Design of a Mirror Positioning System to Enhance the Performance of a PV Array

Saurabh S. Tonapi
Robotics and Spatial Systems Laboratory
Department of Mechanical and Aerospace Engineering
Florida Institute of Technology
Melbourne, Florida 32901
stonapi@fit.edu

Pierre Larochelle
Robotics and Spatial Systems Laboratory
Department of Mechanical and Aerospace Engineering
Florida Institute of Technology
Melbourne, Florida 32901
pierrel@fit.edu

ABSTRACT

In this paper we present an overview of an ongoing research project that seeks to design a novel auxiliary mirror drive mechanism for photo voltaic (PV) cell arrays. These auxiliary mirrors will be used with fixed PV cell arrays to increase the amount of solar radiation on the panels thereby increasing the amount of electricity generated. We present an overview of the entire system, a summary of the motion planning and control issues, and preliminary results with respect to the detailed design of the novel mirror position device. For moving the auxiliary mirror a spherical 5 bar mechanism called the Mirror Positioning Device has been used. A computer graphics simulation developed for the purpose has also been presented.

Keywords

Photo Voltaic cells, Spherical 5 bar mechanism, Auxiliary Mirrors, Mirror Positioning

Abbreviations:

MPD: Mirror Positioning Device

ECS: Equatorial Coordinate System

GCS: Geographic Coordinate System

HCS: Horizontal Coordinate System.

OCS: Observer Coordinate System.

1. INTRODUCTION

The overall depletion of conventional sources of energy such as Petroleum and Natural Gas has made man look out for other non-conventional sources of energy. Solar energy seems to be the most promising one after the development of PV cells. Also it is renewable hence very inexpensive. This paper therefore presents the concept and the ongoing work that is being carried out for the Design of a Mirror Positioning System to enhance the performance of a Photo-Voltaic Array. The motivation for this work has mainly been to increase the overall efficiency of the photovoltaic cell. The idea is to increase the intensity of light striking the surface of the PV array thereby producing more power. One way of doing this is to increase the overall area of the PV array but this would add to the root of the problem rather than diminish it as cost becomes an important factor. The approach taken by us essentially includes tracking the sun with a moving reflector in order to direct the solar incident rays onto a stationary PV array. Our current work has been to design and manufacture the Mirror Support Frame (MSF) and the Mirror Positioning Device (MPD). The MPD is a 5 bar spherical mechanism that provides the motion for the reflector. The goal of this research is to determine the overall efficiency of the MPD system.

2. MIRROR POSITIONING DEVICE

2.1 Prior Work

A large amount of research effort has bene focused on improving the technology required to make a PV array. The method used here was to improve the efficiency of PV arrays manufactured with current technology. One of the most efficient ways of doing that was to track the sun's motion across the sky using a moving reflector and thereby manipulating the solar rays on to the PV array [1]. The reason for moving the reflector and not the PV array is because it is much lighter and hence uses much less driving power. Therefore now that we have a stationary PV array, solar tracking involves accurately determining the position of three bodies viz. sun in the sky, the reflector, and the stationary PV array with respect to each other. The prior work done in this area included developing an algorithm to continuously track the sun for a given longitude and latitude. Positional astronomy was used for this purpose where in various co-ordinate systems were defined to locate the sun and the observer. The Equatorial Coordinate System was used to describe the position of the sun [4, 12], while the Geographic Coordinate System [11] was used to describe the position of the observer (reflector) anywhere on the earth. The Horizontal Coordinate System [3, 11, 12] was used to define the position of the sun with respect to the observer and was based at the centre of the earth. For our convenience we converted the HCS into OCS [1]. Finally the ECS and the OCS were related using the techniques from kinematics [6]. To describe the location of the panel with respect to the observer (reflector) a Cartesian coordinate system was used.

Using some physics and kinematics a simulation was developed which directs insolation from the sun onto the PV panel via the MPD. Thus given a physical location on the earth (in terms of longitude and latitude), a date and time, an accurate determination of position of sun (i.e. azimuth and altitude) with respect to the Mirror Positioning Device could be made. Knowing this we can reflect sunrays onto the panel whose position with

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respect to the MPD is known. A suitable mechanism is thus used as a MPD which relates joint space to the solar tracking space.

