International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Journal Européen des Systèmes Automatisés
Vol. 56, No. 1, February, 2023, pp. 165-171
Journal homepage: http://iieta.org/journals/jesa

Solar Power Heliostat Control Using Image Processing Technology and Artificial Neural Networks

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https://doi.org/10.18280/jesa.560120

Received: 17 January 2023
Accepted: 9 February 2023

Keywords:
sun tracking, heliostat field, image processing technique, artificial neural networks

ABSTRACT

Sun tracking is very important to improve the efficiency of the concentrated solar panels (CSP) output power. Hence, high-accuracy sun tracking is needed. In this paper, we propose an innovative approach for the heliostat optimal orientation, overall, the solar tower using a hybrid image processing technique (IPT) and artificial neural networks (ANN). The main objective is to minimize the tracking error and increase the solar power tower plant performance. Image processing is used to locate the Sun position and help the heliostat to achieve its optimal direction. Moreover, using MATLAB/Simulink, the neural network approach is applied in order to simulate the IPT and generalize the heliostat tracking positions.

1. INTRODUCTION

Improving the efficiency of electricity production of the thermal system is one of the most important research directions in the field of renewable energies. In given sunshine conditions, the efficiency can be improved by concentrating sunlight to increase the amount of illumination for the solar concentration system. To this end, a high-accuracy sun tracking system is needed for optimal tracking of the Sun path. Generally, we can classify the sun tracking into one or two axis ones, and the tracking algorithm into three groups, which are open loop, closed loop, and hybrid tracking systems [1, 2].

To determine the sun's position even on cloudy days, an open loop algorithm is used [3-5]. The azimuth or elevation angles can be calculated using the astronomical formulas of the sun's position at a specified date, time, and geographic location. These systems can be monitored using a microcontroller or a control system.

Moreover, in the closed-loop sunlight tracking systems various detection devices, such as a CCD or a photo sensor, give an error signal to turn the tracker in the optimum position. Closed loop systems are used widely in sun tracking, although they do not give good results in variable weather condition, they are costless and time-saving control systems, which encourage the use of them in the case of heliostat tracking [6-11]. Taking the advantage of both open and closed loop tracking algorithms, a hybrid solar tracking system is elaborated for high precision [12-14].

Besides these algorithms, others can be found in the literature that use a camera for sun position tracking [15-21].

The image processing technique is widely used for sun tracking [11]. In the study [7], a webcam is used as the sensor for sun tracking. In the study [12], ellipses fitting method is used to determine the Sunspot center. In reference [22], both centroid geometric center methods have used image processing and made an evaluation based on the beam gray images generated by the heliostat.

Many researchers have studied artificial intelligence systems such as neural networks [23-27], where the main goal is to determine how to optimize and further improve the efficiency of the systems studied.

However, the main drawback of these methods is the computational time and the need for big data analysis.

Several research has been conducted in the field of control systems using artificial intelligence methods. A novel radial basis function neural network is used for optimal PV panel modelling [28]. In the study [29], the adaptive position of the mobile manipulator robot is investigated. Moreover, a control method is presented by Nengmou and Adeli [30], which takes into consideration the nonlinear vibration.

Based on the mentioned literature review, we propose in this paper, a novel hybrid intelligent control scheme of the heliostat being used in solar tower systems. An artificial neural network predictor is used in the case of cloudy skies with an image processing technique that ensures the brightest points tracking, which corresponds to the sun's position. To this end, a CCD camera is used and the heliostat is moved to the considered sunspot.

2. SOLAR TRACKING SYSTEM DESCRIPTION

In this section, we will show in details the three control systems used to control the movements of the heliostats in a solar tower with high pointing accuracy with and without the cloud's presence.

2.1 Open loop control system

Figure 1 shows the operating principles of a solar tracking control strategy in an open loop. In this control mode, the motor control signal is required in order to determine the heliostat position [31, 32].

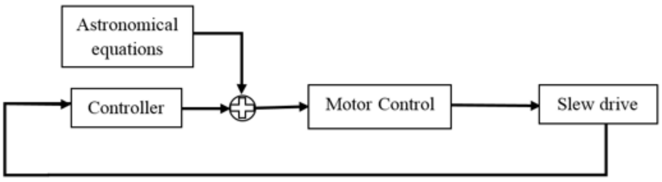

Figure 1. Operational principles of open-loop solar tracking control

The positions of the sun are calculated using the longitude and latitude coordinates, which indicates the two main sun tracking parameters; azimuth and elevation. Only astronomical paraments are used in this control method, which suffer from begin unable to correct the installation and calibration errors of the solar tracker. That leads to accepting all the used parameters, which affect the correct sun's path tracking.

