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Diego A. Flores-Hernández, Sergio Palomino-Resendiz, Alberto Luviano-Juárez, Norma Lozada-Castillo, Jorge I. Chairez-Oria, and Ignacio Antón

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Design Strategy for Low-Power Consumption in Solar Trackers

Diego A. Flores-Hernández¹, a), Sergio Palomino-Resendiz², Alberto Luviano-Juárez² b), Norma Lozada-Castillo², Jorge I. Chairez-Oria³ and Ignacio Antón⁴

¹Centro de Innovación y Desarrollo Tecnológico en Cómputo – IPN, Mexico City, Mexico
²Unidad Profesional Interdisciplinaria en Ingeniería y Tecnologías Avanzadas – IPN, Mexico City, Mexico
³Unidad Profesional Interdisciplinaria de Biotecnología – IPN, Mexico City, Mexico
⁴Instituto de Energía Solar – Universidad Politécnica de Madrid, Madrid, Spain

a)Corresponding author: dfloreshe@ipn.mx
b)aluvianoj@ipn.mx

Abstract. The new energy generation technologies that transform the solar energy, require a high accuracy for the tracking of the solar vector path, which increases the system energy consumption and reduces the entire system performance. From an optimization approach, a novel design strategy for low-power trackers is proposed, which consists of two main stages, a first for the physical tracker design optimization, and a second for the design of the tracker behavior. For the validation of the proposed design strategy, the implementation is presented through the development of a solar tracker prototype. For the implementation of the second stage, three Tracking Error Minimization Strategies (TEMS) are proposed (PI, GPI, and cascade control), and four Energy Saving Strategies (ESS) are proposed. The presented experimental results show that the saving energy strategy can reduce the energy consumption in up to 27.277% in tracking tasks with an absolute maximum tracking error of 0.08°, and obtaining a low-power prototype tracker with 5.4749 Wh energy consumption. The proposed design strategy allows the design of solar trackers with a balance between the energy consumption and the tracking error.

INTRODUCTION

The new energy generation technologies must increase the production efficiency, one part of this can be achieved with solar tracker systems. These systems increase the uptake of solar radiation throughout the day and aim to reduce the tracking error to maintain the collector into a perpendicular position with respect to the solar radiation, although this increases the tracking consumption energy [1]. There exists a variety of solar tracker configurations, and two principal strategies for measuring the sun position: The first one in closed loop employing pointing sensors and the second in open loop employing astronomical Ephemeris [2]. The concentration photovoltaic systems (CPV) require a high accuracy and the open-loop controllers are commonly used, but this needs a high computational effort, and the accuracy is affected by other sources of errors and external effects (optical, mechanical and/or external disturbances). The high concentration photovoltaic systems (HCPV) require almost 0.1° of tracking accuracy, incrementing the tracking costs, and requiring a two axes tracker configuration [3]. To solve this challenge, the integration and validation during the design process with a concurrent approach reduces significantly the tracking errors and the tracking power consumption [4]. The key commitment in the design of solar trackers is the balance between the energy consumption to generate the motion and the power production by the photovoltaic system [5]. The proposed design strategy aims to find a balance between energy consumption and tracking error in solar trackers. The design and implementation of a solar tracker is presented to validate the proposal.
**TRACKER DESIGN STRATEGY**

The proposed design strategy for low-power consumption in solar trackers consist of achieving the balance between reduction of the energy consumption and keep the solar tracking operation inside the maximum permissible tracking error. Fig. 1 shows the general algorithm for the proposed strategy, which consists of two stages, described below:

**Stage 1 – Physical tracker design:** begins with the tracker requirements definition, which can be: the minimum number of modules that the tracker will move, the modules weight and dimensions, the tracking application (i.e. CPV, PV, solar sensing pointing, desalination process, or other) acceptance angle ($\alpha_{app}$), the tracker location requirements (wind forces, daylight duration, relative humidity, environmental conditions, etc.), and the installation requirements, among others. With the requirements defined, it is necessary to define the tracking system configuration (one axis, two axes, open-loop, and closed-loop) and the solar parameters associated to the tracker localization. Depending on the tracker application, it requires the definition of the maximum permissible tracking error ($\varepsilon_{\text{max}}$), which must be lower than the application acceptance angle. The physical design of trackers can be clustered into three major problems, the first for the actuators and hardware selection, considering the minimization of the power consumed without affecting the system performance. The second problem is the transmission design for each axis, maximizing the reduction ratio, which will reduce the actuators electrical power requirement. And finally, the structural design, the deformations that will affect the tracking error must be minimized, as well as the mass reduction of the system, which reduces the power required for the tracking action. Once each problem is solved and integrated, the design of the solar tracker is generated and evaluated with respect to the requirements and constraints. If it complies, the physical tracker design is complete.