2.2 The Spherical Orientation Device

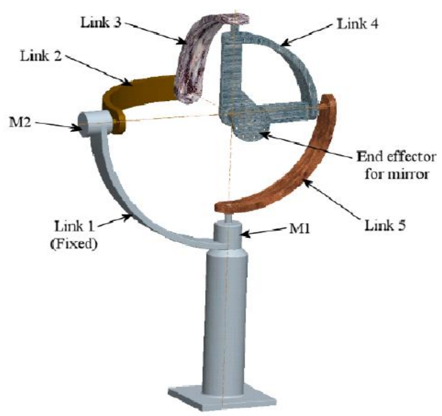

Figure 1

The suitable mechanism in this case is the S.O.D or the Spherical Orientation Device (invented and patented by Gosselin et al.- US Patent no.5,966,991)[2] which is a two degree of freedom 5 bar spherical mechanism. The SOD could be thought of as two linkages defined on the great circles of a sphere that allows for payload support on the orientation axis. The unique design of the mechanism enables positioning of the payload at the geometric centre of rotation. This feature ensures that the inertia is minimized. Additionally this mechanism provides a high stiffness thereby enabling large payloads. Also in terms its workspace the mechanism provides a relatively large outward workspace approximating a hemisphere.

With reference to the Figure 1 Link 1 is fixed while the remainders are movable and form a pair of dyads with each dyad consisting of links of length 90º. The first dyad consists of links 2 and 3 while the second dyad consists of links 4 and 5. Each dyad is connected to an actuator. All the joints in the mechanism are revolute and the two actuators are mounted at locations marked M1 and M2 respectively. The architecture of this mechanism is such that the axes of all 5 joints intersect at a point, known as the center of the mechanism. The links are stacked on concentric spheres of varying radii so as to allow movement without interference between links or joints. The end effector (reflector) is connected to the base by a pair of kinematic chains. The actuators are also connected close to base resulting in high stiffness and higher load carrying capacity. These characteristics are important for such an application due to exposure to potentially high wind loads and vibrations since the device will be located outdoors and cannot be sheltered.

2.3 Mirror Positioning:

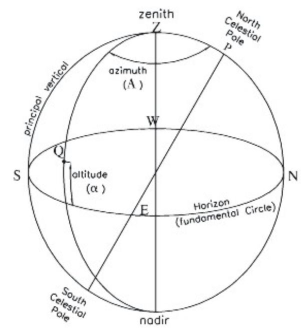

Figure 2

The actual Mirror positioning consists of orienting the reflective surface such that its surface normal will coincide with specified values of α_H and A_H (which happen to be the altitude and azimuth angles of the sun with respect to the observer) [4, 11]. The two degree of freedom device chosen thus suits this requirement. It is important to avoid concentrating too much sunlight on a particular group of cells for a given period of time. Thus, it becomes necessary to distribute the reflected rays over the entire surface of the panel within a short period. A direct consequence of this is the need for quick motion and high performance.

2.4 Orienting the MPD

This task is essentially the inverse kinematics problem of the proposed system. A single ray assumption has been made here that allows for ease of analysis and represents only the direction of the sunrays incident on the MPD. The input parameters are the altitude and the azimuth of the sun for a given day and time. The inverse kinematics therefore involves the determination of joint angles θ_1 and θ_2 [6] for a given set of α_H and A_H. Once these variables are computed, real-time path planning and control of the device can be undertaken. Making use of geometry to solve this problem, we have [1]:

$$\theta_1 = \arctan 2(\sin(\alpha_H) - \cos(A_H)\cos(\alpha_H))$$

$$\theta_2 = \arctan 2(\sin(\alpha_H) - \cos(A_H))$$

Hence, given a specific location, day and time, we can now direct the normal surface of the reflecting surface attached to the MPD along a line which bisects an incoming ray from the sun and accurately reflects it onto a fixed target. This completes the inverse kinematics of the MPD.

2.5 Workspace of the MPD

We know from the previous sections that we need to keep track of two variables to successfully track the movement of the sun on a given day. Therefore in order to determine the required workspace of the MPD we need to first find the minimum and the maximum values of these variables. The days with the longest daylight hours occur in the month of June [9, 10].