2.2 Closed loop control system

In the closed-loop control (Figure 2), and to follow the sun's movement, optimal solar tracking accuracy is ensured with the aid of electronic devices sensitive to light or a camera (CCD). The optimum pointing of the sun's position is achieved using optical feedback. In addition, using the closed-loop control method helps to eliminate the errors introduced by the installation or any mechanical failures. Both image processing and optical solar tracking are used to improve sun movement tracking [32]. The process begins with capturing an image of the sky using a digital camera or sensor. The acquired image is then filtered to remove noise and enhance its quality. Once the pre-processed image is saved, it undergoes binarization to segment the sun's region from the background using thresholding techniques. The sun's center, or centroid, is calculated from the segmented image, providing essential information about the sun's position. Finally, the solar tracking system, or heliostat, adjusts its position based on the calculated sun's center, ensuring efficient tracking and optimal energy capture.

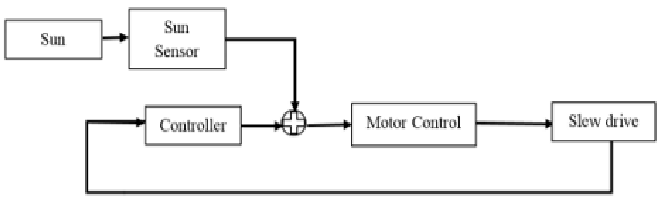

Figure 2. Operational principles of closed-loop solar tracking control

Two position sensors (photodiodes or photovoltaic cells) are used in this kind of tracking system to determine the sun's position. The difference between the sensors measurements determines how much movement of the solar tracker. While there are no strict requirements for sensor placement, it is preferable to position the sensors at the top or sides of the solar panel to ensure optimal sunlight detection and accurate tracking.

Generally, we can use one pair of sensors (Figure 3) in the one-axis tracking systems to control a single heliostat motor or two pairs for full tracking mode. The idea of two sensors is by using two mounted LDR sensors, similar to the human eyes, one sensor will look to the east and the other to the west. And the position of the heliostat is moving toward the sun, which have the highest amount of sunlight. The optimum position is determined using an intelligent control method such as fuzzy logic and the signal is sent to the DC motor for the heliostat movements.

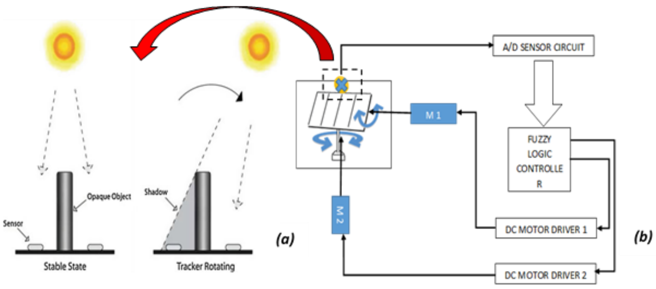

Figure 3. (a). Light sensor array design. (b). Block diagram for the sun tracker system [33]

The presence of clouds, however, is a major disadvantage of closed-loop control. In addition, the solar vector can be hard to detect due to the optical observation problems, which are due to the sun's movement that influences the view field of the camera or the image sensor range. To address this issue, hybrid open/closed loop tracking control is employed.

2.3 Hybrid control system

A hybrid loop is a combination of both advantages of open and closed loops for the optimal dynamic sun tracking system. In this control system, we use generally optical light detection sensors. The type of signal is a time-controller which is either discrete or continuous [32].

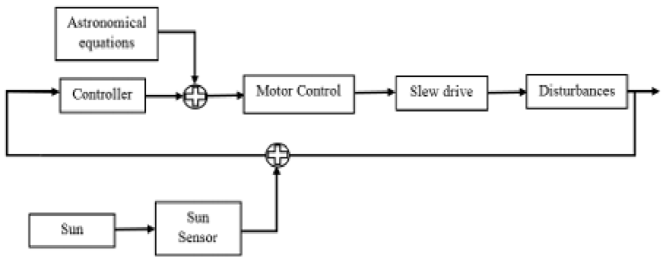

Figure 4. Operational principles of hybrid (open-loop/closed-loop) motion control

In the hybrid control method shown in Figure 4, both astronomical algorithm and optical light sensors are used to track the sun's path. It takes the advantage of both open and closed loop control and give good results, especially in real-time.