**Stage 2 – Tracker behavior design:** begins with the definition of the possible $p$-Tracking Error Minimization Strategies ($\text{TEMS}_p$), and the $q$-Energy Saving Strategies ($\text{ESS}_q$), once the strategies have been defined, the maximum number of combinations between $\text{TEMS}_p$ and $\text{ESS}_q$ strategies is determined, expressed as $\text{CN}_{\text{max}}$. The first

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**FIGURE 1.** General algorithm for the proposal design strategy for low-power consumption in solar trackers, (a) shows the processes for Stage 1 (tracker physical design), and (b) shows the processes for Stage 2 (tracker behavior design).
combination is generated and evaluated with respect to energy consumption and the tracking error, it is called as the initial combination, and expressed as \( C_i \). Another combination is generated and evaluated, called as new combination and expressed as \( C_n \). With the evaluations of both combinations, a comparison process begins, if \( C_n \) is better than \( C_i \), \( C_i \) acquires the values of the \( C_n \), otherwise, the actual \( C_n \) is discarded and \( C_i \) is maintained. This process is iterative until the total number of combinations has been evaluated, when this happens, the result is the best combination of the tracking behavior for the design objectives. With the physical and behavior design, it is determined the maximum number of application modules that the tracker can support without increasing the energy consumption or the tracking error. Finally, the design of a low-power consumption tracker is obtained.

**IMPLEMENTATION STRATEGY**

For the implementation of the proposed design strategy, it is considered the design of a solar tracker with small dimensions for the mounting of pointing sensors (tracking application). Table 1 shows the main requirements and constraints for the design of the tracker. The tracker configuration is azimuthal-elevation movement with open-loop, implementing the ENEA [6] solar tracking algorithm. The development of each of the stages is described below.

**Physical Tracker Design**

**Transmission design:** It was determined to use worm-gear mechanisms for the tracker transmissions. The objective function to optimize the transmission design was the maximization of the gear ratio, having as constraints the boundaries of loads and dimensions for the tracker. Fig. 2 shows the applied loads on the elevation link, where \( \tau_C \) is the applied torque in the elevation joint, \( W_{BC} \) is the elevation link load, \( W_C \) is the collector load, \( F_W \) is the wind force, \( F_{Wy} \) is the wind force in the y direction, \( L_{C/2} \) is the length of the center of mass of the elevation link, and \( L_c \) is the total length of the link. The optimization problem was solved with the general algorithm of Differential Evolution (DE) proposed by Storn and Price in [7]. From the obtained results, standard components were searched and a multi-criteria selection process was carried out, employing the Analytic Hierarchy Process (AHP) proposed by Saaty in [8]. The selection criteria were the following: 1) transmission efficiency, 2) gear ratio, 3) anti-backlash mechanism, 4) lead angle, 5) maintenance, and 6) cost. The selected transmission for both axes has the following main characteristics: 120:1 as gear ratio, anti-backlash mechanism, single thread, 14.5° as pressure angle, bronze QQ-B-637 alloy as material gear, and 303 stainless steel as material worm.

**TABLE 1.** Main requirements and constraints for the design of the low-power consumption solar tracker.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracker location</td>
<td>IES – Madrid, Spain</td>
</tr>
<tr>
<td>Latitude, Longitude</td>
<td>40.4550°, -3.7273°</td>
</tr>
<tr>
<td>Average temperature range</td>
<td>-10°C to 40°C</td>
</tr>
<tr>
<td>Average wind speed range</td>
<td>0 m/s to 25 m/s</td>
</tr>
<tr>
<td>Solar speed average</td>
<td>0.25°/min</td>
</tr>
<tr>
<td>Tracker maximum load</td>
<td>1.5 kg</td>
</tr>
<tr>
<td>Tracking accuracy</td>
<td>±0.25°</td>
</tr>
<tr>
<td>Maximum dimensions</td>
<td>0.4m x 0.4m x 0.4m</td>
</tr>
</tbody>
</table>

