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CODING TEMPLATE OF SENSORLESS SUN TRACKING USING AZIMUTH-ELEVATION MODE

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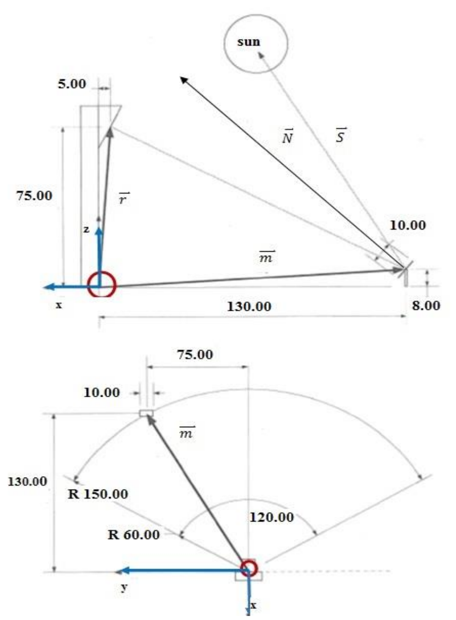
Graphical abstract



Abstract

The next explosion in solar power research was in 1997 as consequence to Kyoto Protocol. This protocol outlined the effect of greenhouse emission which endangers our Earth. As the result, research in solar power field started to take its path again. This work is a part of the UTeM project to build the first CST model in South East Asia and was aimed to develop an azimuth-elevation-mode-based template using MATLAB programming for the calculation of the heliostat position with respect to the heat absorber mounted at the top of the CST. This template will serve as the calculation platform to control the movement of the heliostat using a two-axis motion system so that the sun light will be redirected perfectly to the absorber all day long. Since the heliostat normal vector depends on sun position vector, both vectors were calculated by the program and were set as the output of the program. The input from the user will be the Cartesian coordinate of the heliostat and absorber by taking the absorber tower frontal surface and its base as the origin and also the date. The result will be in vector form and will change automatically according to the Sun movement. These values will be programmed in the micro controller which will control the motion system of the heliostat, which will be done by the Control Department of UTeM. The program´s functionality was proved via several verifications and its accuracy which is 0.0005 as stated and verified via comparison with analytical calculations. From the verifications, it can be seen that difference of the numerical and analytical results varied from 0.0000 to 0.0005 which validates the statement of minimum accuracy of the numerical calculated results is 5/10,000.

Keywords: Heliostat, sun tracking, azimuth-elevation, code

1.0 INTRODUCTION

Sunlight that reaches the Earth is spread out over such a large area. Basically, the Sun does not deliver that much energy to one place at one time [1]. Solar energy received at a place depends on several conditions. They actually act as limitations in solar energy capturing process. These includes the time of the day, the season of the year, the latitude of area and the clearness or cloudiness of sky. Via Concentrating Solar Power (CSP) technology, the solar energy is multiplied from several time to few thousand time as it is concentrated onto a certain size of area before it is converted into electric power. The concentrated sun irradiation is multiplied several times (which is around 600 to 1000 times) producing very high temperature. The temperature is in the range of 800°C to 1000°C [8].

The Concentrating Solar Power system can be divided into two types of system which are line focusing and point focusing. The point focusing system produces higher temperature concentration as sun irradiation is focused on one point compared to line. It also has higher efficiency compared to its counter system [8]. Examples of point-focusing CSP technology are dish stirling and concentrated solar tower (CST) system. There are Malaysian researches involving heliostat.

In 2001, UTM suggested a design for a single layer sun-ray concentrator, a non-imaging focusing heliostat. The design uses several small mirrors to form a heliostat to reduce first order image defect [2]. Malaysia University of Science and Technology (MUST) worked on residual aberration for non-imaging focusing heliostat in 2003 [3]. Universiti Tunku Abdul Rahman (UTAR) derived general formula of system for all existing-method on-axis sun-tracking system in 2009 [4]. In 2011, they did a comparison between the two methods of sun tracking, which are Azimuth-Elevation and Spinning-Elevation methods [5].

