control update rate of the tracker is one minute. The variance is calculated by the position of the sun obtained by the image sensor during one minute. If the variance is larger than the predetermined threshold, we conclude that it is cloudy. If the variance is smaller than the threshold, we conclude that it is sunny. Fig. 12(a) and (b) show the position of the sun obtained by the image sensor when it is sunny and cloudy, respectively.

Fig. 13 presents images of the solar tracker tracing the sun and images of the sun taken by a camera attached to the tracker. The images in this figure are presented in chronological order from the upper left to lower right.

As shown in Fig. 13, the developed solar tracker demonstrates good performance in tracking the sun because the sun in the camera image remains in the center of the image as the tracker moves over time.

IV. Conclusion

In this paper, we have proposed a solar tracking system and an algorithm that uses astronomical estimates of solar position and solar image processing results. In addition, we have proposed an autonomous decision-making algorithm based on weather conditions obtained by the image sensor. We expect that the proposed method will improve acceleration of the local spread of the solar cell module due to the high precision and robustness of the system in cloudy weather conditions.

Acknowledgment

This work was supported by a grant from BK 21 plus project for Secured Smart Electric Vehicle Specialist Education Team.

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JeongJae Yoo was born on May 8, 1984. He received a bachelor's degree in 2011 from Kookmin University, Seoul, Korea. He is currently pursuing a master's degree. His research interests are iterative estimation and tracking of moving targets, and solar energy.

Yeonsik Kang received bachelor's and master's degrees in 2001 from Seoul National University, Seoul, Korea, and a doctoral degree in 2006 from the University of California, Berkeley, in Mechanical Engineering. From 2007 to 2011 he served as a research engineer. He is currently a professor in the Department of Automotive Engineering, Kookmin University, Seoul, Korea. His research interests are model predictive control, obstacle avoidance, and modeling and controller design.

Bongsob Song received the B.S. degree in mechanical engineering from Hanyang University, Seoul, Korea, in 1996 and the M.S. and Ph.D. degrees in mechanical engineering from the University of California (UC), Berkeley, in 1999 and 2002, respectively.

He was a Research Engineer with the California Partners for Advanced Transit and Highways Program, UC Berkeley, until 2003. He is currently an Associate Professor with the Department of Mechanical Engineering, Ajou University, Suwon, Korea. His research interests include sensor fusion, convex optimization, and nonlinear and robust control with applications to intelligent vehicles.

Jinseop Song is currently with Department of System Eng., Korea Institute of Machinery and Materials, Daejeon, Korea

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