3. METHODOLOGY

Our objective is to obtain the optimal sun-tracking system. Hence, a hybrid control method is proposed. It is composed of two main categories; the first one is a closed loop scheme based on the response of the CCD camera to calculate the heliostat angles, which helps to determine the sun's position.

The second category is an open loop control scheme based on astronomical formulas to predict the trajectories of heliostats by using artificial neural networks without any feedback [34].

The flowchart of the adopted methodology is shown in Figure 5. The angles of the heliostat are used to detect the center of the Sun. If the sun is covered by clouds. The system will send a signal to the motors from the neural predictor. This will continue until the sun appears in the sky. When the sun is detected, the system will and analyze the position of the sun to determine the center of the sunspot. This is applying to the azimuth and elevation of the motors. The reflector of the heliostat is positioned by the pointing mechanism of the sun so that the normal to its surface is the bisector. The angle between the incident solar rays and the line from the central reflector rotates the heliostat to the target at the top of tower.

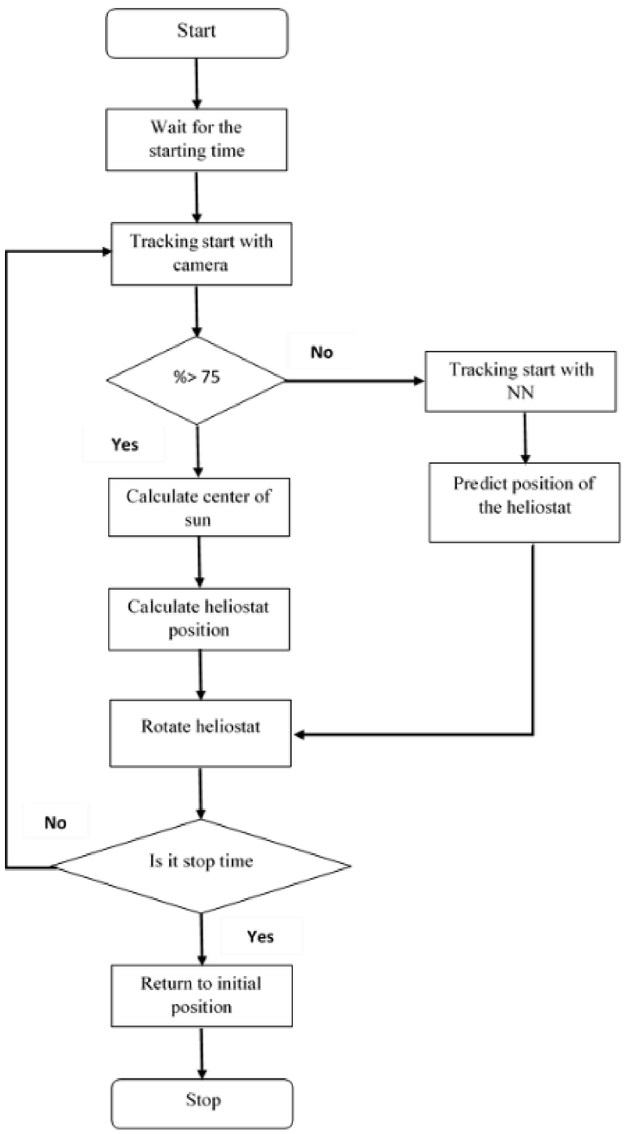

Figure 5. Flowchart of the hybrid algorithm of heliostat control

3.1 Image processing technique

The orientation of the normal vector to the reflective surface of the heliostat (NH) is calculated using the image captured by the cam as input.

Figure 6 shows the block diagram of the open loop control system

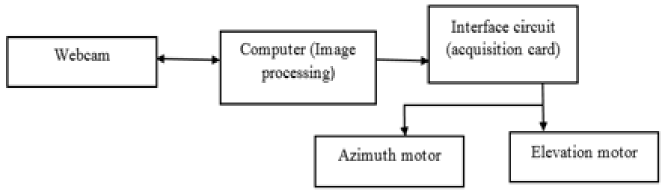

Figure 6. Experimental assembly block diagram for image processing technique

The image-processing algorithm for tracking and positioning the sun heliostats is shown in Figure 7.

