PV Panel Positioning using a Robot Manipulator

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Abstract—The need for automatic orientation of solar panels in order to increase the amount of the collected sun rays is increasing. In this paper, the orientation and positioning of solar panels by employing a robot manipulator is presented. The robot manipulator system structure has first been presented. The robot controller is then modeled. The solar altitude and azimuth movements with two decoupled movement are the outputs of the controller. The determination of the position of the sun at anytime and anywhere on the globe is performed using MATLAB software. The results have been validated by comparing them with those obtained by the PVSYST software. Four situation tests have been performed: panel tilted at 0°, panel tilted at 30°, one axis tracking and finally the two axes tracking cases with a robot controlling a solar PV panel. The application has been done for Algiers. A gain about 34% in terms of solar energy yield compared to fixed panel case has been obtained.

Keywords - Control model, Robot manipulator, PV panel, Solar radiation, Tracking System.

I. INTRODUCTION

The position of the sun varies throughout the day. To collect the maximum energy, sun tracking systems are used. They must be adjusted so that the photovoltaic panels are always perpendicular to solar radiation. The single axis solar tracking systems are less expensive and their control is easy to implement, but, their efficiency is lower than that of two axes ones [1]. The latter requires an appropriate control of the two decoupled movements and used in thermal concentrating heliostats for guiding [2] and for photovoltaic to increase their efficiency which can reach values of 34% compared to fixed tilt angle systems [3]. Some studies have been found in the literature. S. Abdallah et al [1] have designed a two axes sun tracking system have reached an efficiency of 41.43% compared to a fixed system. G.C. Bakos et al [3], made a comparative study of a collected solar energy by two axes system and a fixed one. An efficiency of 46.46% compared to a fixed one is reached. The obtained gain in this paper is 34%. This paper is complementary to the author’s reference [7]. Indeed putting the two papers together allows for a better understanding of the author’s approach to indicate that the dual tracking is definitely better than fixed position one. This paper also indicates that one axial tracking is not as good as the fixed position panel. The system has been simulated for Algiers and for a specified date. Daily solar radiations have been also been computed for this site. And finally benchmarking the MATLAB application against a third party software PV sys are considered as added values.

II. SOLAR ANGLES

A. Determination of the Azimuth and altitude angles

Consider Fig. 1, which represents the celestial sphere, where the point ‘O’ represents the earth and the point ‘A’ represents the sun (the star studied).

The altitude angle \( h \) is made between the horizontal plane and the sun lights direction. It varies from +90° (zenith) to -90° (nadir). It corresponds to sun set and sunrise when it is null.

Azimuth angle \( a \) is formed by the sun lights direction projection on the horizontal plane and the south. It is negative eastwards and positive westwards and varies from 180° to -180°. The hour angle \( \omega \) of a point on the earth surface is formed between the meridian and the sun lights. It is positive westwards the meridian and zero at local solar noon [5].

The declination angle of the sun \( \delta \) is formed through the equator and the sun lights direction. It varies during the year in a symmetric manner from -23°26’ to +23°26’ [5].

![Figure 1. The celestial sphere](image)

- **Figure 1. The celestial sphere**
The solar altitude 'h' and azimuth 'a' angles projected on the horizontal plane according to the declination \( \delta \), the local latitude \( \varphi \) and hour angle \( \omega \) are given by [5, 6]:

\[
\sin h = \cos \delta . \cos \omega . \cos \varphi + \sin \delta . \sin \varphi
\]

\[
\sin a = \frac{\cos \delta . \sin \omega}{\cos h}
\]

III. MODELING OF THE ROBOT USED

In this work, we use a robot arm (manipulator with two degrees of freedom), for the orientation of the solar panel to track the sun [4, 7]. The solar panel is associated to a reference frame R3 formed by X3, Y3 and Z3. The robot reference frame is R0 composed of X0, Y0 and Z0. To control our robot for panel orientation, the reference frame R3 must be defined with respect to reference frame R0 of the robot. For this purpose, we calculate the homogeneous transformation matrix of our system which will define the position and orientation of the reference frame R3 (of the panel) in the reference frame R0 of the robot.

\[
\begin{bmatrix}
S1. C2 & -S1. S2 & -C1 & d2. C2 \\
S2 & C2 & 0 & d2. S2 + r1 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