**Actuators and hardware selection:** the selection process in this design process was based on the AHP method. Based on the tracker configuration, the requirements, the constraints and the desired behavior, it was determined that the actuators must be direct current motors. Thus, to minimize the energy consumption of the motors, it was determined to select geared motors, which allows to increase the total gear ratio, reducing the electrical power of the motor. The motors for both axes were selected employing the AHP method, with the following criteria: 1) transmission efficiency, 2) electrical power, 3) gear ratio, 4) torque, 5) dimensions, and 6) cost. The selected geared DC motor has the following characteristics: 392:1 as gear ratio, 0.20 Nm as rated torque, 5 rpm as rated speed, 45 mA as rated current, and 12VDC as nominal voltage. For the data processing hardware, the criteria were: 1) electrical power, 2) sleep modes, 3) I/O ports, 4) memory, 5) processor speed, 6) connectivity, and 7) cost. The selected hardware data processing device was an Arduino Mega 2560 Rev3, with 54 digital I/O ports, 16 analog I/O
ports, 8 KB SRAM memory, 4 KB EEPROM memory, 5 VDC operating voltage, and six sleep modes. The sleep mode activates and deactivates functions of the processing hardware during a period or an established action, each mode has configurations to obtain different energy consumptions. For the measurement of the position of each axis, two incremental rotatory encoders were selected, with the following characteristics: 1,024 pulses per revolution, 5VDC input voltage, up to 200 kHz response frequency, and 50 mA current consumption. Other hardware selected were: a dual-driver motor for the motor control, a DC to DC converter for the power conditioning, a real time clock for measuring the time in the solar position calculation, two optical limit sensors for setting the tracker home position, and two relative humidity and temperature sensors for the environment measures.

**Structural design:** The objective function to optimize the structural design was the minimization of the weight and the deformation, this function directly affects the tracking error as well as the energy consumption associated with the loads and the structural deformations. The optimization problem was solved with the DE algorithm, the dimensions of the elevation link and the cross section were obtained, as well as the maximum load that the tracker supports.

Once the hardware were selected, the transmission and structural were designed, the tracker must be detailed and carried on the necessary simulations for validation, when the design integration was ended the first stage of the proposed strategy was concluded.

**Tracker Behavior Design**

**Tracking Error Minimization Strategies (TEMS):** three strategies were developed for the minimization of the tracking error, the TEMS1 strategy based on a Proportional Integral controller with an average establishment time (te1) of 4.8 seconds for each step of the trajectory and an absolute tracking error (ε1) of 0.134° [9], the TEMS2 strategy based on Generalized Proportional Integral (GPI) controller with an average establishment time (te2) of 0.9 seconds and an absolute tracking error (ε2) of 0.08° [4], and a TEMS3 strategy based on a cascade control with an average establishment time (te3) of 1.2 seconds and an absolute tracking error (ε3) of 0.014° [9].

**Energy Saving Strategies (ESS):** four strategies were developed, the ESS1 strategy is the sequential activation and of the motors without a hardware sleep mode, the ESS2 is the parallel activation of the motor with serial tuning and without hardware sleep mode, the ESS3 strategy is the sequential activation and of the motors with a hardware sleep mode, and the ESS4 is the parallel activation of the motor with serial tuning and with hardware sleep mode.

The maximum number of combinations CN\_max is equal to 12. The tracking error for each combination is determined by computational multi-body simulations. Using the kinematic and dynamic model of the tracker, and the DC motor model, as well as the estimation of the energy transformation losses along the transmission, the calculation of the total energy consumption (ECT) is determined by the following expression:

$$E_{CT} = E_{C_{TOP}} + E_{C_{ID}} = \sum_{k=1}^{m} \left[ \int_{t_{OP_k}}^{t_{ID_k}} \sum_{i=1}^{n} P_{OP_i}(t) dt \right] + \sum_{k=1}^{m} \int_{t_{ID_k}}^{t_{OP_k}} P_{ID_i}(t) dt \]$$

(1)

where ECT\_TOP is the total energy consumption by the tracker during the operation time, and the EC\_ID is total energy consumption by the tracker in the idle time. The idle time is the period in which the solar tracker is in the desired position, waiting for the sun to advance to make the next step in the trajectory. POP\_i is the electrical power during the period of operation time and PID\_i is the electrical power during the period of idle time of the n-th axis (n=2) of the tracker in the k-th step in the tracking trajectory.

**EXPERIMENTAL RESULTS**

For the validation of the tracker design results, the tracker was manufactured and the proposed strategies were implemented. Fig. 3 shows the instrumented prototype for the experimental tests. The experimental tests were carried out at the Instituto de Energía Solar (IES), in Madrid (Spain) on April 3rd, 2018. For the calculations and simulations, the data for that day were considered, being: sunrise time at 06:54:05, sunset time at 19:42:28, and noon
at time 13:18:16. Taking a total of 12.8063 hours of sunlight. The solar position was determined by an algorithm based on the ephemerides calculation, having the following values for the azimuthal/elevation movements: $81.8^\circ$ (A)/$-0.833^\circ$ (E) at sunrise, $180.09^\circ$ (A)/$55.39^\circ$ (E) at noon, and $278.47^\circ$ (A)/$-0.833^\circ$ (E) at sunset. For the experimental measurements of the currents and the voltages a Fluke model 289 true RMS multimeter was used, recording three samples per second during the operation, along the tracking path.

![Figure 3](image-url)  
**FIGURE 3.** (a) Two-axes solar tracker prototype with lower-consumption design strategy implementation, and (b) solar tracker azimuthal mechanism for lower-friction and anti-backlash worm-gear transmission.

