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Energy Conversion and Management 48 (2007) 2174–2184

ENERGY CONVERSION & MANAGEMENT

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Application of new control strategy for sun tracking

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Received 12 June 2006; accepted 24 December 2006
Available online 26 February 2007

Abstract

The application of high concentration solar cells technology allows a significant increase in the amount of energy collected by solar arrays per unit area. However, to make it possible, more severe specifications on the sun pointing error are required. In fact, the performance of solar cells with concentrators decreases drastically if this error is greater than a small value. These specifications are not fulfilled by simple tracking systems due to different sources of errors (e.g., small misalignments of the structure with respect to geographical north) that appear in practice in low cost, domestic applications.

This paper presents a control application of a sun tracker that is able to follow the sun with high accuracy without the necessity of either a precise procedure of installation or recalibration. A hybrid tracking system that consists of a combination of open loop tracking strategies based on solar movement models and closed loop strategies using a dynamic feedback controller is presented. Energy saving factors are taken into account, which implies that, among other factors, the sun is not constantly tracked with the same accuracy, to prevent energy overconsumption by the motors. Simulation and experimental results with a low cost two axes solar tracker are exposed, including a comparison between a classical open loop tracking strategy and the proposed hybrid one.

Keywords: Closed loop control; Sun tracking strategy; Low cost two axes solar tracker; Robust performance

1. Introduction

Thanks to the technical advances, reasonable priced high concentration solar photovoltaics (PV) arrays are supposed to be available within a close time. However, the future use of this kind of solar PV arrays in low cost installations will bring a new type of problem: the necessity of high accuracy solar pointing. High concentration solar PV arrays require greater solar tracking precision than conventional photovoltaic arrays, and therefore, a relatively low pointing error must be achieved for this class of installations. Since, in large plants, the design and installation is optimized, they can usually achieve this low error requirement. Nevertheless, the cost of such optimization is prohibitive for low cost installations.

This paper discusses the design and implementation of a control algorithm for a low cost mechanical structure that can support photovoltaic modules and that acts as a sun tracker.

Several classes of structure can be distinguished depending on the classification criteria:

- Regarding movement capability, three main types of sun trackers exist [1]: fixed surfaces, one axis trackers (see [2]) and two axes trackers (see [3]). The main difference among them is the ability to reduce the pointing error, increasing the daily irradiation that the solar cells receive and, thus, the electric energy that they produce. A theoretical comparative study between the energy available to a two axes tracker, an east–west tracker and a fixed surface was presented in [4]. As main results, it concluded that the annual energy available to the ideal tracker is higher by 5–10% and 50% than the east–west tracker and the fixed surface, respectively.

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doi:10.1016/j.enconman.2006.12.020

- Regarding control units, the main types of solar trackers are [5]: passive, microprocessor and electro-optical controlled units. The first ones do not use any electronic control or motor (see [6]). The second ones use mathematical formulae to predict the sun's movement and need not sense the sunlight. An example of this kind of unit can be found in [3]. Finally, the electro-optical controlled units that use the information of some kind of sensor (e.g., auxiliary bifacial solar cell panel, pyrheliometer) to estimate the sun's real position is used in the control algorithm (see [2,7]).

This paper presents a control strategy for two axes trackers that is executed in a microprocessor. Correct pointing is inferred from the generated electrical power, which must be sensed on line.

The proposed control strategy consists of a combination between: (1) An open loop tracking strategy, which corresponds to the *microprocessor controller* in the classification [5]. This controller is based on a solar movement model. (2) A closed loop strategy, which corresponds to the *electro-optical controller* in the previous classification. This strategy consists of a dynamic controller that feeds back generated power measurements.

Furthermore, in order to make the system autonomous, a search mode that operates when the tracking error is too large is included. To prevent the system from going into the search mode too often, a reduced table of errors (updated every half an hour if there is enough radiation) is also stored.

The main differences between this strategy and the ones presented in other works, such as [7] or [8], with similar purposes are the following:

- Those works deal with open loop control and with estimated pointing errors. These errors are stored for later analysis. Thus, those strategies do not use on line feedback control, while ours uses a dynamic controller.
- A large amount of memory is needed to hold the stored error database in those works. This problem would be more serious if a two axes tracker was used. This fact requires that new hardware be used for control purposes. Thereby, those algorithms are not useful when a small amount of memory is available. In this case, the combination of on line feedback control and a quite small error table is more than sufficient to make the system work with the required precision.
- In addition, energy saving factors are taken into account in the proposed strategy. This implies that, among other factors, the sun is not constantly tracked with the same accuracy to prevent energy overconsumption by the motors.

The control algorithm takes into account the different types of errors that can appear in practice in low cost domestic systems, e.g., the placement and problems with the mechanical structure and errors of time and location. As a result, whatever the type of error, the controller can make the tracker follow the sun. In fact, the proposed algorithm is also valid for large high precision trackers since it contributes to decreasing these errors.

In summary, there are three main aspects concerned with this control strategy:

- A new sun tracking strategy for low cost positioners with two degrees of freedom was developed.
- A simulator that allows us to evaluate how the tracking strategy is working as well as to program other strategies was built.
- A mechanical structure that acts as a solar tracker and a monitoring and positioning control system for two degrees of freedom was built (see pictures of the tracker in Fig. 11).

The remainder of the paper is organized as follows: the tracking strategy is explained in detail in Section 2. Section 3 describes the structure of the control system. Experimental results, including a comparison between an open loop and the proposed hybrid strategies, are shown Section 4. Finally, the main conclusions of this work are drawn in Section 5.

2. Automatic tracking strategy

A hybrid tracking strategy that basically consists of two modes was used: in one mode, normal sun tracking is performed, maintaining a tracking error less than a pre-specified value. In the other, a sun search is undertaken by means of an ever widening rectangular spiral; this is necessary when the sun needs to be located because of some external disturbance (for example, a period of prolonged cloudiness). Each of these modes is described in greater detail below.

