An open-loop control algorithm for improved tracking in a heliostat

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Abstract: The growing energy demand and its relation to climate change have driven the search for sustainable alternatives, such as concentrated solar energy. In this context, heliostats play a crucial role by reflecting and concentrating solar light onto a receiver. However, traditional control approaches based on geographical data have limitations. This study introduces an autonomous control system for heliostats that eliminates the need for preloaded geographical data. The approach is based on communication between the heliostat and the solar tracker, with two configuration modes: map calibration and automatic. Centralized and autonomous heliostats are distinguished, with the latter being the focus of the study. Autonomous heliostats have their own control system and can make decisions regarding positioning and safety. The methodology involves a mathematical algorithm that calculates the optimal rotation and tilt of the heliostat to redirect light toward a target. Simulation and physical prototype testing validate a remarkable consistency between simulated and experimental data. A key result is the surprising similarity of 97.9% between the obtained data, validating the algorithm's effectiveness. This study provides a robust approach for designing autonomous heliostat control systems, integrating simulation and experimentation. These results support the algorithm's precision and ability to direct solar radiation effectively. Expanding towards autonomous control and complete heliostat system evaluation facilitates the path toward more efficient and sustainable concentrated solar energy.

Keywords: heliostat; solar tracker; simulation; algorithm design.

Introduction

One of society's contemporary challenges is the rising energy need linked to the growing population, high greenhouse emissions gases, and consequently global warming. Central solar power energy has become a more popular and attractive option for renewable energy generation moreover, it respects the environment. Among devices used in concentrating systems, heliostats can reflect and redirect solar light toward a target. (Cock Martínez, 2018).

In a heliostat field, a compound for controlled mirrors that reflects and concentrates solar light in a central collector requires an efficient control system. During the operation of the field, each heliostat is individually aligned in such a way that the normal to the surface bisects the angle between the sun's position and the target point coordinates on the receiver. However, achieving precise alignment of up to 1 milliradian for all heliostats relative to the target points on the receiver without a calibration system is considered unrealistic due to various sources of tracking error. This challenge highlights the importance of a calibration system to improve the accuracy of redirection to achieve desired flow distributions, as well as to reduce or eliminate spillage, as presented by Sattler and others, who offer an overview of the sources of tracking error and the basic requirements of an ideal calibration system (Sattler *et al.,* 2020).

Tracking errors can occur for several reasons. In an exhaustive study conducted by Jones and Stone, the sources of heliostat tracking error at the Solar Two plant were examined and detailed, including bending due to gravity, pivot point shift, atmospheric refraction, among others. This in-depth analysis helps to understand the specific challenges that need to be addressed to improve accuracy in the heliostat field (Jones & Stone, 1999).

Additionally, Díaz-Félix and others evaluated the global distributions of tracking error in the heliostat field, identifying specific errors such as angular displacement in the reference position of the tracking mechanisms, imperfect leveling of the heliostat pedestal, and lack of perpendicularity between the tracking axes (Díaz-Félix *et al.,* 2014). These findings, along with observations by Gross and Balz about disagreements between the coordinate systems used by solar, civil, and topographic engineers, illustrate the complexity of tracking errors and underline the need to comprehensively address these errors (Gross & Balz, 2020).

Furthermore, a detailed study conducted by Freeman and others, focused on the errors affecting the design of calibration and control systems, assessed the impacts of individual errors. Errors with a strong impact include those in sensors and actuators, as well as installation errors, highlighting the importance of carefully considering these factors in the design of calibration systems to mitigate their impact and optimize the performance of the heliostat system (Freeman *et al.,* 2014).

One of the most used strategies in open-loop heliostat redirection systems is using algorithms that calculate and can predict the solar trajectory during the day. Carvajal presents a heliostat design with solar tracking to redirect incident radiation to a parabolic concentrator, which is based on real-time zenithal and azimuthal calculations with short time steps. The core algorithm contains a considerable number of initial parameters for its execution (Carvajal, 2018).