Tracker experiments were performed additionally without implementing the proposal strategies, this serves to determine the reference energy consumption and error values, the first reference is activating the motors sequentially without activation the sleep mode, the second reference is activating the motors sequentially with sleep mode. Fig. 4 shows (a) the affection in the operation and idle time for the different combinations, and (b) the total energy consumption for each combination, considering the motors energy, the energy consumption for the hardware devices in operation and idle time, SD-OP and SD-ID respectively. It is appreciated that the larger energy saving is when the idle times are increased, which increases the activation period of the hardware sleep mode.

![Figure 4](image-url)  
**FIGURE 4.** (a) Comparison of the operation time and the idle time for each strategy combination, and (b) the energy consumption of the different combinations.

Table 2 shows the results obtained from the experiments to the different combinations, where $E_{CT}$ is the total energy consumption of the tracker in Wh, $SE_{\%}$ is the combination saving energy percentage [%] compared with the reference combination Ref1, and $\theta_{\text{track}}$ is the maximum measured tracking error in degrees. Although the combinations with the TEMS3 strategy have a lower tracking error, the energy consumption is higher because the establishment time, therefore the combinations with lower energy consumption have priority. The best combination

Table 2

<table>
<thead>
<tr>
<th>Combination</th>
<th>$E_{CT}$ (Wh)</th>
<th>$SE_{%}$</th>
<th>$\theta_{\text{track}}$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref1</td>
<td>10.5</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>C1</td>
<td>9.8</td>
<td>-3</td>
<td>0.3</td>
</tr>
<tr>
<td>C2</td>
<td>9.2</td>
<td>-5</td>
<td>0.2</td>
</tr>
<tr>
<td>C3</td>
<td>8.9</td>
<td>-7</td>
<td>0.1</td>
</tr>
<tr>
<td>C4</td>
<td>8.5</td>
<td>-9</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Table 2. Results obtained from the experiments to the different combinations.
is the C11, which has an error saving percentage of 27.27714%, and a total energy consumption of 5.4749Wh. This combination consists of a TEMS2 with a GPI controller and ESS4 with a parallel activation of the motors, with serial tuning, and a hardware saving mode activation. The total idle time is 11.92 hours, and the operation time is 0.88 hours. If the tracking systems remain active for long periods, over ten years, then the calculation of the energy savings is affected by the number of decimals in the saving energy percentage.

<table>
<thead>
<tr>
<th>Data</th>
<th>Ref1</th>
<th>Ref2</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>C6</th>
<th>C7</th>
<th>C8</th>
<th>C9</th>
<th>C10</th>
<th>C11</th>
<th>C12</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECT</td>
<td>7.52</td>
<td>5.37</td>
<td>7.76</td>
<td>7.84</td>
<td>7.83</td>
<td>7.76</td>
<td>7.84</td>
<td>7.83</td>
<td>6.02</td>
<td>5.49</td>
<td>5.53</td>
<td>6.00</td>
<td>5.47</td>
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</tr>
<tr>
<td>SE%</td>
<td>0.00</td>
<td>28.66</td>
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<td>-4.16</td>
<td>-4.08</td>
<td>-3.11</td>
<td>-4.20</td>
<td>-4.11</td>
<td>19.99</td>
<td>27.04</td>
<td>26.50</td>
<td>20.22</td>
<td>27.27</td>
<td>26.73</td>
</tr>
<tr>
<td>( \epsilon_{\text{track}} )</td>
<td>0.5</td>
<td>0.5</td>
<td>0.134</td>
<td>0.08</td>
<td>0.014</td>
<td>0.134</td>
<td>0.08</td>
<td>0.014</td>
<td>0.134</td>
<td>0.08</td>
<td>0.014</td>
<td>0.134</td>
<td>0.08</td>
<td>0.014</td>
</tr>
</tbody>
</table>

### CONCLUSIONS

The proposed design strategy allows the design of low-power solar trackers, increasing the energy efficiency and reducing the errors associated to the tracker (backlash, deformation, assembly and manufacturing) and the action of tracking, due to the considerations along the design process. The experimental implementation allows to validate the proposed strategy, obtaining an energy saving of 27.27714% and a low-power tracker with 5.4749Wh energy consumption. The implementation of more complex control algorithms for the reduction of the tracking error does not significantly affect the energy consumption of the processing components, but it can affect the idle times and increasing the operation time. More complex TEMS should be search to increase the idle times of the tracker, reducing the establishment times within the desired tracking error range. Finally, the design strategy allows to implement the Stage 2 (Tracker behavior design) in already operating trackers, which can represent a significant energy consumption savings, and reduction of the actual tracking error.

### ACKNOWLEDGMENTS

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