2.1. Normal tracking mode

This mode is in effect whenever the sun tracking error is smaller than a specified bound and the solar radiation great enough for the system to produce electric energy.

It is a hybrid tracking system that consists of a combination of open loop tracking strategies based on solar movement models (feedforward control) and closed loop control strategies using a feedback controller. The feedback controller is designed to correct the tracking errors made by the feedforward controller in the open loop mode. The operation in this mode is shown schematically in Fig. 1.

In this figure, u represents the position (azimuth and elevation) the tracking system assumes is the location of the sun. It can be seen that this estimated position of the sun is obtained by adding two values: $\bar{u}$, which is the position obtained from the equations that model the sun's movement, and $\tilde{u}$, which is a correction of that position based on the estimated position of the sun, $\bar{y}$.

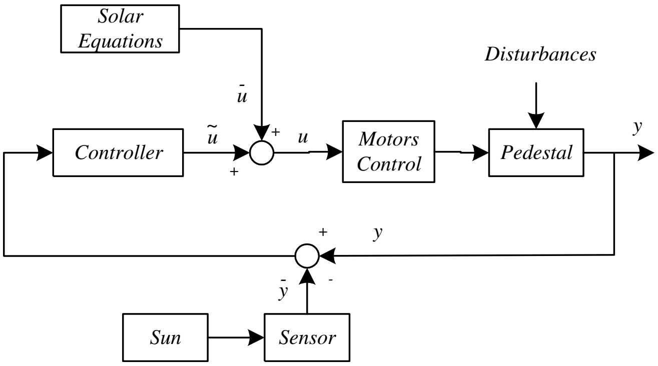


Fig. 1. Operation in tracking mode.

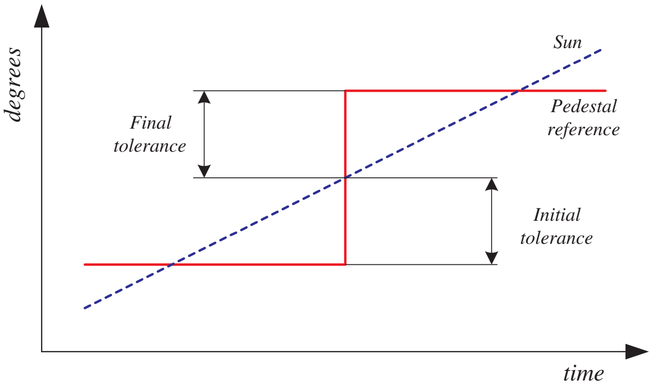


Fig. 2. Basic scheme for the movement of the mechanical structure.

There are several algorithms for calculating the position of the sun ($\bar{u}$) based on the date and time provided by an auxiliary clock and geographical data (longitude and latitude of the point used to estimate the position of the sun). This work used the PSA algorithm, developed by the Plataforma Solar de Almería [9], which has improved the calculation of universal time as well as the treatment of leap years and which also makes the calculation more quickly and robustly, eliminating unnecessary operations by using simple, valid equations in both hemispheres.

However, despite the precision of this algorithm, errors in the estimation of the sun's position are possible for several reasons, such as variations in the time given by the auxiliary clock with regard to actual solar time, lack of precision in the geographical location of the driver (errors in the estimation of latitude and longitude, although they usually are small if GPS technology is used), and errors in the alignment of the mechanical structure with respect to geographical north (different from magnetic north). In fact, this last kind of error is very frequent in low priced installations if no specialized staff is employed for setup adjustment, or if the wind causes any misalignment.

This fact justifies the necessity of including a correction ($\tilde{u}$) for the sun's feedforward position ($\bar{u}$) in order to obtain a better estimate of its real position (u), especially when it is important for the tracking error to be very low, as is the case here. This correction is provided by the *Controller*, which will be analyzed later.

Once a realistic estimate of the sun's position is obtained (u), the *Motors Control* block gives the necessary commands to the motors driver in order to move the platform according to the solar trajectory. For energy reasons, as the main objective of the strategy is the generation of energy using the sun as a source, the tracker is not commanded to follow the sun at all times because this would cause continuous movement of the driver motors, which would, in turn, result in excessive energy consumption. Instead, to prevent unnecessary movement of the mechanical structure (see [10,8]), the strategy implemented in the controller is the following (Fig. 2): the structure does not move as long as the tracking error (assuming that the sun is where the u signal says it is) is less than a certain tolerance. When this error is greater than this tolerance, the controller orders the driver to move to a point at which the sun will arrive in a certain amount of time. Thus, the tracker "*waits*" for the sun. This process is identical and independent for each axis. However, the two axes never move at the same time: before ordering the movement of one of the axes, a check is made to ensure that the other axis is not moving. The two axes are not allowed to move simultaneously because of the type of sensor used to indicate whether the tracking of the sun is correct, as will be seen afterwards.

As the sun moves along its trajectory throughout the day, signals are sent so that the driver moves appropriately, thus generating the electrical energy that this project was designed to provide. The power is used as a *Sensor* to confirm that the driver is tracking the sun correctly, so a decrease in the power generated (under normal external conditions, i.e. without taking into account extended cloudy periods, for example) indicates tracking problems. It is known that the greater the error is in either of the two coordinates (azimuth and elevation), the less power is generated. As a result, if the driver moves on either of the coordinates (while the other remains fixed) it can be assumed that the real position of the sun for that coordinate corresponds to the point where the maximum power was produced during that movement. This is why both motors cannot move simultaneously. In this way, the power generated is used as a sensor to determine the sun's position.

