PHOTOGRAMMETRIC ESTIMATION OF SHADING IMPACTS ON PHOTOVOLTAIC SYSTEMS

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ABSTRACT

In order to decide the place to install a PV system and to estimate its performance, it is important to consider the effect of shadows on the PV array before and after PV system comes into operation. However, the shading effect cannot be evaluated easily on site because the position of obstacles surrounding the PV system is difficult to specify. Therefore, this paper is intended to develop new software for estimating the position of obstacles and their shadow by using the triangulation with two photographs or more.

INTRODUCTION

An ideal place to install a PV system is where no obstacles exist which shut out the solar radiation. However, in practice, few PV systems can be installed such as ideal place. Almost all PV systems are installed under the condition that buildings or trees cast their shadow on the modules. In order to decide the place to install a PV system and to estimate its performance, it is important to consider the effect of shadows on the PV array before and after PV system comes into operation. Estimation of shadow on PV system gives the estimation of irradiation reduced by the shadow and the estimation of output energy from PV. Moreover, it can be applied to a prior evaluation of the PV module arrangement.

Our laboratory has studied to estimate the shadowing on PV array using the photogrammetry which specifies the position of obstacles [1]. The purpose of this paper is to develop new software for estimating the position of obstacles by using the triangulation with two photographs, which also estimates the shadows on sloping PV array, at an arbitrary time.

METHOD OF SURVEYING THE OBSTACLES BY USING PHOTOGRAPHS

The conceptual diagram for estimating the obstacles is shown in Fig.1. Point **P** is the target point. Point $\mathbf{O_L}$ and $\mathbf{O_R}$ indicate the left and right camera positions. The distance between $\mathbf{O_L}$ and $\mathbf{O_R}$ is given as *d*. At first, it is needed to set the 3D coordinate (*x*, *y*, *z*), then the left plate coordinate (X_L, Y_L) and the right one (X_R, Y_R) are defined with taking their coordinate origin at (*0, 0, f*) and (*d, 0, f*) respectively, where *f* is the focal distance of the camera. The point $\mathbf{P_L}$ which is on the plate coordinate of the left photograph and the point $\mathbf{P_R}$ which is on that of the right photograph are corresponding to the point **P**. The coordinate of the point **P** can be estimated from equations (1) by using data of left and right plate coordinates.

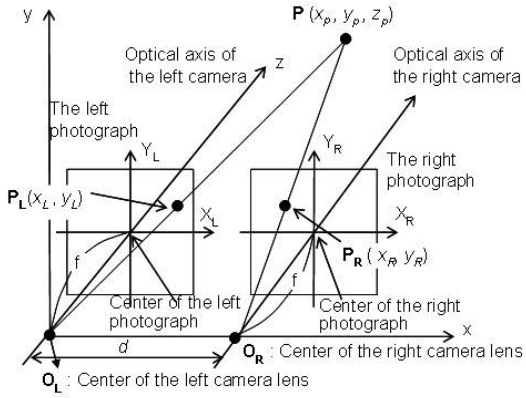


Fig.1 Calculation of the coordinates by triangulation

$$x_p = \frac{d \cdot x_L}{x_L - x_R}, y_p = \frac{d \cdot y_L}{x_L - x_R}, z_p = \frac{d \cdot f}{x_L - x_R} \quad (1)$$

ESTIMATING THE SUN POSITION AND THE SHADOW

Positions of shadows are estimated from the latitude and the azimuth angle of the sun at a given time, *α*, *h*, and a height of target point y_p. A conceptual diagram for estimating the shadows is shown in Fig.2.

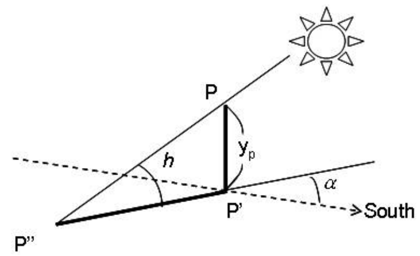


Fig. 2 Conceptual diagram of estimating shadows

From Fig. 2,

$$\mathrm{P'P''} = \frac{y_p}{\tan h} \tag{2}$$

is derived. Assuming the east-west direction is x-axis and the south-north direction is z-axis, coordinate of **P”** is obtained by the following equation.

$$X = \frac{\sin \alpha}{\tan h} y_p \tag{3}$$

$$Z = \frac{\cos \alpha}{\tan h} y_p \tag{4}$$

Calculating each point of objects, their shadows can be estimated.