This work is focused on developing a system control design for a heliostat field interconnected to a solar tracker which dismisses the need for preloading tables data and geographic location process. In this first stage, this design is for just one heliostat. To raise this, an innovative approach is proposed based on the communication between solar tracker and heliostat. In this system, it's considered two configuration modes:

1. Map calibration: The Heliostat is positioned at the desired target and collects a defined number of instances where it reports to the solar tracker time, azimuth, and zenith data corresponding to the location. With this information, the solar tracker constructs a map of the work area.
2. Automatic: The solar tracker collects the sun's current position, both in terms of azimuth and altitude, and simultaneously transfers it to the heliostat. This information allows the heliostat to adjust its position optimally to maximize the capture of solar energy at each required moment. The implementation and communication process must be validated through simulation and experimentation, and it is expected that the results obtained will support the feasibility of this approach and open new possibilities in the field of concentrated solar energy.

Materials and Methods

Methodology

According to their management and operating system, heliostats are divided into centralized and autonomous heliostats. Centralized heliostats are connected to a central control system that sends signals to each actuator of the heliostats belonging to the same solar thermal energy concentration array. This control can be based on tracking the sun's movement, which requires a shared solar tracker for all heliostats in the group. However, it is also possible to employ an approach that relies on astronomical calculations to predict the sun's position at separate times of the day, thus eliminating the need for the solar tracker.

On the other hand, autonomous heliostats have their own independent control system, which operates independently of other heliostats on the same platform as well as the central collection system. Like centralized heliostats, autonomous ones can either use a solar tracking system or rely on astronomical calculations to determine the relative position of the Sun and Earth. In the first case, each autonomous heliostat requires its own solar tracker, along with a synchronization mechanism (either mechanical or electronic) to control the actuators. The concept of autonomy applied to heliostats involves incorporating a local control unit that modifies various aspects of their operation, calculations, safety, and power supply, among others. This ensures that the heliostats consistently reflect direct solar radiation toward a fixed target, achieving solar tracking without depending on external devices. (Nakamura*,* 2004).

An autonomous heliostat can perform the following functions on its own:

- Perform positioning, axis guidance functions, and calculations and determine solar positioning and focus control, eliminating the need for central control assistance (autonomous calculations).
- Ensure making decisions about its own safety, protection, and integrity, thanks to the knowledge it acquires of external weather conditions or internal malfunctions (safety autonomy).
- Accomplish operational cycles thanks to the equipped local control. Cycles can be identified remotely or declared in advance (García Navajas & Egea Gea*,* 2000).

For these reasons, it demands extreme precision during solar tracking, otherwise, it will arise following deviations. They are referred to as a disparity presented between theoretical and real orientation and heliostat's optic axis through a year. This kind of deviation comes from a wrong alignment of activators or a failure of the calculus of solar position. Deviations can be tackled individually to quantify and fix them, achieving this by obtaining discrepancies for different solar incidence angles. This, in turn, is accomplished by directing the focus toward a camera that calculates and evaluates the deviation of the given focal point. (Pfahl *et al.*, 2017).

As a pilot stage of this project, a strategic mathematical data processing design is proposed to control an autonomous heliostat communicating with a solar tracker. Once the design is achieved, simulations are planned (to analyze and adjust variables and pseudocode processes to optimize their performance before physical implementation, which can lead to improvements in efficiency and productivity), validating the model that will be implemented in the heliostat and solar tracker prototypes, respectively. Therefore, the physical experimentation will be carried out manually in the prototypes as the first stage.

Algorithm design

In this first stage of the project, a control algorithm of a mathematical and trigonometric nature was established for processing, which will have the function of performing optimal calculations for the rotation and tilt of the heliostat to redirect incident rays from its surface toward the target, regardless of its location and geographical orientation, while also eliminating the time variable, as shown in Figure 1.