Finally, in order to close the feedback control loop, the *Controller* block was designed, which implements a proportional and integral (PI) control strategy for each coordinate independently, whose purpose is to bring about a difference of zero between the u signal and the real position of the sun. This controller uses an estimate of this difference, which is calculated as follows: as the system moves from one position to the next (keep in mind that the system moves ahead to wait for the sun), the control system samples the power generated by the power sensor. It is assumed that the point at which the maximum amount of power is produced is equal to the position of the sun for the coordinate of which the mechanical structure is being oriented (as was explained in the preceding paragraph). Thus, by comparing the sun's position according to this system with the value given by the corrected solar equations, the tracking error for each axis is obtained.

The error estimate is computed taking past and present error measurements into account. It is defined by the PI controller, applied in a discrete manner:

$$\tilde{u}_{k+1} = K_p\left(\tilde{y}_k + \frac{1}{T_i}S_k\right) \tag{1}$$

$$S_k = S_{k-1} + T_{mk}\tilde{y}_k \tag{2}$$

where $\tilde{u}_{k+1}$ is the present error estimate, $\tilde{y}_k$ is the last tracking error measurement, S_k is the integral of the time varying discrete error signal, T_{mk} is the present sampling period and K_p and T_i are constants tuned to give an adequate relative weight to the proportional and integral parts in the computation of the error estimate.

Regarding the sampling process for the power signal generated, it should be noted that it needs to be frequent enough for us to have enough points to estimate the real position of the sun for each coordinate with a certain amount of precision.

With regard to the PI control strategy employed in the *Controller*, it is worth noting that the control laws (one for each coordinate) will not be executed with a constant sampling time, as is usually the case with conventional discrete time control systems, even though the changes in sampling time are small. In this case, the PI's will only operate when each incremental movement of the structure has finished, and the structure has reached its final reference point. Given that these movements are determined by a certain tolerance in the orientation error (remember the strategy followed by the *Controller*) and the velocity of the sun (for both coordinates) is not constant throughout the day, the time that the structure must wait for the sun, and consequently, the corresponding PI sampling time will vary depending on the position of the sun. Furthermore, since both motors cannot move simultaneously, there is yet another delay in the movement of one of the motors if the other is moving at that time.

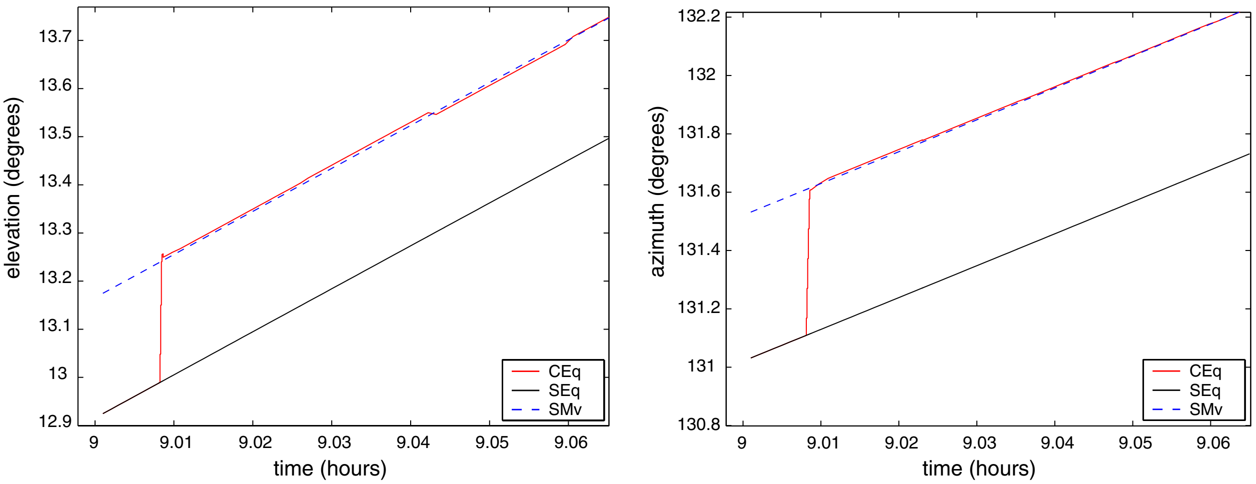
Given the proposed control law, that the controller has an integral effect regardless of the sampling time used and that the variations of the sampling time are small, this controller will incorporate the error measured between the sun's real position and the estimated position, u, providing a correction, $\tilde{u}$, that will cause the estimated position of the sun to move toward the real position. Note as well that this controller provides a continuous error of almost zero when taking into account that the usual time of the correction performed by the controller is well below the characteristic time of the variations in the sun's position throughout the day.

This tracking strategy produces a close approximation of the evolution of the sun's elevation and azimuth even if the solar equations yield quite large errors. Fig. 3 shows a simulated example of the evolution of the three variables (the sun's real movement (SMv), the progression of the values yielded by the solar equations (SEq) and the evolution obtained after the corrections (CEq)).

From the results of these simulations, it can be seen that the correction provided by the PI controller causes the corrected trajectory, which was initially the same as the trajectory calculated based on the solar movement equations (feedforward control), to tend toward the sun's real trajectory, both with regard to the azimuth and the elevation coordinates. It can also be seen that the update time of the corrected trajectory (the PI sampling time) varies because of the type of strategy employed in the *Controller* that moves the mechanical structure.

2.2. Search mode

As was mentioned above, the normal tracking mode operates as long as the sun tracking error is small enough and the solar radiation great enough for the system to pro-



Elevation

Azimuth

Fig. 3. Evolution of the coordinates.

duce electric energy, and then, the previous strategy is possible. If the tracking error is larger, no electric energy is produced, and the sensor strategy will not work. Thus, for the system to function autonomously, how the system will react when one of these premises ceases to be true also has to be taken into account.

This section will describe how the search mode was designed. This mode will only operate when the tracking error is not small enough but the solar radiation is great enough for the system to produce electric energy. Note that for this to occur, there must be an additional solar radiation sensor (e.g., a pyrheliometer) that indicates whether the radiation exceeds the minimum threshold required.

