A *PI* BASED HYBRID SUN TRACKING ALGORITHM FOR PHOTOVOLTAIC CONCENTRATION

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ABSTRACT: A sun tracking error correcting routine, following the principles of classical controllers, is presented for integration in hybrid sun tracking strategies working on an open loop sun ephemeris basis, which is to be subsequently adjusted. Space scanning routines for feedback acquisition and tabulation of error estimates are introduced to complete the strategy. First analysis of the behavior of this strategy is obtained through custom-developed simulation software. In this context *EUCLIDES* concentrator error correcting routine is reviewed, and its comparison with the *PI* strategy gives way for extrapolation to a more general framework for hybrid strategies, which opens a range of different possibilities.

Keywords: Tracking, Concentrators, Calibration

1 INTRODUCTION

This paper presents a novel sun tracking strategy for photovoltaic concentrators. This can be integrated in the so called hybrid strategies, which built around a calculated sun ephemeris core, add different types of error correcting routines to compensate on the one hand for timing drifts, and on the other for self-characterization errors due to a faulty installation, assembly, or manufacturing, or in the time evolving side those caused by stress bending or landslides, which ultimately blur the “picture” the tracking control has of its tracker.

Hybrid sun tracking strategies intend to combine the best of both open-loop ephemeris computing, and closed-loop sun pointing sensor based controllers, while avoiding their problems. By using an open-loop sun primary acquisition phase, hybrid controllers wake and stow at specified positions and times and their effectiveness is immune to sunshine conditions or drifts in sensor calibration, thus avoiding the problems in acquiring and locking onto the sun that occur with closed-loop systems. By using a closed-loop error correction phase, hybrid controllers avoid the open-loop controller problems of needing accurate alignment, assembly, and time information. These error correction routines usually take as feedback signal the array’s power output thus relying on the obvious equivalence between precise sun pointing and maximum generation.

The main difference between the error correcting routines integrated into hybrid strategies to date, remains on whether they are based or not on a tracking error model. Model-based error correction routines resort to a physical model, which accounts for the set of the systematic errors which may affect a sun ephemeris based tracking routine in a certain tracker design. Characterized by a set of parameters, this model will be fitted with an array of tracking error measurements or observations acquired at onset, after which and if time varying errors can be disregarded, it should not be necessary to undertake further calibration. However error sources overlooked by the model will degrade the model’s best fit, and consequently its correcting power, therefore a good model adequately tailored to the tracker of its implementation is a must for error model based calibration.

Model-free error correcting routines make no initial assumptions on the tracking errors that will be encountered, being of a general purpose conception able to cope with any sort of tracking errors at whichever tracker design. However routines offering this versatility require permanent error surveillance implying scanning movements which to some extent will increase motor consumption and fatigue and might bring down average tracking accuracy.

2 THE *PI* STRATEGY

The correcting routine proposed requires no error model, and its main feature comes from the adjustment of the classical *PI* (Proportional Integral) controller to the sun tracking process. For this purpose sun tracking, using the language of basic control theory, is taken as a discrete time process for which we have a mathematical model providing a feedforward open loop estimation of the sun’s position as a function of time and geographical coordinates, and a set of disturbances which introduce errors in that model. A feedback loop is introduced for the correction of the tracking errors which derive from the disturbances in the process’ model and which after measuring them inserts them in a controller which tries to forecast this error, adjust the model’s output, and increase its tracking accuracy.

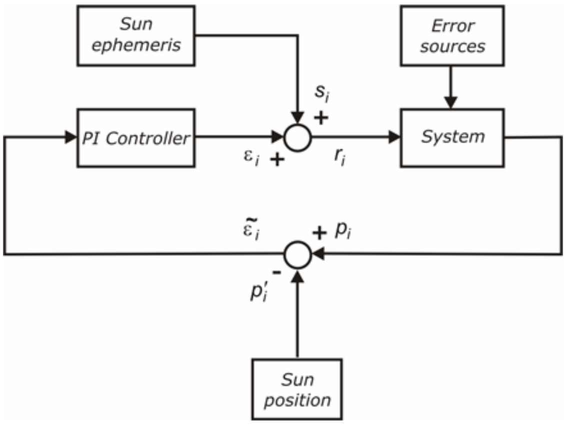


Figure 1: Block diagram of the PI correcting routine

The block diagram in figure 1 represents the overall sun tracking strategy for which, in an iterative process, a tracking reference position r_i is provided to each axis of the tracker (the system), this being the sum of the present sun's position according to the sun ephemeris equations s_i , and the output of the *PI* controller ε_i which can be taken as an estimation of the error of the sun equations at the present stage based on its past history. The last iteration's tracking error measurement $\tilde{\varepsilon}_i$ is obtained as the difference in each axis between the position reached by the system p_i when processing the reference position, and the real sun's position p'_i as determined by whichever means going from sun pointing sensors to the maximization of PV power output.