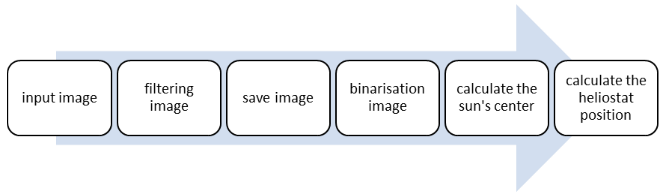

Figure 7. Image processing algorithm

The cam has been connected to a PC via the input port (USB). We have used MATLAB software for image processing to determine the sun's position and calculate the azimuth and elevation of the heliostat so that the surface normal of the mirror bisects the angle between radiation incident and reflected as shown in Figure 8.

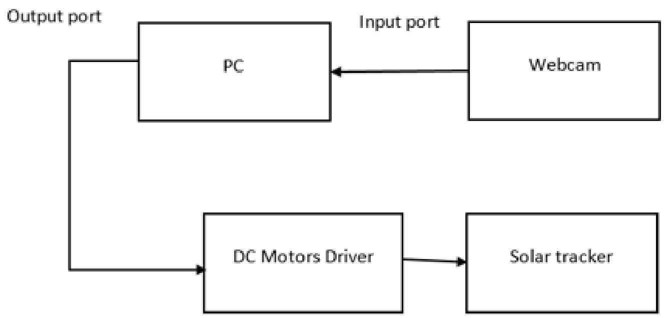

Figure 8. Diagram of the solar tracker system using image processing

The optimum position of the sun's reflection is calculated using this system by detecting its center. This can be done by controlling the electric motors through the command signal given by a PC. In the case of the sun's movement, another signal is sent to the heliostat in order to correct its movement toward the sun's new center.

In order to determine the coordinates of the sun's center, the sun's image is needed for each processing step, which is ensured using the developed MATLAB program.

In the case where the percentage of the circular shape of the sun does not exceed 75% or the solar image is outside the webcam frame, the procedure executes the estimation of the solar position by the artificial neural network.

3.2 Neural network predictor of the heliostat position

The ANN predictor is shown in Figure 9 consists of using an artificial neural network in order to estimate the angles of the azimuth or the elevation of the heliostat. For that, five parameters are used as inputs, which are, the data and time of the sun based on the geographical location of the solar tower;

the positions of the Sun and the heliostats and historical data of the azimuth and elevation of the heliostat [34].

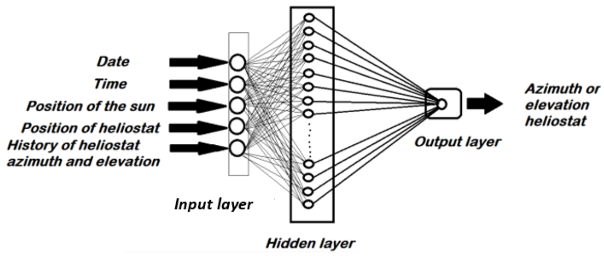

Figure 9. Neural Network movement estimating model

4. RESULTS AND DISCUSSIONS

Our objective is to track the sun's path using hybrid image processing and neural network. For each image, a conversion chain is needed; from real image to a grayscale one to a binary image. This conversion helps to detect the circular shape of the sun from each image. The results of various processing steps of the sunspot are shown in Figure 10.

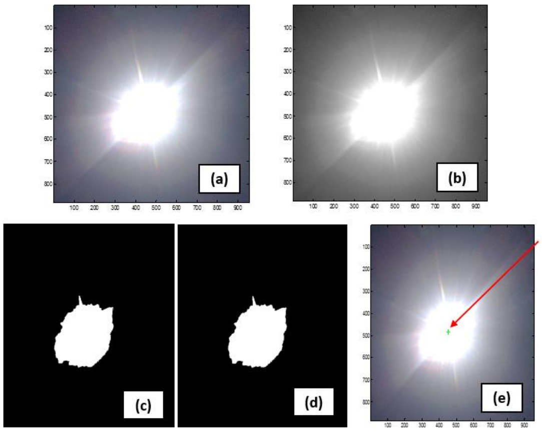

Figure 10. Various processing steps of the sunspot; (a) the sunspot color, (b) the sunspot grayscale, (c) binarization of the sunspot, (d) expansion of the morphology of the sunspot, (e) center detection of the sunspot (px=453.9255, py=483.6863)

This image processing procedure detects the center of a circle (Sun) in a color image captured by the webcam. To identify the shape of the sun, we convert the colored image to grayscale and then into a binary image.