Thus, if the sun tracking error is too great (greater than a given upper bound) due to a combination of time errors, errors in the alignment of the mechanical structure and external disturbances, the solar arrays will not produce electric power, and it will not be possible to feedback any information about the tracking errors. A clear example of this problem would be the presence of clouds for a prolonged period of time. During this time interval, no corrections are produced as a result of feedback from the system, and the reference will be that provided by the equations (in open loop) that are available when the clouds disappear. If it remains cloudy for a long enough period of time and the errors associated with the equations are great, the misalignment between the sun and the position sought by the positioner when the structure begins to move again may be rather great. Consequently, the power sensor will not provide adequate information with which to correct this problem.

It is, thus, necessary to create a procedure that allows tracker to find the sun when, for whatever reason, feedback does not occur. This is the search mode algorithm. An exception is the case in which the lack of energy produced by the inverter is a result of low solar radiation (caused, for instance, by the presence of clouds). That case will be analyzed in the next section. In that case, no matter how great the tracking error, the search mode should not be used because the low solar radiation keeps us from detecting when the mechanical structure is at the correct tracking point.

In the search mode, the movement of the structure follows a square spiral in the azimuth–elevation plane in order to try to detect the position of the sun (see Fig. 4). As the movement takes place, a check is made as to whether the system is generating electric power. As soon as electric power is produced, this mode is abandoned, and the controller enters the normal tracking mode.

As Fig. 4 shows, the structure movement in the azimuth–elevation plane is completely rectangular because of the alternation in the movement of both its mobile axes.

The amount by which the range of the movement is increased with each step is important. Special care must be taken in order not to increase the distance so much as not to detect the sun between one movement and the next along the same side of the spiral. If the specifications require finding the sun within, for example, one degree, an increment in the spiral too close to this value cannot be allowed, or the risk of not detecting the sun in the first step and having gone too far with regard to the sun's position in the second step is taken. An example of this is shown in Fig. 5.

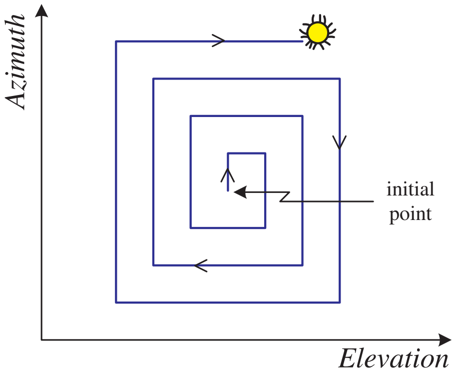


Fig. 4. Search mode.

Thus, special care has to be taken when choosing by how much to increment the step for the spiral. The most delicate point is at the end or the beginning of each step because, at these points, the distance between one trajectory and the next is the value of the step multiplied by the square root of two, as is shown in the figure above. Furthermore, it must be taken into account that during this search, the sun does not remain fixed but rather continues along its trajectory. These two circles should overlap enough in order to ensure that the sun is not by passed without realizing it.

2.3. Other situations

This section briefly presents the actions taken when the solar radiation level is lower than the minimum level

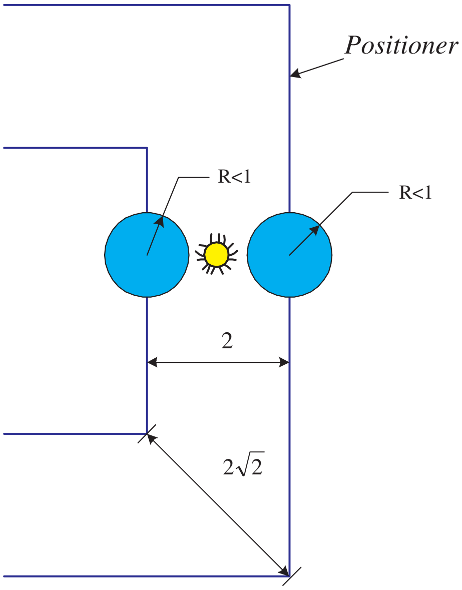


Fig. 5. Incorrect search step.

established for generating electrical energy by means of the system.

There are different possible actions in this case, each one with advantages and disadvantages. However, the option of not moving the mechanical structure to follow the movement of the sun as long as the radiation threshold is not met, has been chosen. The main advantage of this option is that no energy is consumed by moving the structure; the main disadvantage is that no energy is produced until there is again sufficient radiation and the structure has tracked the sun.

With this strategy, the main problem comes when it is time to track the mechanical structure because during the cloudy period, there has been no feedback on the actual solar position, i.e. the *Controller* block has not been operating.

This means that, at first, the estimated position of the sun would be the position generated using the solar equations along with the last correction generated by the PI controller. Theoretically, there should not be any problems with the automatic operation of the system. If the position given by the solar equations is not precise enough, the system will go into the search mode until proper tracking is achieved, and then, the system will return to the normal tracking mode.

However, in practical implementation, the system might go into search mode too often and, thus, waste energy. To prevent this, a small table was incorporated where, periodically (in this case, every half hour), the calculated errors from the periods when there were no clouds are stored. Simulations have shown that using this table prevents excessive use of the search mode after prolonged cloudy periods.