ESTIMATING THE SHADOW ON INCLINE

Estimating the shadow on a plane is described in the previous section. However, usually, PV arrays are set on an incline. Estimating the shadow on an incline is necessity. In this section, the shadow on PV arrays set on an incline is estimated. The conceptual diagram for estimating the shadow on an incline is shown in Fig.3. The point P casts its shadow at $\mathbf{P_A}$ on the inclined PV module. On a plane, the point P casts its shadow at **P”** (*X*, *Z)*. The height of point **P** is y_p and α is the direction of $\mathbf{P_A}$ from z-axis. H_A, D_A and i are height of array, depth, and slope angle. The distance between the point **P** and the front edge of PV array is *d*.

The first step is thinking of Z direction of PV array. Fig.4 is a side view of the PV array shown in Fig.3. From the relation between gray triangles of the zoom up of Fig.4, H_1 and H_2 are derived. Also, H_3 and Z_1 are derived from the zoom up of Fig.4. Z_A is the distance between the front edge of the PV array and $\mathbf{P_A}$. Equation (9) is derived from (5), (6), (7) and (8).

$$H_1 = \frac{Z - d}{Z} y_p \tag{5}$$

$$H_2 = \frac{Z - d - D_A}{Z} y_p \tag{6}$$

$$H_3 = H_A - \frac{Z - d - D_A}{Z} y_p \tag{7}$$

$$Z_1 = \frac{D_A}{\cos i} \tag{8}$$

$$Z_A = Z_1 \times \frac{H_1}{(H_1 + H_3)} = \frac{D_A}{\cos i} \times \frac{(Z - d) y_p}{H_A Z + D_A y_p} \tag{9}$$

The next step is thinking of X direction of PV array. Fig.5 is top view of PV array in Fig.3. Using the right-angled triangle, the length of the segment X_A on PV array is obtained. From Fig.5, X_1 is derived. From Fig.4 and Fig.5, D_1 is derived. From gray triangle in Fig.5, equation (12) is derived.

$$X_1 = d \times \tan \alpha \tag{10}$$

$$D_1 = Z_A \times \cos i \tag{11}$$

$$X_A = \frac{X_1 \times (d + D_1)}{d} = \tan \alpha \times (d + Z_A \cos i) \tag{12}$$

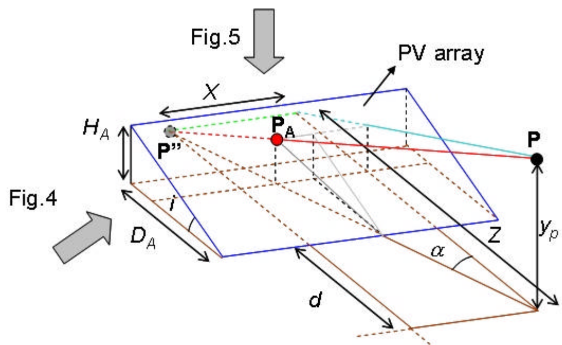


Fig.3 Relation between point P and PV array

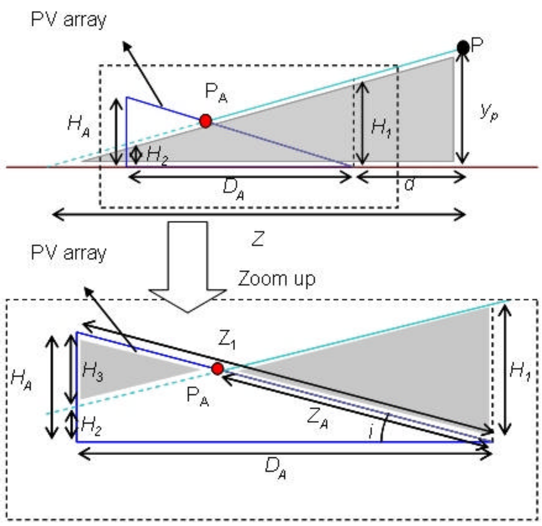


Fig.4 Side view of PV array in fig.3

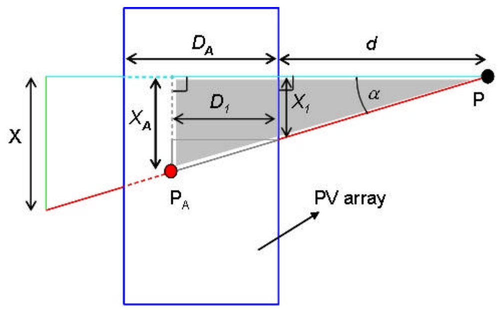


Fig.5 Top view of PV array in Fig.3

EXAMINATION BY USING TURNING CAMERA PHOTOGRAPHS

Estimating the shadow by using parallel camera photographs has been explained at the previous section. However, in order to make it easier to take photographs on site, an idea is to use turning camera photographs for the estimation of shadows.

In order to estimate the shadow by using turning camera photograph, the turning camera photographs need to be transformed into the parallel camera photographs. The authors proposed and examined two image transformation methods [2].