Otsu's method [35] is used to perform automatic thresholding from the shape of the histogram of the image, the method then assumes that the binarized image contains only black and white pixels., and then calculates the optimum threshold to minimize intra-class between the two classes.

The main element in the image processing technique is to find the center of a monochrome image on a dark background (binary image) using the Fourier algorithm. This function calculates the X and Y coordinates of the center of the solar image.

Area and sun image center are the two parameters' properties to determine the position of the sun. For each image, we need to remove small size objects by comparing them with reference values (using Area), and we need also the heliostat orientation to be in its optimal position (using the sun's centroid). In the case of the cloud covering the sun, this cannot be applied due to the asymmetry in the sun's form. As a solution, we have introduced a detection program in MATLAB for circle similarity in the exported shape from the captured image; if the percentage of the shape presented in the image is similar to a circle shape between 75% to 99%, then the image processing algorithm is applied, if not the ANN method is introduced.

The summary of the circle shape detection program is given in what follows:

1- Thresholding the image using Otsu's method (binarization image).
2- Elimination of small objects.
3- Inflate the morphology of the binary image
4- Morphological operation to remove small objects.
5- Calculate the percentage of the circular shape of the sun.
6- Determine the center of the sunspot in grayscale.

For more explication about the selection method, we have given an example of the captured image with cloud processing as shown in Figure 11.

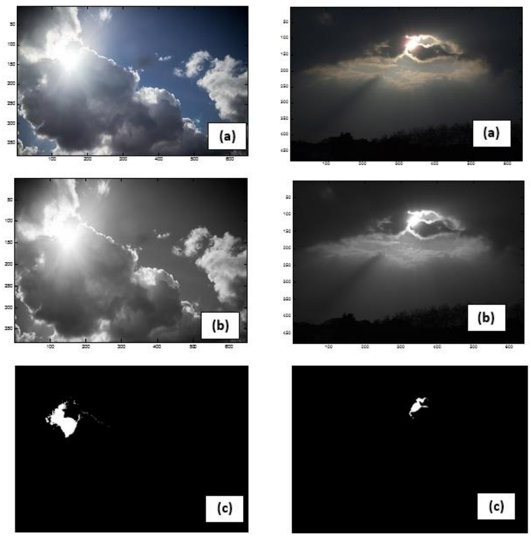

Figure 11. Various processing steps of the sunspot with the percentage of the circular shape of the sun less than 75%; (a) the sunspot color, (b) the sunspot grayscale, (c) the binarization of the sunspot

In the case where, the percentage of the circular shape of the sun is less than 75% or the solar image is outside the webcam frame; the procedure executes the estimation of the solar position by the artificial neural network (ANN).

4.1 Estimation by the neural network in the case of cloud

This estimation consists of using a non-linear regression model with artificial neural networks to predict the sun's position as well as the heliostat angles; the pattern is formed using the data calculated in reference [34].

The parameters used in this case are: (day number: n=50; Altitude: fi=43.604; receiver height: Ht=100m; heliostat tower distance: D=168.09m; east-west distance; Ap=0m; north-south distance: Dp=168.09m)

The obtained results of the heliostat's movements, real vs. estimated heliostat position elevation, and trajectory using ANN are shown in Figures 12-16.

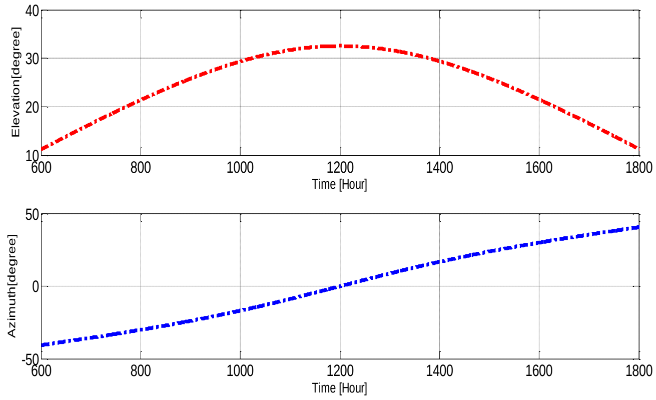

Figure 12. Heliostat’s movements (azimuth and elevation) - day 50 with cloud between 06:00 and 18:00