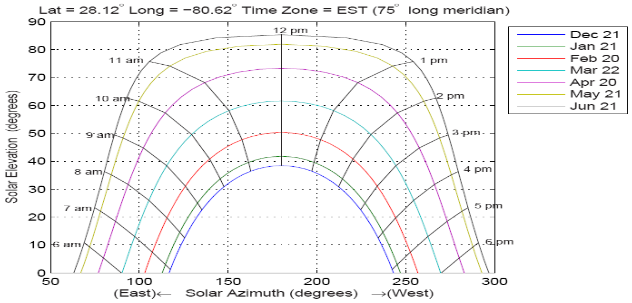

Figure 3

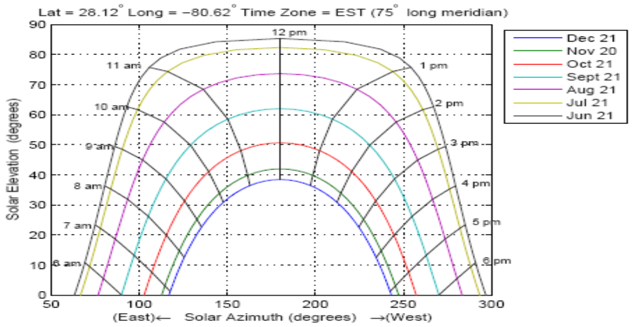

Figure 4

The maximum altitude attainable by the sun also occurs during this month. Therefore the data collected in the month of June happens to be of utmost importance to us.

Range of Altitude α_H: From the above charts it is evident that we are concerned only with the range between 0º and 90º with respect to the horizon. This happens to be about 50% of the capable altitude range of the MPD and hence within the operating range of the mechanism [1].

Range of Azimuth A_H: There are four possible arrangements of the sun, MPD and the PV panel [1, 3, 12]. These are four top views of scenarios keeping in mind that the MPD is assumed to be in the Northern hemisphere and hence facing the south.

Case I:

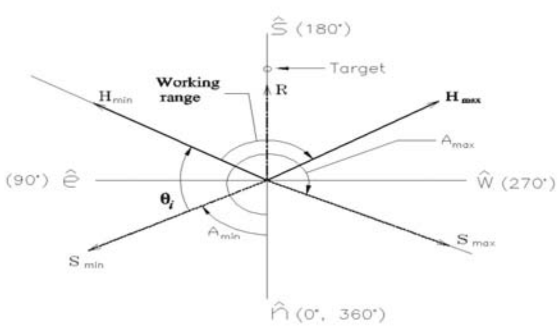

Figure 5

Here, S= Incoming ray from the sun.

R= Reflected ray to target.

H= Surface normal to the reflector.

A= Azimuth angle of the sun.

Δ = Working range i.e. angle between H_{min} and H_{max}

θ_1 = Azimuth of H_{min}

θ_2 = Azimuth of H_{max}

γ = angle between H_{max} and R

r_i = Azimuth of R (target) for case i

s = angle between H_{max} and s axis

then,
$$\theta_i = \frac{r - A_{\min}}{2} \tag{3.1}$$

$$\gamma = \frac{A_{\min} - r}{2} \tag{3.2}$$

$$\theta_1 = A_{\min} + \theta_i \tag{3.3}$$

With reference to the above figure we see that the target is located on the north-south axis. Therefore the working range is computed as follows:

$$\theta_2 = r_1 + \gamma = r_1 + s \tag{3.4}$$

$$\Delta = \theta_2 - \theta_1 \tag{3.5}$$

Suitably substituting the values for θ_1 and θ_2, we have

$$\Delta = \frac{A_{\max} - A_{\min}}{2} \tag{3.6}$$

This means that the required working range, Δ will always be less than 180º since $A_{\max} - A_{\min} < 360^\circ$. Such an arrangement therefore poses no problems in terms of range capability of the MPD [1].