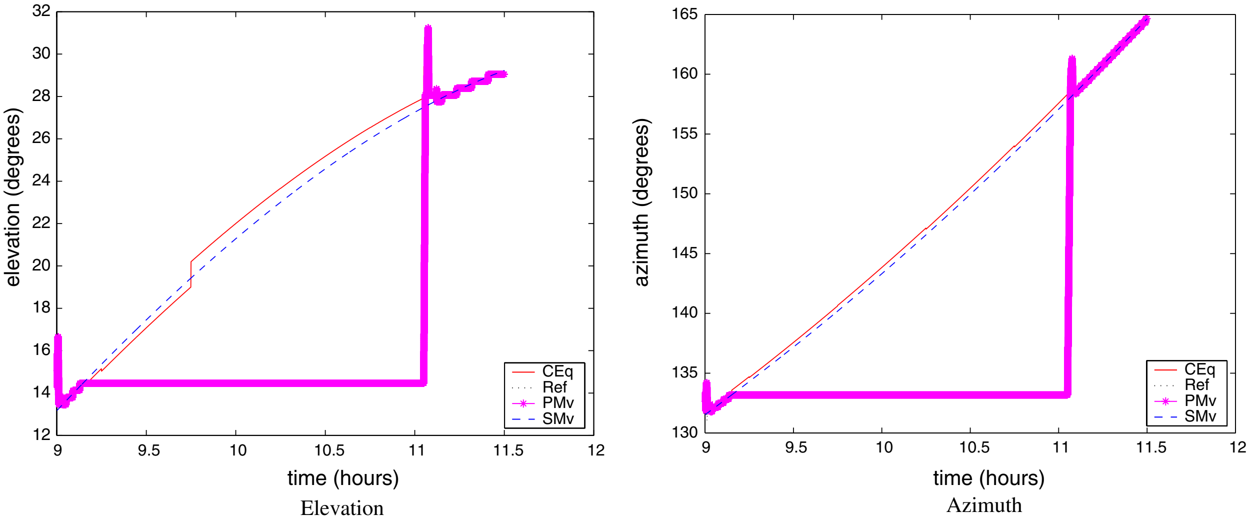
The main difference between this tracking system and other systems (e.g., [5,7,8]) is that it is not necessary to store the errors with regard to each of the structure positions. Were this the case, it would be problematic, given that there are two degrees of freedom in our system instead of just one, as in [8].

To illustrate the behavior of this strategy, in the following, the result of several simulations is shown, which were performed using the simulator described below. In the simulations, there is a cloudy period between 9:00 and 11:00 (solar time) approximately. Furthermore, different sources of error were introduced: time error, tracking errors etc. The results of two simulations are shown: one without and the other with the error table mentioned above. It can be noticed that without the table, the behavior is worse than when the table is used. This is because, without the table, the corrections made in the equations are not good enough to prevent a considerable misalignment.

Fig. 6 shows simulations of the evolution of the sun (SMv) and the corrected equations (CEq, which corresponds with signal u in Fig. 1), as well as the movement of the mechanical structure (PMv) when the error table is not use. Since, for clarity's sake, the structure was kept still during the cloudy period (from about 9:00 to 11:00), there is a great discrepancy between the curve for the mechanical structure movement and the other curves. This discrepancy will not have much of an effect because the system cannot generate energy when the sun is hidden by the clouds. At the end of the cloudy period, the structure moves toward the sun, and except for an overshoot evident in the graphs, the curves appear to overlap the rest of the time. The overshoot is a result of the search mode, as will be seen in Fig. 8.

When the error tables are used, the corrections as a result of feedback are much better, and a search is unnecessary. Thus, a series of movements is avoided that would consume part of the energy generated. This can be observed in Fig. 7.

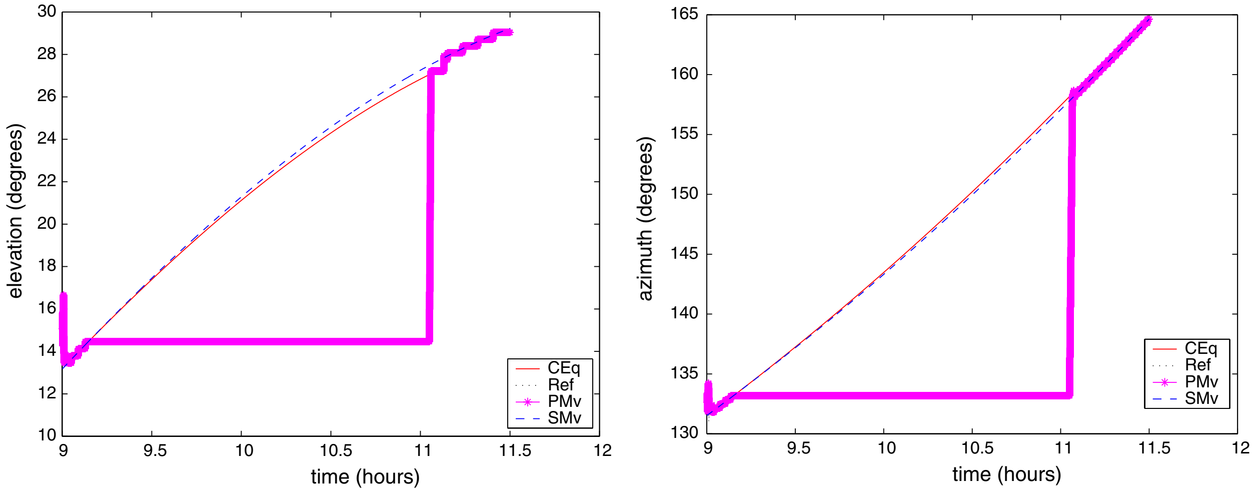
Fig. 8 shows the same movements exposed in Figs. 6 and 7 in the azimuth–elevation plane. The system starts from similar initial conditions (i.e. from the search mode) in both



Elevation

Azimuth

Fig. 6. Mechanical structure movement without using error table.



Elevation

Azimuth

Fig. 7. Mechanical structure movement using error table.