Where: \( C_i = \cos (\Theta_i) \) and \( S_i = \sin (\Theta_i) \)

The orientation of the X3 axis in the reference frame R0 is given by the first column of the matrix (3), \( ^0S_3 \) as follows:

\[
^0S_3 = [C1.C2 \quad S1.C2 \quad S2]^T
\]

Where: \( \Theta1 \) is the angle of rotation of the first axis of a robot, and \( \Theta2 \) is the angle of rotation of the second axis of the robot, and they represent the parameters of the robot controller. The X3 axis must follow the sun in two directions, vertical and horizontal. The coordinates for the orientation of the sun along the axes X0, Y0 and Z0 are represented [4, 7]:

Along the axis X0: \( \cos (\alpha). \cos (\beta) \)
Along the axis Y0: \( \cos (\alpha). \sin (\beta) \)
Along the axis Z0: \( \sin (\alpha) \)

Finally the above expressions lead to:

\[
\Theta1 = \alpha \quad \text{and} \quad \Theta2 = \beta
\]

Where \( \beta \) is the tilt angle [5]:

\[
\beta = 90 - h
\]

IV. ARTICULATION CONTROL

The design and control of robots need the calculation of some mathematical models, such as the models of transformation between the operational space and the joint space [1]. The heliostat is directly attached to the second body of the robot manipulator. The mechanical design of the robot arm affects the choice of the control diagram. The articulation control, PID type is the best adapted to our system. The control law is given by:

\[
\Gamma = K_p (q - q_d) + K_d (\dot{q} - \dot{q}_d) + K_i \int_{t_0}^{\tau} (q - q_d) d\tau
\]

Where:

\( q_d(t) \) and \( \dot{q}_d(t) \) Denote the desired position and velocity.

\( K_p, K_d \) and \( K_i \) are diagonal matrices of dimension \((n \times n)\) positive definite respectively. It contains the proportional \( K_{pj} \), derivative \( K_{dj} \) and integrator gains \( K_{ij} \) respectively.

![Figure 2. Robot manipulator with two axes](image)

![Figure 3. Schematic diagram of a PID control system of the articulation](image)

The calculation of the gains \( K_p, K_d \) and \( K_i \) is carried by considering the model of joint \( j \) represented by the second order linear system with constant coefficients according:
\[ \Gamma_j = a_j + F, a_j + r d \] (8)

Where: \( a_j = A_{j} \text{max} \) is the maximum value of \( A_{j} \) elements of the robot’s inertia matrix. \( r d \) is a disturbance torque where \( r \) is the gear ratio.

Results of the simulation are shown in Figure 5, Figure 6, Figure 7 and Figure 8 for the first and second articulation of the robot respectively. The red curves denote the reference and the blue color is the output. One can notice that the output follows the reference and the controller gives a stable system.

Figure 9 represents the variation of torque as a function of time of the two joints (articulation) where the red and blue colors indicate the torques provided at the first and second articulation respectively.

V. TEST AND VALIDATION

We developed a MATLAB program that calculates the values of the altitude angle ‘\( h \)’ and azimuth angle ‘\( a \)’ for any point on the globe, at any time of any day of the years.

This program was applied to the city of Algiers for the day of April 16, 2011 at 10:00 AM. The coordinates for Algiers are: Latitude: 36.3 °, Longitude: 2.6 °, Time zone: +1 GMT, summer time: 0. After processing by our program, we obtained the results of the position of the sun throughout the day on April 16, 2011 at 10:00 am. These results were
compared with those calculated by the software system PVSYST 5.52 as shown in Table I.

**TABLE I.**

<table>
<thead>
<tr>
<th>Angle(°)</th>
<th>h</th>
<th>a</th>
<th>δ</th>
<th>ω</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our Program</td>
<td>43.46</td>
<td>-66.09</td>
<td>9.79</td>
<td>-42.33</td>
</tr>
<tr>
<td>PVSYST</td>
<td>43.58</td>
<td>-66.33</td>
<td>10.01</td>
<td>-42.35</td>
</tr>
</tbody>
</table>

One can notice from table I that the values obtained with our program are close to the values obtained with PVSYST 5.52, the difference is about 0.27% for the height h of 0.35% for the azimuth of 2.11% for the variation δ and 0.047% for the hour angle ω. In addition, calculations for the entire day of April 16, 2011 from 8:00 am to 18:00 in the afternoon (6:00 PM) have been performed. The obtained results at each hour are illustrated in Figures 10, 11, 12 and 13.