Case II:

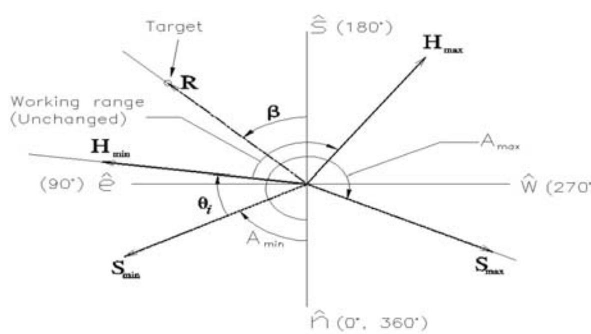

Figure 6

The target is offset from north- south axis by and angle β, in the counter-clockwise direction. Figure 6 illustrates this scenario.

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$$\theta_2 = r_2 + \gamma = r_1 - \beta + s + \beta = r_1 + s \qquad (3.7)$$

$\Delta = \theta_2 - \theta_1$, yields the same result as case I, thus

$$\Delta = \frac{A_{\max} - A_{\min}}{2} \text{ (deg.)}$$

Equation (3.7) implies that the azimuth of H_{min} is shifted by β in the counter-clockwise direction to compensate for the shift of β by R in the same direction so that its 'bisector' status is maintained. The end result is that Δ in this instance will also always be less than 180º. Therefore this arrangement also poses no problems in terms of the azimuth range capability of the MPD [1].

Case III:

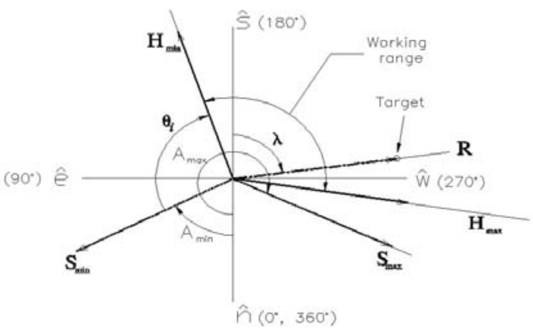

Figure 7

In this case, shown in Figure 7, the target is offset from the north-south axis by an angle λ, in the counter-clockwise direction. The analysis for this is the same as in case II, except that this time all movements are clockwise as opposed to counter-clockwise. The end result is that H_{max}- H_{min} will always be less than 180º. Thus conclusion in case II applies here as well [1].

Case IV:

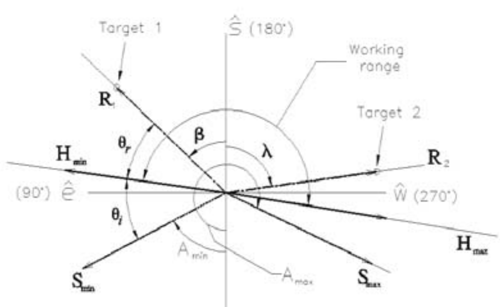

Figure 8

The target is offset from the north-south axis by an angle β, in the counter-clockwise direction by an angle λ, in the clockwise direction. Looking at figure 8, let r_3=the azimuth of R_1, r_4= the azimuth of R_2, then

$$\theta_i = \frac{r_3 - A_{\min}}{2} \qquad (3.8)$$

$$\gamma = \frac{A_{\max} - r_4}{2} = \frac{A_{\max} - r_3 - \beta - \lambda}{2} \qquad (3.9)$$

$$r_4 = r_3 + \beta + \lambda \qquad (3.10)$$

$$\theta_1 = A_{\min} + \theta_i = \frac{A_{\min} + r_3}{2} \qquad (3.11)$$

$$\theta_2 = r_4 + \gamma = \frac{r_3 + \beta + \lambda + A_{\max}}{2} \qquad (3.12)$$

$$\Delta = \theta_2 - \theta_1 = \left(\frac{A_{\max} - A_{\min}}{2}\right) + \left(\frac{\beta + \lambda}{2}\right) \qquad (3.13)$$

The numerator of the first term in equation (3.13) is the maximum solar azimuth range per year. Typically this is around 220º-250º, for instance looking at figures 1 and 2, it is about 230º. Working with the upper limit, the first term in equation (3.13) evaluates to around 125º. Recalling that

$$\Delta \leq 180^\circ$$

$$\frac{\beta + \lambda}{2} \leq 180 - 125 = 55^\circ$$

$$\Rightarrow \beta + \lambda \leq 110^\circ \text{ approximately}$$

It follows that once the required range to be covered by the reflector is within approximately 110º, the MPD will be able to cover it with reasonable accuracy [1].