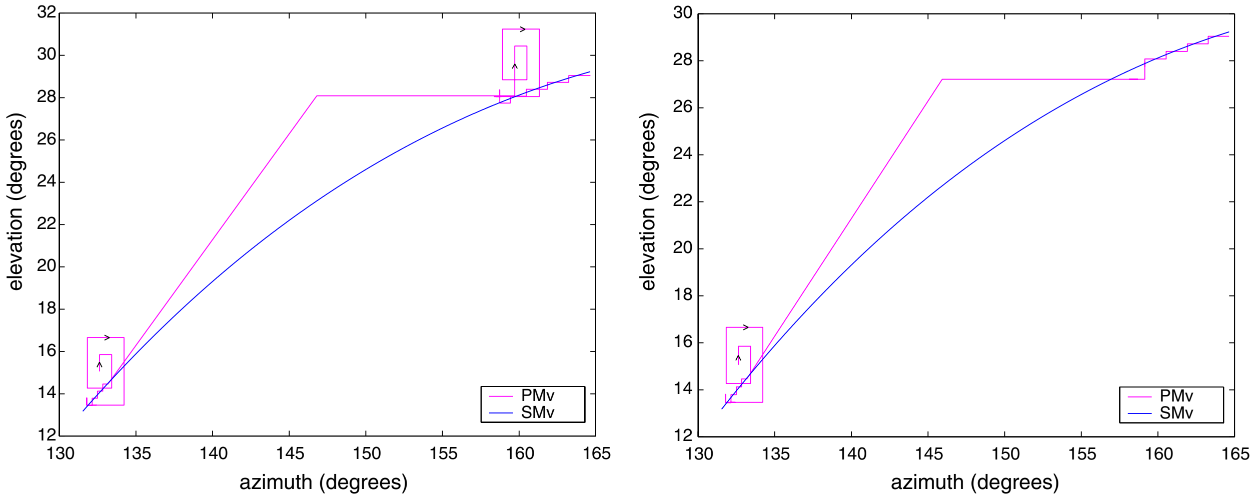
cases. It can be seen that when the error table is not included, there is a great discrepancy between the value of the corrected equations and the position of the sun at the moment when the clouds disappear. This fact makes the search mode necessary again. However, when the error table is used, these discrepancies are not significant, which implies that a second call to the search mode is not necessary anymore.

Obviously, the tables of error have limited validity in time. Apart from the possible changes in origin or values of error, it has to be taken into account that the trajectory that the sun follows varies as the days go by, and this variation is different depending on the time of the year.

After having done different simulations, if the table for when there is no need of a search to resume tracking after an extended cloudy period is considered valid, it is possible to consider about a 25–30 day margin valid when the date is near the winter or summer solstices and 15–20 days when the date is near the spring or autumn equinoxes.

This means that after 15–20 days of continuous, total cloudiness, when the sun comes back out, the operation will be normal, with no need for a search. For longer periods of cloudiness, a search would be necessary before resuming normal tracking, but in general, the system will be adequate.

Finally, it should be noted that additional questions were not considered, such as safety routines to preserve the mechanical structure, e.g., the inclusion of a predetermined defense position in which the structure would offer minimal aerodynamic resistance. The mechanical structure could adopt this position, for instance, if wind speeds endangered the structure itself (which would also imply the inclusion of an anemometer in the sensor system) or at night, when the sun is not out.



Without using the error table

Using the error table

Fig. 8. Mechanical structure movements in elevation and azimuth coordinates.

2.4. Simulator

To test the reliability of the different control strategies, it is necessary to do different tests, simulating, insofar as possible, the environmental conditions that can be encountered in reality. The simulator allows us to do that and, thus, draw conclusions that indicate the correct operation of the tracker, as well as possible improvements.

Doing different tests under different conditions forces creation of an environment that would allow introducing the values that define the particular characteristics for each situation. Thus, the introduction of changes in the data for each simulation, as well as obtaining information from each one, is facilitated.

With the easy to manage graphical environment within Matlab, it is possible to:

- Specify the longitude and latitude of the system location.
- Specify the initial and final times of the simulation.
- Define the different parameters that define the tracking strategy, such as the PI constants etc.
- Define the sources of tracking error using solar equations: mistakes in latitude and longitude, constant errors with regard to orientation and elevation and time errors.
- Specify cloudy periods.

3. Control system structure

Fig. 9 shows the control system structure developed for the positioner. This structure can be divided into two subsystems. The first one is a low level motor control system based on the feedback from the angular position. The second one is a high level control system based on the power feedback generated by the photovoltaic arrays.

The motor control subsystem takes care of the tracking of the motors according to a given reference. The loop closes with the feedback from the position of the motors given by the pulse readings from the encoders. This system underlies the high level system.

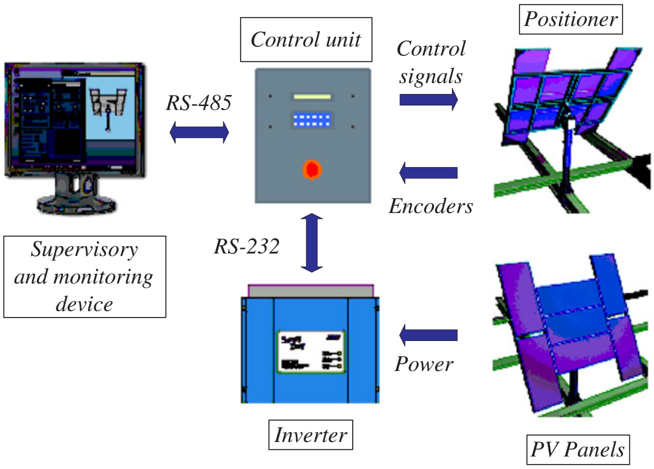


Fig. 9. Control loop scheme.

The high level system is based on the power feedback generated by the photovoltaic arrays. This system implements the strategy described in Section 2.

The information from the instantaneous power generated by the arrays is measured by a sensor that emits a signal proportional to this power. This sensor is connected to the A/D module of the microcontroller. It continuously provides the power measurement.

Furthermore, there is a Sunny Boy 700 power inverter that allows us to transform the constant tension generated by the arrays into AC voltage of 220 V and 50 Hz.