In a discrete version of the classical linear *PI* controller, the estimate of the error is provided as a weighted sum of the last error measurement (the proportional part) and the integration of the discrete time series of tracking error measurements since their commencement (the integral part):

$$\begin{cases} \varepsilon_i = K_P\left(\tilde{\varepsilon}_i + \dfrac{1}{K_I}S_i\right) \\ S_i = S_{i-1} + T_{mi}\tilde{\varepsilon}_i \end{cases} \qquad (1)$$

Where K_P and K_I are used to adjust the contribution of the proportional and the integral respectively to the error estimate. S_i computes the integral of the discrete series of tracking error measurements, where T_{mi} stands for the time interval in between measurements. If we subtract the expression of ε_i , from that of ε_{i-1} we cancel all terms but the last one in S_i and we obtain a recursive formulation for the error estimation routine as:

$$\varepsilon_i = \varepsilon_{i-1} + K_P\left(1 + \frac{T_{mi}}{K_I}\right)\tilde{\varepsilon}_i - K_P\tilde{\varepsilon}_{i-1} \qquad (2)$$

also recognizable as an infinite impulse response filter (IIR) or auto regressive moving average filter (ARMA)

To avoid hunting due to backlash, motor inertia, or other dead zone non-linearities, and reduce power consumption, sun tracking is usually performed in constant speed, discrete steps, also called a "bang-bang" control approach. Movement in each axis is dictated whenever the reference position supplied by the control system grows over the present orientation a certain error angle. Everyone of those movements constitutes an iteration of the above process in which a tracking error observation $\tilde{\varepsilon}_i$ is recorded, and that keeps a certain time interval to the last iteration T_{mi} , which due to the varying angular speed of the sun in each axis along the day, will not be constant for all iterations but time dependant and specific to each iteration.

The implementation of this correcting routine demands some additional methodology in the tracking error measurement process. An auxiliary global radiation sensor in the concentrator's aperture plane will inhibit error measurement movements in a iteration, whenever radiation falls below a certain threshold which prevents the determination of the precise sun orientation.

Also location of a precise sun position for tracking error determination may not be straightforward if it happens to be outside the acceptance angle of whichever type of pointing sensor we use, when moving to the reference position, thus we will have to make a "blind" and foolproof approach to this position until we get it within the sensor's field of view. If on a single axis tracker, progressively increasing alternative movements in one turning sense and the opposite until sensor output rises over a threshold seems the most obvious. In the case of a two axis tracker the one axis procedure can be maintained but now also alternating the moving axes thus resulting in a squared spiral scan of a two dimensional space. The difference here with the one axis case is that now the movement increases in successive scans within an axis is not arbitrary because it determines the angular step between neighboring paths which should not be greater than twice the acceptance angle ς of the pointing sensor, so there is no possibility to miss the sun.

An efficiency measure for this two dimensional scanning is the area to arc length ratio, which is equivalent to the area swept per time unit and at speed unit, and it can easily be proven that it is highest for a linear spiral (also known as Archimedes' spiral which in polar coordinates follows from $\rho = a\theta$) which also has the property of maintaining constant spacing between successive arms equal to $2\pi a$ and therefore preventing missing the sun. Here the physical meaning of the radius ρ corresponds to the angle to the starting point of the orientations within the scanning path, and will depend on the precise tracking axes system chosen, e.g. for an azimuth-elevation system:

$$\arccos(\cos\Delta\gamma\cos\Delta\alpha) = \frac{\varsigma}{\pi}\arctan\left(\frac{\Delta\alpha}{\Delta\gamma}\right) \qquad (3)$$

Where $\Delta\gamma$, and $\Delta\alpha$ are respectively the azimuth and elevation angle differences between the points in the spiral and its central starting point.

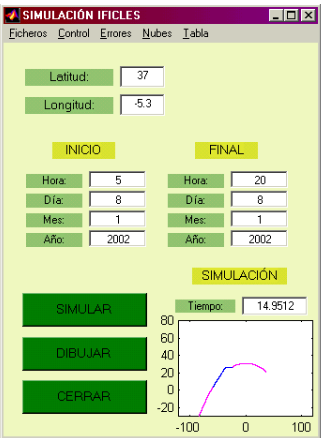
Once the scanning manouvers place the sun within the pointing sensor acceptance angle, if this is some sort of quadrature sensor providing directional information, the precise sun position is rapidly obtained, however care will have to be taken with this sensor's calibration. If instead precise sun pointing is attained through PV power feedback or some equivalent measurement, there is no directional information at hand. In the simplest case if the profile of this feedback variable as a function of the two axes angular coordinates is rotationally symmetric, then the maximum can be sought first in one axis and then in the other thus arriving to the global one, if not some set of conjugate directions will have to be generated by means of Powell's algorithms and linear maximization succesively performed along them.