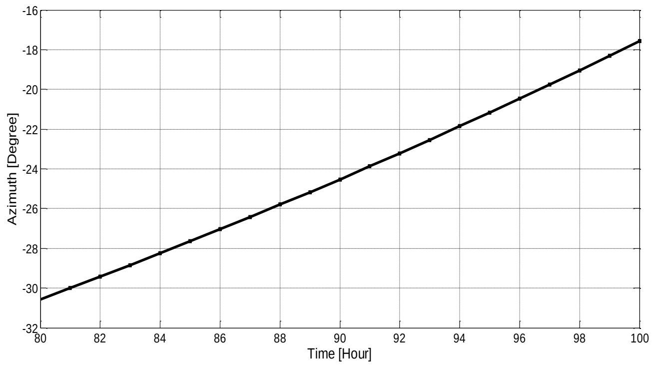

Figure 13. Heliostat position real and estimated by the neural network (azimuth) - day 50 between 08:00 and 10:00

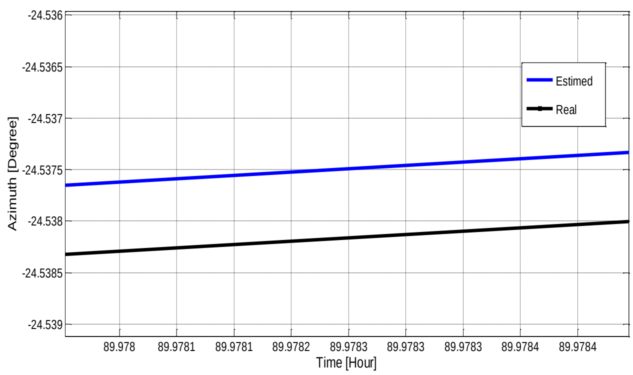

Figure 14. Heliostat real trajectories and estimated by the ANN (azimuth) - day 50

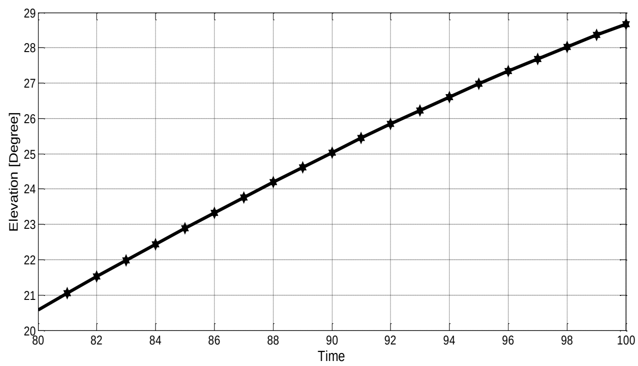

Figure 15. Heliostat position estimated by the neural network (elevation) - day 50 between 08:00 and 10:00

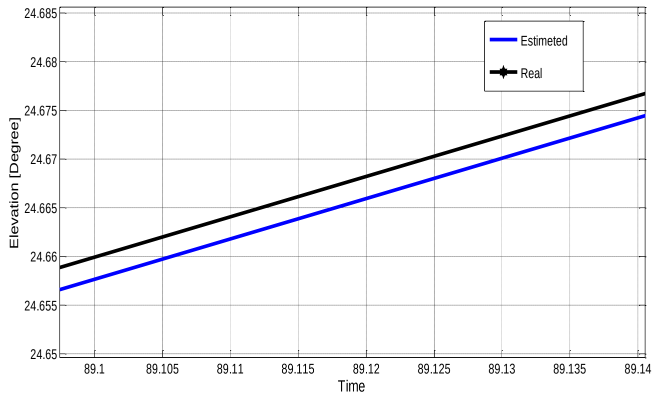

Figure 16. Heliostats real trajectories and estimated by the ANN (elevation) - day 50

From the results of Figures 12-16 the tracking error does not exceed 0.1. Moreover, it means that this method is acceptable for controlling heliostats in a solar tower. In addition, the hybrid method gives good results, especially in the presence of clouds.

5. CONCLUSION

This work deals with the monitoring and control of the heliostat position using hybrid image processing and artificial neural network. The image processing is used to determine the sunspot using reference images taken by webcam, while the ANN is used to estimate the heliostat position, especially in the presence of clouds. The use of this hybrid method gives reliable and good results compared to astronomical data.

Moreover, the use of hybrid image processing with neural networks improves solar tower efficiency by using more reflected radiation. These potential advantages can be proven through numerical simulation. And we can confirm that this method is ready for real application testing and large-scale heliostat fields.

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