3.1. Monitoring and supervision system

The control unit is connected to a PC for supervision and monitoring. A SCADA application developed in LabVIEW is executed using that PC. Communication is accomplished via a serial port with an intensity loop in the control unit. This application allows for the remote operation of the control unit and data visualization, as well as the log file storage. Therefore, this is an additional module that is not essential for industrial purposes.

This system basically has three functions. The first one is to allow for the remote operation of the control unit. That way, any function of the control unit can be performed from the PC, such as the execution of movement orders.

The second function is to receive and store data from the driver in real time. The application allows storing all the data requested from the control unit during its operation in the log files. Finally, it also allows for remote configuration of the operating parameters of the control unit.

Apart from the SCADA application, there is a three dimensional model of the tracker that moves as data are received from the central control unit. This allows the operator to follow the operation more intuitively.

3.2. Control unit software

The control unit has three operating modes: configuration mode, manual mode and automatic mode. In all of these modes, the communication between the remote monitoring system and the driver is working.

Before operating in the configuration and manual modes, an initial module is executed to initiate communications and peripherals. This module initializes the decoder cards and the power modulation and amplification card and establishes the initial conditions for moving on to the normal execution mode. To initialize the decoder card, the two axes of the tracker move until the limit switches are activated. When that happens, the pulse counters are set to 0 and the initial operation mode, i.e. the automatic tracking mode, is activated.

In the configuration mode, any type of control action is sent to the tracker. The axes remain fixed in the last position reached and the alignment signals of both motors are disabled. This mode allows for modification of the operating parameters of the control unit. These parameters can be related to the control algorithms, communications configuration or they can be movement parameters, such as software movement limits or night position. These parameters can be modified using the keyboard and screen of the control unit via the RS-485 port series.

The manual mode allows moving the tracker directly. In this case, the control loop is only closed at the motor levels, without feedback from the power generated by the arrays. This mode is useful for position calibration and for maintenance. Again, in this mode, the tracker can be operated directly or remotely.

Finally, in the automatic mode, the high level solar trajectory tracking loop is closed by feeding back the power generated by the arrays. This measurement is transmitted in each control cycle to the central unit via an RS-232 line.

The automatic mode has two routines. The first one is a supervision routine that determines which of the motors should move and where to, following the strategy described in Section 2.

The second routine is that of the motor position control. In this routine, the low level loop mentioned above is implemented. In this mode, the control unit periodically sends data about the movement to the supervision system (time, position of the tracker, power generated by the arrays, tracking error). It is also able to respond to requests, such as the change in the operation mode or in the frequency of data transmission.

Finally, in all of the operation modes, the system protections remain active: the software movement limits, the limit

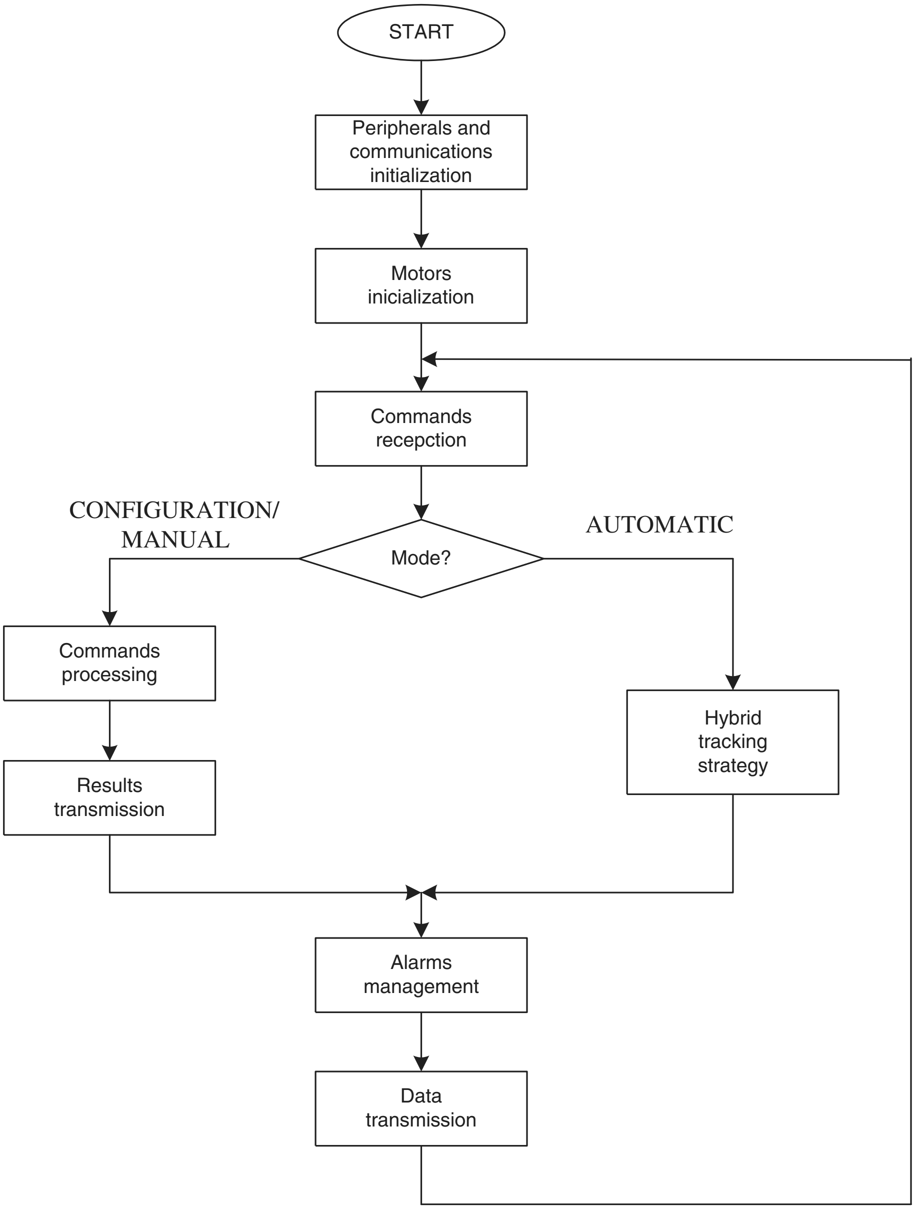


Fig. 10. Flow diagram of the control application.

switches, detection of motor blockage (the power supply is cut off to prevent the motors from burning out) and detection of blockage in the main unit by means of a hardware watchdog.