For the sun's path to drift appart from the tracker up to the point in which it leaves the field of view of its sun pointing sensor, the most possible reason lies in the appearance of clouds which during a certain period inhibit sun error observations to feed the *PI* controller correction. As soon as the tracker can not "see" the sun it switches to spiral scanning mode, which nevertheless its reliability does not mean effective tracking. In order to reduce as much as possible the scanning mode, during the sunny days the average PI correction is computed at fixed time intervals (e.g. every half hour) and stored in a table which will be daily updated always holding the average of the last sunny day. Now when a cloudy period ends the error estimate employed by the tracking routine to deliver the final reference position will be not the last one computed before cloud appearance, but the one stored in the table which corresponds to the present time period.

3 SIMULATION

A simulation tool was programmed in the *Matlab-Simulink* environment to test the behaviour of the devised sun tracking strategy. In figure 2 we can see the opening window of this simulation software, in which a set of parameters may be fixed such as:

- Lat & Long of the tracker
- Start & End hour for the simulation
- Parameters of the control strategy
- Cloudy periods



Latitud: 37
Longitud: -5.3

INICIO
Hora: 5
Día: 8
Mes: 1
Año: 2002

FINAL
Hora: 20
Día: 8
Mes: 1
Año: 2002

Tiempo: 14.9512

Figure 2: Opening window of the simulation software

Also some reference open-loop systematic errors may be introduced to alter the sun ephemeris core:

- Errors in Latitude & Longitude
- Offset errors in both axis positioning sensors
- Offset and linear drift in the timing

Assuming a pedestal Az.-El. Tracker several types of plots can be obtained such as (i) pedestal path (with simple first order linear models for its dynamics), with the corrected reference and real sun's path vs. time (ii) open-loop and controller corrected reference evolution in time along with real sun's path in both axes, (iii) tracking error in both axes and global vs. time. Final summaries are computed of the tracker's performance giving the maximum, mean and variance of the tracking error in both axes and globally, as well as total power-on time of the motors and number of switchings.

In figure 3 we have a simple example of how sun equations affected by an offset error in the elevation axis positioning sensor (digital encoder or equivalent) are progressively corrected in each movement in which the tracking error is acquired and integrated in the PI error estimation, thus finally converging to the real sun's path.

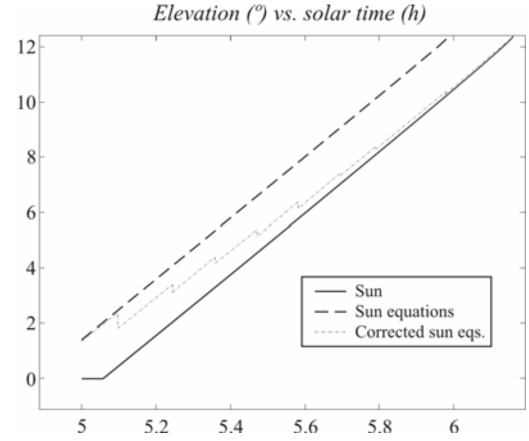


Figure 3: Simulation plot representing the real and erroneously calculated sun's path (º) vs. time (h), along with the progressively corrected sun equations.

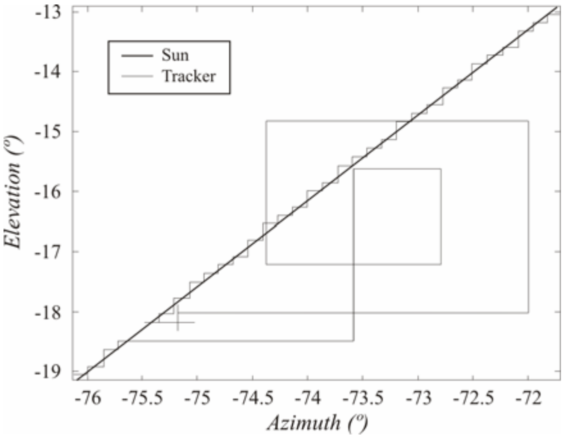


Figure 4: Simulation showing in an Elevation vs. Azimuth plot the sun's and trackers' path when a severe tracking errors appears which drives tracking into spiral scanning.

In figure 4 we have, a plot of the behavior of the tracking strategy when we introduce a sudden offset error in both axes – e.g. replacement of the digital encoders – error which opens between the sun's real path and that dictated by the corrected sun equations, a bigger distance than that covered within the acceptance angle of the tracking error sensor. This drives tracking into the spiral scanning mode, here in its squared version, until the sensor again starts to provide feedback. In this simulation we use a sensor lacking directional information and the spiral ends after two consecutive feedback signal line maximizations. Once the sun is found the tracker again assumes normal tracking mode.