This work is part of the feasibility study and CST mini model generation project and is aimed to develop a template using MATLAB programming for the calculation of the heliostat position with respect to the heat absorber mounted at the top of the CST via azimuth-elevation mode. This is done by calculating sun position vector and heliostat normal vector based on the calculated sun position by implementing the developed MATLAB code. The developed code will then be utilized by other UTeM team to realize the azimuth-elevation mode of sun tracking of the heliostat of mini CST project.

The input from the user will be the Cartesian coordinate of the heliostat and absorber by taking the absorber tower frontal surface and its base as the origin and also the date. The result will be in vector form and will change automatically according to the Sun movement. These values will be programmed in the micro controller which will control the motion system of the heliostat.

2.0 EXPERIMENTAL

The theory behind sun-tracking procedures and its corresponding calculation are well understood. The related calculations are inter alia sun position, azimuth angle, heliostat normal, the Sun irradiation redirection vector.

An analytical calculation of a sample case is then done as reference values to ensure that the output values from to-be-developed code are correct. Only after achieving this, the code can be developed.

Every calculation step which is taken from the theory part should be converted to MATLAB code. The input should be the date (no. of month and no. of day are entered separately), the Cartesian coordinate of heliostat, the Cartesian coordinate of the tower. Latitude is set as a fixed value in this code, which is the latitude of UTeM. Whereas outputs are sun position and heliostat mirror normal vector. The code is developed for the utilization between 7 a.m. and 7 p.m. as the Sun is assumed to be only available during this time range.

The verification of the result is done by testing the code of several different dates and comparing the outputs with analytical calculation for several cases of different dates with selected solar time. The accuracy of the calculated numerical results will be found and stated afterwards by comparing them with analytical calculated results. The code is then ready to be used after all the verification processes are done.

Theory of Sun Position and Heliostat Normal Calculation

The components of heliostat normal vector are inter alia sun position $\overrightarrow{S}$ and redirection of Sun ray vector $\overrightarrow{R}$ and angle of Sun ray incidence on mirror and angle of redirection of the Sun ray towards the receiver (since angle of incidence and reflection have the same value) or denoted as θ. Refer Figure 1.

In a two-component gel, it is easy to modify the molecular structure of either of the two components.

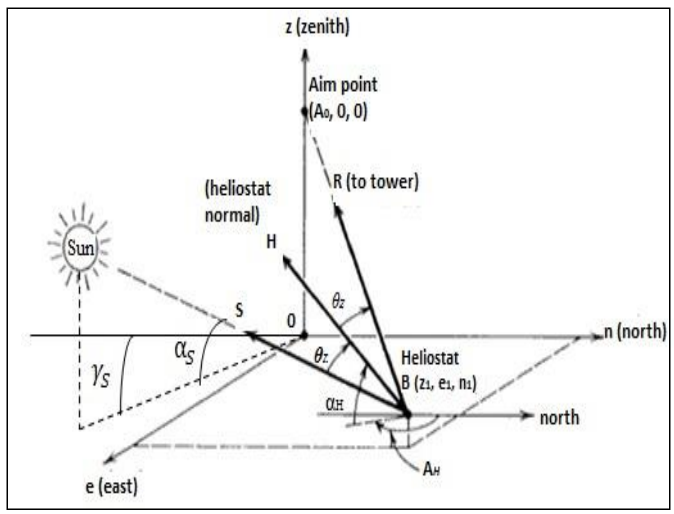


Figure 1 Geometric relationships between heliostat and receiver in a zenith-east-north Cartesian coordinate system, *Source:* [8]