2.6 Path Planning for the MPD

As mentioned earlier greater power from the PV array is obtained if the solar irradiance on it is increased. Knowing this though, one has to take care not to increase the incident solar radiation too much as it may damage the PV cells. This requires the MPD to have the capability of uniform distribution of the reflected rays over the entire panel surface. A suitable path for the reflected ray, R to follow must therefore be predetermined.

The path needs to be planned in such a way that the rays should cover the entire path keeping in mind that no path segments must intersect or overlap. Straight line trajectories would be most suitable as this would make the control relatively easier. Also as far as possible the path segments should be either parallel or orthogonal to each other [8]. Keeping all these things in mind, the most suitable type of path planning technique for this task is the *Trapezoidal Decomposition*. Also known as the slab method, it involves the space to be covered be divided into trapezoidal cells [5]. Such division enables coverage in each cell to be achieved by back and forth motions. Keeping in mind that the overall strategy for a complete path has to be a closed loop cycle, we have three basic strategies which have been shown graphically as follows:

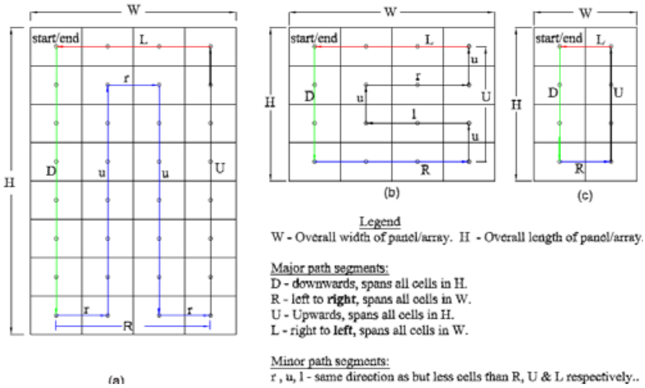

Figure 9

Computation of R is then carried out using Snell's law of specular reflection (which gives us angle of reflection/incidence) [7]. It is adequate to track the sun's position at 20-minute intervals given that the sun moves at approximately 15º per hour. The actual number of cycles attainable per interval is dependent on the size of the coverage area and the speed of the MPD.

Therefore a flowchart is developed [1] which is as follows:

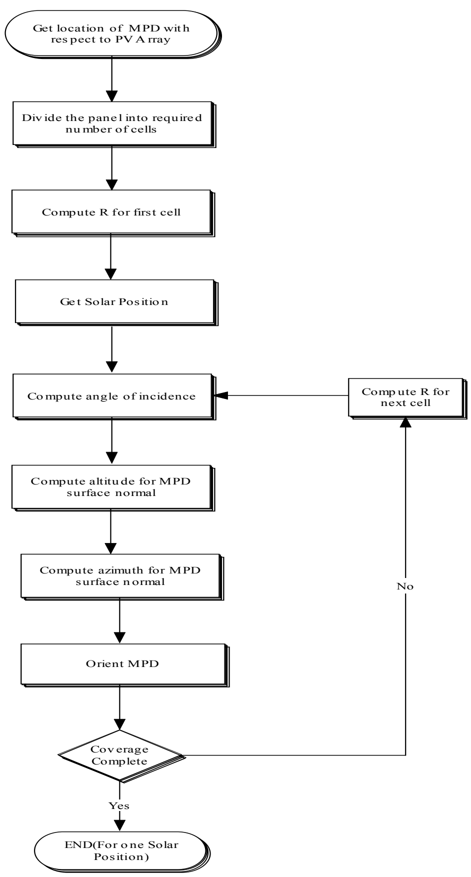

Figure 10

Based on this Flowchart a simulation is developed.

2.7 Computer Graphics Simulation

The simulation has three basic modules [1]:

1. Solar Tracking Module: It contains the math subprogram behind the simulation program. It has been directly derived from the algorithm.

2. Computer Graphics Module: In this module all the components and their respective roles are defined.

3. Graphical User Interface: This module displays the outcome of the simulation process and provides the means for the user to interact with the program.