(1) Reverse turn transformation:
From the difference between the reference point of the turning camera photograph and the ideal parallel camera photograph, the angle of rotation of the camera is calculated. Then, the coordinates of the turning camera photograph is multiplied by the reverse rotation matrix.
(2) Parallel translation transformation:
The reference point of the turning camera photograph is fitted and moved to the coordinate of the reference point of the ideal parallel camera photograph.

THE RESULT OF CORRECTION BY IMAGE TRANSFORMATION METHODS

Fig.6 shows the estimation of errors of y coordinate by using two image transformation methods with turning camera photographs. The error means the ratio of the difference between estimated y coordinate and true y coordinate to true y coordinate. Axis of abscissas shows the ratio of the distance between the right camera and the left camera to the distance between the cameras and the target point. Axis of ordinates shows the absolute value of the error. The averaged value of errors with the reverse turn transformation is 35.6%. The result shows the correction is not appropriate. The reason of the error is the difference between the center of optical axis and the center of photograph. It was not taken into consideration when the rotation angle was calculated. On the other hand, the averaged value of the errors with the parallel translation transformation is 4.7%. In the parallel translation it seems to be corrected the turn and also the difference of the two centers.

Fig.7 shows the estimation of errors of y coordinate by using the parallel camera photographs including the difference between the center of the optical axis and the center of the photograph. The averaged of absolute value of errors before the transform is 40.0%. On the other hand, average of the absolute value of errors with the parallel translation transformation is 2.6%. In the parallel translation transformation it can be corrected the turn and the difference of the two centers. These conclude that the parallel translation transformation is effective.

DEVELOPED SOFTWARE

On the basis of the above results, we developed new software for photogrammetry and estimation of shading adopting parallel translation transformation. Fig.8 shows a flow of photogrammetry and estimation of shadow in the software.

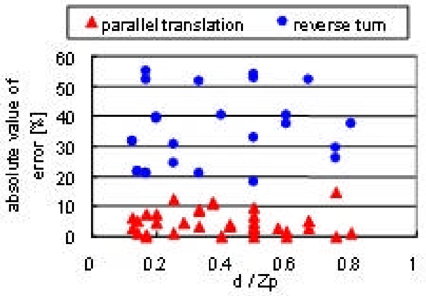


Fig.6 Estimation of errors of y coordinates by using the turning camera images

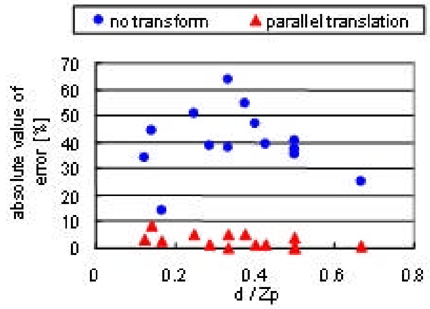


Fig.7 Estimation of errors of y coordinates by using the parallel camera images

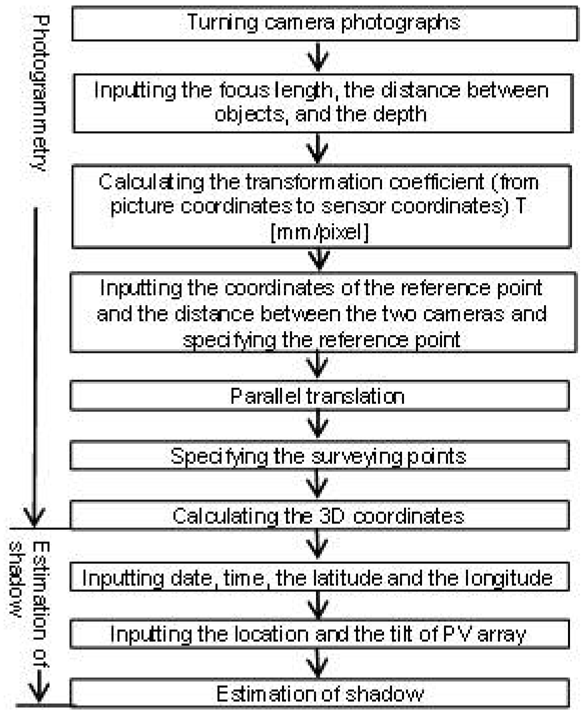


Fig.8 Flow of photogrammetry and estimation of shadow

Magnetic declination also can be calculated with this software. Magnetic declination is difference between the true north and the magnetic north. Only we can estimate is on the magnetic north on site. Magnetic declination is calculated by inputting the latitude and the longitude. From the magnetic declination, the true position of the sun is calculated. Shadow positions can be estimated with the true position of the sun.