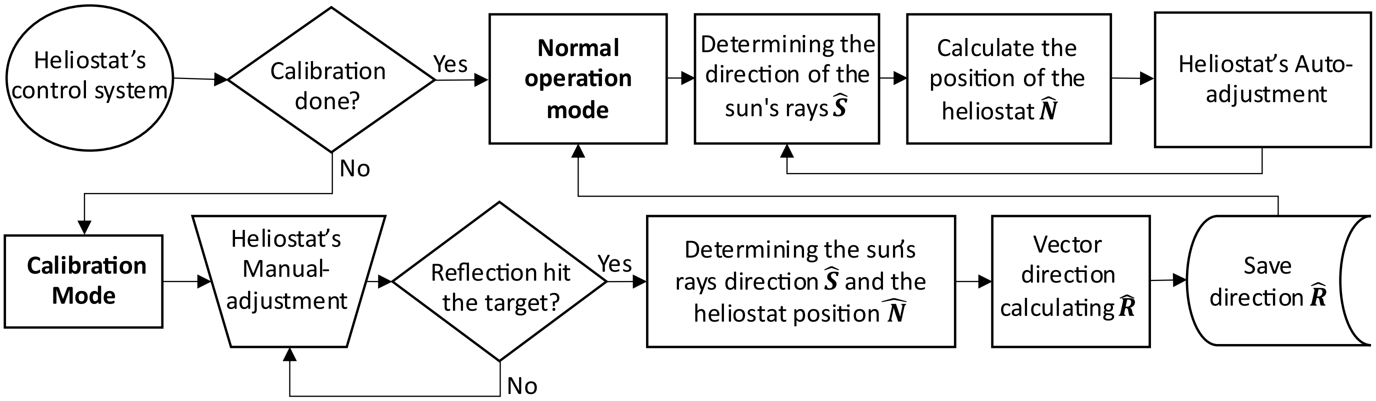

Figure 1. Flowchart.

The solar tracker is responsible for tracking the movement of the sun and reporting the azimuth (γ_s) and solar altitude α_s, which can be represented as a unit vector $\hat{\boldsymbol{S}}$ (solar ray) in our reference system. The heliostat always knows its rotation and tilt positioning, which can be represented as a unit orientation vector $\hat{\boldsymbol{N}}$ that is perpendicular to the reflective surface.

Calibration mode can permit that at a specific moment, the user manually provides the heliostat with the correct orientation using a joystick to accurately redirect the sunlight to a predetermined target. For this moment, it is possible to calculate the direction of a third unit direction vector $\hat{\boldsymbol{R}}$ using Equation 1, as seen in Figure 2. This direction $\hat{\boldsymbol{R}}$ will be a constant associated with the heliostat since the target is a fixed point that does not change throughout the day.

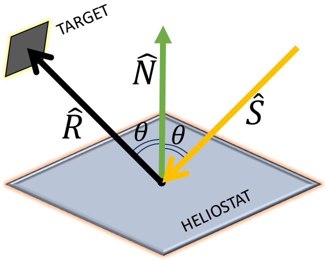

Figure 2. Established vector system.

$$\hat{\boldsymbol{R}} = 2\left(\hat{\boldsymbol{N}}\cdot\left(-\hat{\boldsymbol{S}}\right)\right)\hat{\boldsymbol{N}}+\hat{\boldsymbol{S}} \tag{1}$$

In normal operation mode, it is possible to calculate the position vector $\hat{\boldsymbol{N}}$ using Equation 2, thanks to having the direction $\hat{\boldsymbol{S}}$, which is a variable reported by the solar tracker, while $\hat{\boldsymbol{R}}$ was previously calculated.

$$\hat{\boldsymbol{N}} = \frac{\hat{\boldsymbol{R}}+\left(-\hat{\boldsymbol{S}}\right)}{\left|\hat{\boldsymbol{R}}+\left(-\hat{\boldsymbol{S}}\right)\right|} \tag{2}$$

To validate the a priori calculation algorithm through physical experimentation, TracePro software was used. TracePro is a tool used for optical-mechanical simulation through ray tracing. This application is responsible for tracking the intensity of each ray as it propagates through different paths in the solid models imported into its working environment (see Figure 3). Additionally, it incorporates a function known as Macro, which allows the software to receive instructions through lines of code, providing the capability to be controlled by another application using the Dynamic Data Exchange communication protocol. (García-Lara *et al*., 2021).