The curves of Figure 10 and Figure 12 are similar and have the same pattern and behavior. We chose the 1:00 p.m. hour to show that the values of the altitude angle (h) at that moment, with both systems, are very close and equal, we can say the same thing for Figure 11 and Figure 13. This leads us to conclude that our program gives good results. From this deduction, we continue our work by injecting these values in the control of our robot manipulator to guide a solar panel to harvest the maximum energy and optimize electricity production.

VI. RESULTS AND DISCUSSION

In order to show the advantage of using a panel with a robot manipulator to capture solar energy, a comparison with a single axis (variable tilt only) system, a 0° and 30° tilted systems all facing to the south has been performed. The robot power consumption is neglected in this simulation.

**A. Robot using One Axis Tracking**

The obtained results are shown in Figure 14. Curve 2 represents the result obtained with using a robot manipulator for one axis tracking, representing the movement of the tilt...
angle $\beta$, facing to the south i.e. with azimuth angle $\alpha = 0^\circ$.
Curve 3 is the result for a system with fixed $\beta = 30^\circ$, facing to the south i.e. with azimuth angle $\alpha = 0^\circ$.
Curve 4 is the result for a system with fixed $\beta = 0^\circ$ and facing to the south i.e. with azimuth angle $\alpha = 0^\circ$.

Figure 14 presents three case studies, of the results obtained, we noticed that the three curves behave in the same way, they have the same shape. We note that curves 2 and 3 are the most interesting to study; they reach the same maximum values.

By comparing the average daily output irradiance for each case, we have noticed that a panel oriented at 30° (curve 3) provides the best performance as shown in Table II. In this case, it is better to use a fixed panel oriented at 30° than a tracker system with an axis.

![Figure 14. Daily solar irradiance for April 16th 2011, with one axis tracking](image)

### TABLE II

<table>
<thead>
<tr>
<th>Curve</th>
<th>Daily Average Irradiance (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Daily Average power</td>
<td>651.5</td>
</tr>
</tbody>
</table>

**B. Robot using Two Axes Tracking**

Fig. 8 shows the results of different tests. Curve 1 shows the tests with the robot manipulator with two axes tracking.

Three cases studies are presented. On the results obtained, we notice that the curve 1 has a behavior different form of curves 3 and 4. The energy collected by a system using a 2-axes robot is almost the same throughout the day. Between the three cases, that of the 2-axes robot offers us the best daily average irradiance as shown in Table III.

![Figure 15. Daily solar irradiance for April 16th 2011, with two axes tracking](image)

### TABLE III

<table>
<thead>
<tr>
<th>Curve</th>
<th>Daily Average Irradiance (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Daily Average power</td>
<td>973.5</td>
</tr>
</tbody>
</table>

One can notice from Figure 14 and Figure 15, that the curves 2, 3 and 4 have the same shape, except the curve 1 corresponding to the system with a robot manipulator with two axes which is particularly strong in the morning from 8:00 am to 11:00 am and afternoon 2:00 pm to 6:00 pm. The performance achieved by the system during these times is more important than the other curve, especially in the beginning and end of the day. It reaches up 65% gain compared to others. While between 12:00 am and 1:00 pm yields are practically the same in all cases. The maximum power noticed is obtained between 11: am and 2:00 pm for all cases.

**VII. Conclusion**

Solar tracking system based on a robot arm with two degrees of freedom has been studied. In addition to the mono and two axes tracking, two fixed tilt angles were simulated and compared. Before that the model of the robot was presented for automatic control of sun tracking. The MATLAB program has also been benchmarked against a third party software PV sys. The daily solar irradiance for Algiers has been computed and plotted as a real application.

A very significant energy savings of about 34% compared to the others systems was found. The simulation results have allowed us to see the possibility of combining the robot arm technology to solar energy applications. The study has also proposed the use of a PID controller for the robot articulation in closed loop in the objective of better monitoring and a precise control of the guidance system. This work aims to be an introduction of the integration of robotics in renewable energy domain.

The future of this work is the implementation of the system in reality, in order to demonstrate the importance and the gain in terms of energy that can make this achievement. Furthermore the power consumption of the robot that has been neglected in this paper should also be considered.

**References**