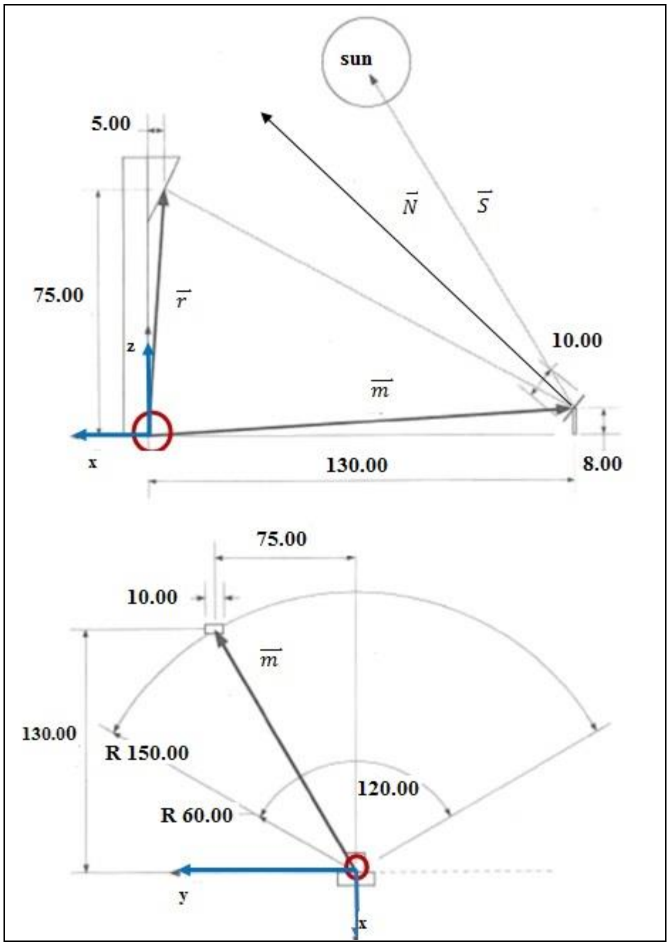


Figure 2 Sketch of side and top view of CST and its coordinate systems

It is important to note the coordinate system used before calculations are proceeded. Based on the Figure 2, heliostat or mirror and receiver or also known as absorber vectors utilize the tower base as reference. The vectors are denoted as $\vec{m}$ and $\vec{r}$ respectively and these vectors are user's input. The x-axis lies right under the tower base itself, whereas z-axis coincides with the front surface of the tower, if both axes are observed from the side view of the tower. Y-axis lies in the middle of the tower if it is observed from bird's eye view.

Based on Figure 2, sun position vector $\vec{S}$ and heliostat normal vector $\vec{N}$ take the center of the heliostat as the origin. These two vectors are the output of the developed program. In other words, there are two different origin used in the calculation.

To calculate sun position for a certain day, the date of the day must be known and be provided to determine the nth day of the year.

With the known solar altitude α_s and azimuth angle γ_s the sun position vector $\vec{S}$ with respect to horizontal surface at any point on the Earth can be determined using below formula:

$$S_z = S_z = \sin\alpha_s,$$
$$S_e = S_y = \cos\alpha_s \sin\gamma_s,$$
$$S_n = S_x = \cos\alpha_s \cos\gamma_s \quad (1)$$

The law of specular reflection is applied in the redirection of the Sun ray calculation. This law states that the angle of incidence is equal to the angle of reflection.

Receiver vector, $\vec{r} = \begin{pmatrix} n_0 \\ e_0 \\ z_0 \end{pmatrix} = \begin{pmatrix} x_0 \\ y_0 \\ z_0 \end{pmatrix}$;

Mirror vector, $\vec{m} = \begin{pmatrix} n_1 \\ e_1 \\ z_1 \end{pmatrix} = \begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix}$;

Redirection of the Sun ray vector,

$$\vec{R} = \frac{[(z_0 - z_1)\,\hat{\imath} + (e_0 - e_1)\,\hat{\jmath} + (n_0 - n_1)\,\hat{k}]}{\sqrt[2]{[(z_0 - z_1)^2 + (e_0 - e_1)^2 + (n_0 - n_1)^2]}} \quad (2)$$