ESTIMATION OF SHADING OF OBSTACLE BY USING DEVELOPED SOFTWARE

We surveyed an obstacle by using developed software with the turning camera images. Fig.9 shows a schematic diagram of the photogrammetry and the condition. The obstacle is a rectangle box of 81.5×18×34 cm (length, width, and depth). The photography is taken as follows. The points of photography are on the line which is 200cm from the obstacle. The photography of right side is taken with two cameras 40cm between the two cameras. The photography of left side is taken in the same way at 60cm interval between the cameras.

THE RESULT OF PHOTOGRAMMETRY

Fig.10 shows the estimation results of the obstacles position. The errors of the estimation are less than 4.5cm for the length (y) and width (x). The errors of the estimation are less than 17.1cm for the depth (z). These results indicate the validity of estimating obstacle.

THE RESULT OF ESTIMATING SHADOW

Shadow of the obstacle is estimated on the roof of TUAT by using developed software on July 13 in 2004. Fig. 11 shows the measured data and the estimated ones. This figure is an overhead view over the rectangle box. Between 10:30 and 14:30, the measured data and the estimation are agreed well. The errors of the estimation are less than 5.6cm of the shadow at 16:00. These results indicate the validity of estimating shadow.

CONCLUSION

A novel method of photogrammetry by using the turning camera photographs to estimate the shadow on incline has been proposed. New software for estimating the position of the obstacles and the shadows on an incline has been developed. This software can easily estimate the shadows on PV without technical knowledge or instrument. The future direction of this study will be the evaluation in an on-site on PV system in order to confirm the validity of the developed software.

REFERENCES

[1] Tomori et al., “ON-SITE BIPV ARRAY SHADING EVALUATION TOOL USING STEREO-FISHEYE PHOTOGRAPHS”, *28th IEEE PVSC*, 2000, pp.1599-1602

[2] Ike et al., “Estimation of obstacles for PV systems by using photogrammetry”, *2004 NATIONAL CONVENTION RECORD I.E.E. JAPAN*, 2004, pp.59-60

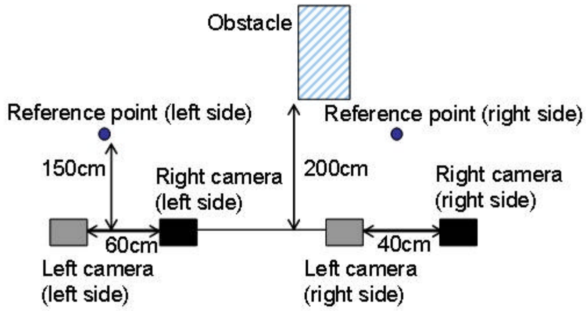
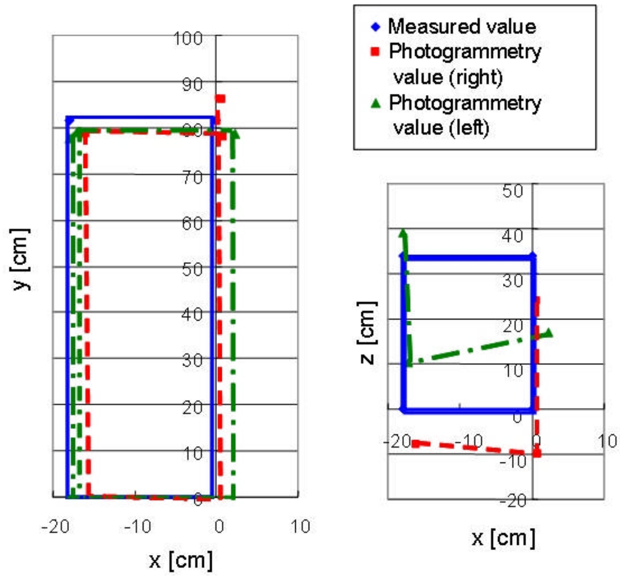


Fig.9 Schematic diagram of photogrammetry and the condition



(a) x y coordinate plane (b) x z coordinate plane

Fig.10 Estimation results of the obstacles position

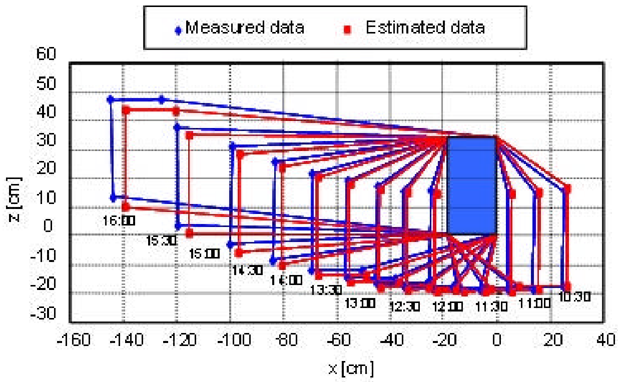


Fig.11 Estimation results of shadow by using developed software