The GUI for the simulation looks like:

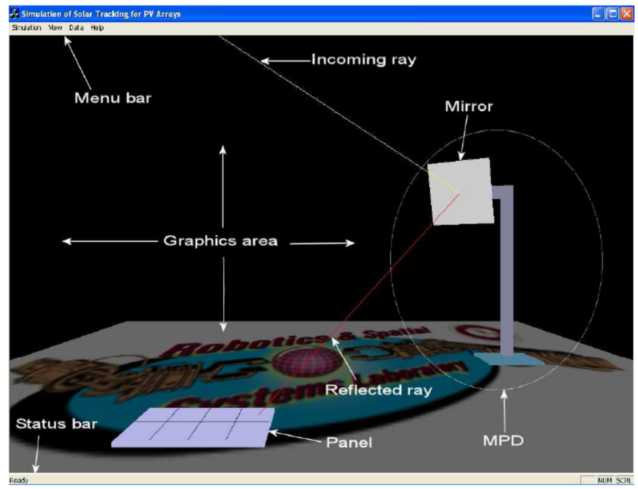

Figure 11

The simulation has three basic menus: Simulation, View and Data as well as a standard Help menu. These three menus in turn have sub-menus using which position of sun, location of observer and time parameters can be changed. The GUI enables the display of data during the simulation process.

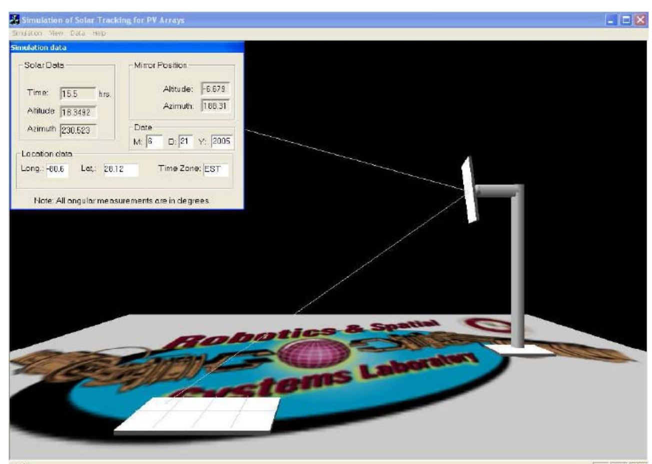

Figure 12

3. ONGOING RESEARCH

The ongoing research involves making the actual mechanism and the controller based on the study done so far. One

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of the first tasks undertaken and successfully completed has been the design of the Mirror Support Frame (MSF) which included finding the material for it. Aluminum extrusion 6105-T5 has been used for making the framework while the fasteners have been made from molded plastic. A detailed drawing of the MSF has been made in PRO-E as well.

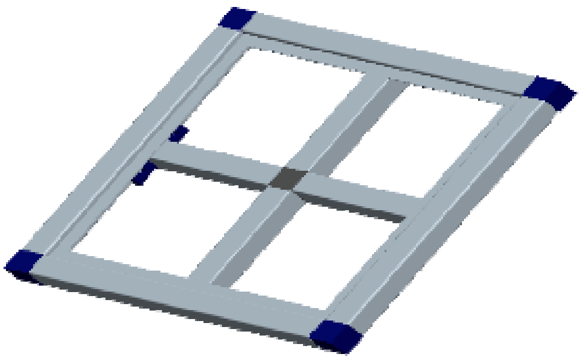

Figure 13

The installation of pyranometers will be done to measure the amount of solar radiation on various points of the PV array from which the overall efficiency will then be calculated. The heat transfer study will also help to optimize the path planning and control of the MPD.

The work henceforth includes completed detailed design of the MPD and its manufacture. The manufacturing will encompass the MPD's construction and its control system. A prototype will then be constructed for experiments. Two AC servomotors will actuate the system. Experimental data will be collected to analyze the solar power produced and the overall efficiency of the system will then be analyzed. This work will be completed by early Fall of 2006.

4. ACKNOWLEDGMENTS

We thank the Florida Solar Energy Center (FSEC) for providing us with the opportunity to work on this research. We would also like to thank Dr. Kunal Mitra and Mr. Sudhir Kulkarni for their valuable collaborations.

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