The scalar point between the vectors of $\vec{S}$ and $\vec{R}$ results in cosines of two-time angle of incidence θ like in following expression:

$$\cos 2\theta = \vec{S}.\vec{R} =$$
$$R_z \sin\alpha_s + R_e \cos\alpha_s \sin\gamma_s + R_n \cos\alpha_s \cos\gamma_s \quad (3)$$

$\vec{N}$ is a normal vector of heliostat at a moment, at which sun ray arrives parallel to the vector $\vec{S}$ and the ray is reflected onto the receiver or absorber. It can be calculated via addition of incidence $\vec{S}$ and reflection vectors $\vec{R}$ and via division of the added vector values with the suitable scalar quantity:

$$\vec{N} = \frac{[(R_z + S_z)\hat{\imath} + (R_e + S_e)\hat{\jmath} + (R_n + S_n)\hat{k}]}{2\cos\theta} \quad (4)$$

where component x is denoted by unit vector $\hat{k}$, component y is denoted by unit vector $\hat{\jmath}$ and component z is denoted by unit vector $\hat{\imath}$ along north, east and zenith direction respectively.

3.0 RESULTS AND DISCUSSION

In developing the code, several important parameters which determine the sun position and the resulting heliostat normal such as the date of a certain day, heliostat and receiver position are set as variables, so that user can determine the input as needed. For example, the date must be keyed in to tell the program what day it is to determine nth day of the year and celestial declination/inclination δ. The celestial declination/inclination δ is a necessary component for sun position vector calculation. Different day gives different sun position. This explains the reason of the date being important to be set as a variable. Whilst heliostat and receiver positions are also set as variable since both vectors depend on the heliostat field design and layout. Therefore, this program can be used for an independant single heliostat, which its position is determined by user. The output of this programme are sun position of a certain day and also the corresponding heliostat normal, so that incident sun ray will be reflected exactly on the receiver.

Following is the summary of the numerically and analytically calculated results with the aid of the developed program. They are tabulated as follows:

Table 1 Output from the developed code for all five cases

No. of Verification	Date and Time	Sun Position Vector	Heliostat Normal Vector
Sample Case	24th July 3 p.m.	Numerical: [0.1295 0.6652 0.7353] Analytical: [0.1300 0.6653 0.7352]	Numerical: [0.6186 0.1324 0.7744] Analytical: [0.6189 0.1324 0.7742]
1	24th July 7 a.m.	Numerical: [0.1243 -0.9087 0.3985] Analytical: [0.1242 -0.9088 0.3983]	Numerical: [0.4941 -0.7506 0.4387] Analytical: [0.4940 -0.7508 0.4385]
2	3rd Sept. 7 p.m.	Numerical: [-0.2514 0.9588 -0.1323] Analytical: [-0.2514 0.9588 -0.1323]	Numerical: [0.6880 0.6325 0.3557] Analytical: [0.6879 0.6325 0.3555]

From Table 1, it is shown that the calculated results are only accurate to 0.0005 metre since numerical and analytical results differs up to 5/10,000 due to some rounding error. However, the result deviation is too small which generates only less than one degree, since the distance range between the heliostat and receiver is normally will not exceed one kilometre [6].

4.0 CONCLUSION

This work has produced a MATLAB program to calculate the hourly sun position and heliostat normal vector from 7 a.m. to 7 p.m for a given day. User should enter the day of the desired output, heliostat/mirror and also receiver/absorber position vector as input. The program will automatically calculate the related sun position vector and the corresponding heliostat normal vector, at which the sun ray will be redirected onto the receiver hourly for a time range from 7 a.m. to 7 p.m.. The program´s functionality has been proved via several verifications and its accuracy which is 0.0005 has been stated and verified.

However, the generated code is only for a single heliostat utilization and also to calculate the sun position hourly. In addition the code is in M-file form. Therefore, future works may include calculation not only for a single mirror, but for n mirrors and the calculation may be carried out for every minute instead of hourly to guarantee a more precise sun position and corresponding heliostat normal vector. Moreover, this work may be converted to 'Graphic User Interface' (GUI) form to make it interactive and user friendly.

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