A general flow diagram of the control application is shown in Fig. 10.

4. Experimental results

The operation of the prototype of the control unit developed was tested using the mechanical structure shown in Fig. 11. This low cost positioning system is located on the roof of the *Department of Systems and Automatic Control Engineering Laboratories* at the *University of Seville*, in *Spain*. It was checked to make sure that it worked correctly, with regard to both hardware (movement of both axes, decoding etc.) and software (execution of basic programs, monitoring etc.).

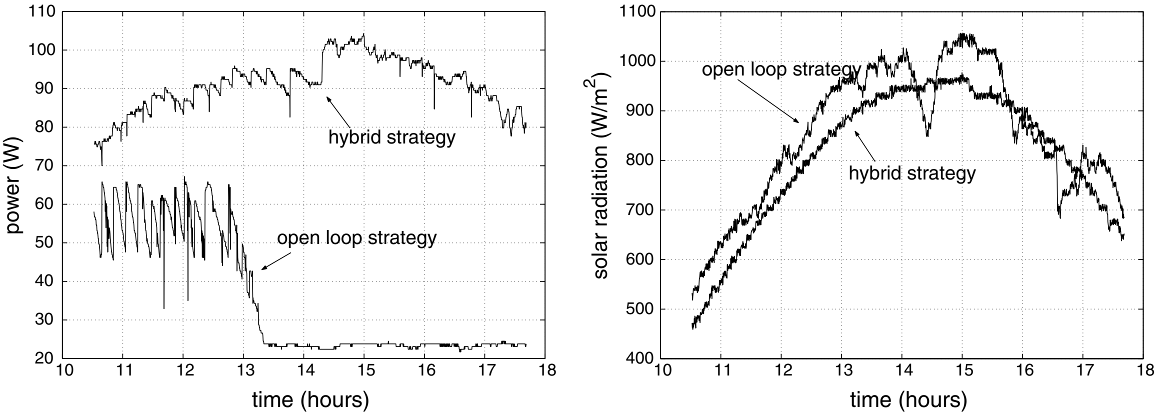
As can be seen in Fig. 11, the positioning system supports flat plate PV arrays instead of concentrating PV system. Since high concentration solar arrays were not available, several cells of slender built tubes were mounted on the arrays. These cells guarantee that no solar radiation gets to the arrays when the tracking error is greater than some degrees.

The different strategies tested in simulation were performed in the control unit in order to fine tune the controllers. In order to check the robustness of the algorithms, several error sources were included in the experiments, such as an offset in the time given by the auxiliary clock and a misalignment on the mechanical structure orientation with respect to geographical north.

Fig. 12 shows the experimental power attained using the open loop tracking strategy, as well as the one obtained using the proposed hybrid strategy. Solar radiation graphs are also included, showing that the experiments were performed under similar solar radiation conditions during the first four hours. In this period of time, the electric power generated using the hybrid strategy is, in mean values, 55% higher than the open loop one.

Frontface Backface

Fig. 11. Mechanical structure of the solar tracker.



Electric power generated Solar radiation

Fig. 12. Experimental results using an open-loop and the proposed hybrid strategy.

It can be observed that the power generated by the solar arrays using the open loop strategy has a maximum level about 65 W during almost two hours at noon. However, the positioner loses the sun in the afternoon and afterwards. This implies that the cells of slender built tubes throw shadow upon some solar cells, with the consequent decreased level of the electric power generated.

The above mentioned fact does not happen when the proposed hybrid tracking strategy is used. Besides that, the level of generated power is about 90 W at noon (a benefit of about 40% with respect to the open loop strategy, despite the low quality of the mechanical structure). Additionally, the arrays not only do not lose the sun but also their alignments are corrected, with the consequent increment of electric power generated (with a maximum greater than 100 W).[1]

5. Conclusions

A new sun tracking strategy that provides small sun tracking errors (needed, e.g., by high concentration solar arrays) has been developed. The algorithm consists of two tracking modes: a *normal tracking mode*, used whenever the sun tracking error is small enough and the solar radiation is great enough; and a *search mode*, which operates as long as the first of the above conditions is not fulfilled, but there is sufficient solar radiation to produce a minimum amount of electric power. Energy saving factors have been taken into account in the tracking strategy design. Simulated and experimental results have been presented that show the benefits of the new strategy with respect to a classical open loop strategy when errors in the estimation of the sun's position (such as variations in the time given by the auxiliary clock or lack of precision in the alignment of the mechanical structure with respect to geographical north) are included.

Acknowledgements

The authors would like to acknowledge MEC-FEDER for funding this work under grants DPI2004-06419 and DPI2006-07338. They also would like to thank Oscar Collazo and Oscar Pereles for their collaboration in conducting the tests and Ignacio Luque for many helpful suggestions during the project IFICLES.

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[1] The reader may be surprised that the amount of generated power is so low. This is due to the fact that the experiments were conducted using a constant non-optimal electric load. Of course, the level of power could have been increased if a *MPPT* (*maximum power point tracking*) device had been used (see, for example, [11] and references therein). However, since the goal of these experiments is to evaluate the sun's pointing error using different tracking strategies, the comparison between the level of generated power was taken into consideration, but not the level of power per se.