3 THE *EUCLIDES* STRATEGY

The *EUCLIDES* concentrator tracking strategy which to a great extent has inspired the method here presented was developed at IES-UPM [1] and implemented by INSPIRA in its *EPS-Tenerife®* sun tracking control unit, which was produced for the 480kWp concentrator plant in Tenerife Isl. [2] – the world's biggest – and that since 1998 sums more than 700.000 almost flawless operating hours, as recognized by the CPV community [3].

As the *PI* based strategy that of *EUCLIDES* is an hybrid one with a model free error correcting routine, the main difference between them, mostly relies in the fact the latter is conceived for a one axis concentrator, this greatly easing scanning operations necessary for tracking error measurement. In fact interest in a model free correcting routine for point focus optics concentrators with two tracking axes is behind the development of the *PI* strategy [4].

A tracking error correcting routine can be viewed as a time series forecasting system, which estimates the tracking error to appear in the next movement out of past tracking error measurements and estimates. In fact *EUCLIDES* correcting routine is based on one of the most simple and widely used time series forecasting methods as is exponential smoothing

$$\varepsilon_i = \beta\tilde{\varepsilon}_i + \sum_{n=1}^{n=i-1}(1-\beta)^{i-n}\tilde{\varepsilon}_n \quad \Rightarrow \qquad (4)$$

$$\varepsilon_i = \varepsilon_{i-1} + \beta(\tilde{\varepsilon}_i - \varepsilon_{i-1}) \quad \Rightarrow \qquad (5)$$

$$\varepsilon_i = (1-\beta)\varepsilon_{i-1} + \beta\tilde{\varepsilon}_i \qquad (6)$$

with $0 < \beta < 1$ and in which the tracking error estimate which can be viewed as the geometric sum of past error observations (4), or the weighted sum of the last estimate and its forecasting error (5), or also a weighted sum of the last estimate and the last observation (6).

This exponential smoothing is an *ad-hoc* method which makes no special assumption about the time series to be predicted, and usually works well on time series with no clear trends or seasonality. When these appear it is outperformed by the more complex Holt-Winters exponential smoothing.

Specifically *EUCLIDES* works with an adaptive version of exponential smoothing in which the β constant which determines the weight in the new estimate of its last value and the last observation, gradually increases or decreases – also governed by an exponential smoothing law – with the amount of recent observations gathered. It reflects system's "self-reliance".

Again assuming error correlation in between different days, estimates are also stored in a table but now grouping is done considering space intervals – 1º angle sectors – instead of time periods.

Migration of the *EUCLIDES* strategy to two axes tracking only requires integration of two axis scanning routines based on those of the *PI* strategy.

4 A GENERAL FRAMEWORK

The previous section's review of the *EUCLIDES* strategy in the light of the *PI* strategy enables some generalization of model-free error correcting routines, in which the PI controller box of figure 1 is replaced by any suitable time series forecasting method which generates error estimates out of past estimates and observations (fig. 5). On this respect there is a well provided mathematical toolbox in which we can find from exponential smoothing or ARMA models, to the more recent nonlinear models such as neural networks.

Averages of the error estimates are stored in time or space segmented tables (ε_{i,t_j} or ε_{i,θ_j} respectively) in order to profit from their daily correlation and use them whenever observations can not be made.

Occasionally this model-free correcting routine could be blended with a model-based calibration stage which would operate at onset (search of solution parameters fitting an error model to an ensemble of tracking error observations) and would remove from the sun ephemeris all errors due to modeled sources, thus hopefully reducing the tracking errors which must be handled by the model-free correcting routine. Figure 5 presents the box diagram of this general framework for hybrid sun tracking strategies.

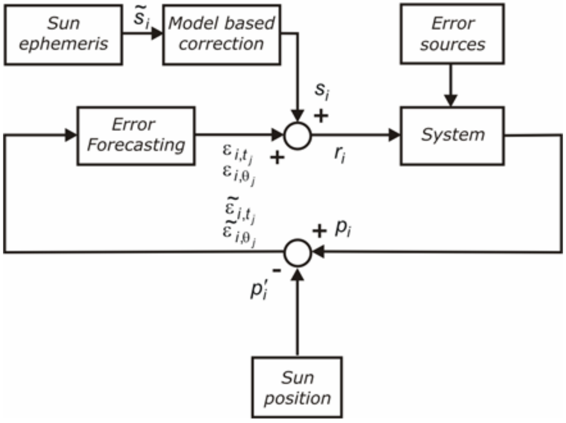


Figure 5: Block diagram of a general model-free correcting routine blended with a model based onset calibration routine.

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