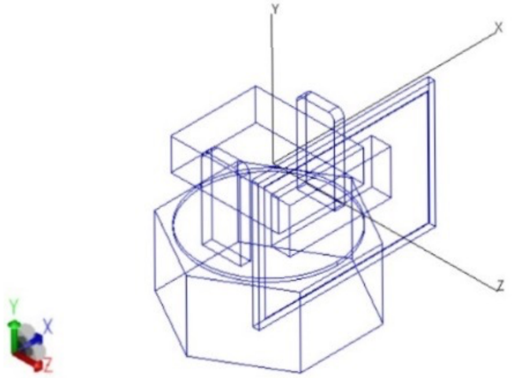

Figure 3. 3D model of heliostat's prototype in TracePro.

Experimentation and simulation

Experimental tests were carried out with the heliostat and tracker prototypes (see Figure 4) for five days in July 2023 in the municipality of Escobedo, Nuevo León. For each test, different times of the day and different reading frequencies (every 20, 30, or 60 minutes) were selected. It is important to note that in this initial stage of the study, the heliostat was operated electronically (non-autonomously) using a joystick for control. It should be emphasized that for this study, a functional mechanized prototype of the heliostat and solar tracker is available, and therefore, the mirror's geometry, rotation axes, link dimensions, and electronic control have already been determined in a previous study (Ordaz *et al*., 2023) and are not the focus of this study.

(a) **(b)**

Figure 4. Prototypes for physical experimentation: (a) heliostat and (b) Solar tracker.

During the experimentation, the solar azimuth angles (γ_s) and solar elevation angles (α_s) were documented, as well as the rotation and inclination of the heliostat (angles γ_h, α_h) for each moment. With this information, a simulation was conducted using Matlab and TracePro by inputting the real variables required by the vector calculation algorithm to verify the operation and feasibility.

Results and Discussion

The physical experimentation spanned several days in July 2023; however, data (Time, rotation angles, and inclination) from the heliostat operation are reported for 4 hours starting at 8:45 AM on July 13, 2023, with 30-minute intervals evaluated. Taking this into account, the obtained data from the Matlab-TracePro simulation were recorded, analyzing the same input variables (γ_s, α_s) from the solar tracker with the same sampling rate as the event, as shown in Table 1.

Table 1. Heliostat output angles in the experimentation and simulation on July 13, 2023.

	Experimentation		Simulation	
Hour	**Rotation [°]**	**Inclination [°]**	**Rotation [°]**	**Inclination [°]**
08:45	54	34.5	54.77	32.68
09:15	58	37.5	58.24	35.63
09:45	63	39.5	62.15	38.61
10:15	68	41.5	65.98	41.02
10:45	73	42.5	70.66	43.14
11:15	77	44.5	75.45	45.00
11:45	84	45.5	80.60	46.71
12:15	86	46.5	86.76	47.59
12:45	91	46.5	91.38	48.10

In the same way a table was created that shows the percentage of similarity between the output angles for both processes of the methodology at the same moments, as shown in Table 2.

Table 2. Percentage of similarities of angles between simulation and experimentation.

Hour	Rotation	Inclination
08:45	98.6%	94.7%
09:15	99.6%	95.0%
09:45	98.7%	97.7%
10:15	97.0%	98.8%
10:45	96.8%	98.5%
11:15	98.0%	98.9%
11:45	96.0%	97.4%
12:15	99.1%	97.7%
12:45	99.6%	96.7%

Photographs of the incident light on the predetermined target were taken during the experimentation. The comparison of the images resulting from the simulation and those captured during the experimentation plays a crucial role in this study (Figure 5). By comparing the images representing the redirection of light onto the target with the irradiance maps calculated through simulations, we aim to evaluate the consistency and validity of the simulation model used. This direct comparison will help determine whether the degree of similarity observed in Table 2 has a coherent correlation with experimental reality. In this way, we seek to support the reliability of the simulation approach and provide greater confidence in the results obtained, thereby strengthening the conclusions and contributions of this multidisciplinary study. It is important to emphasize that the black center on the target serves as a reference point for image capture and does not contribute positively or negatively to the results of the tests obtained.

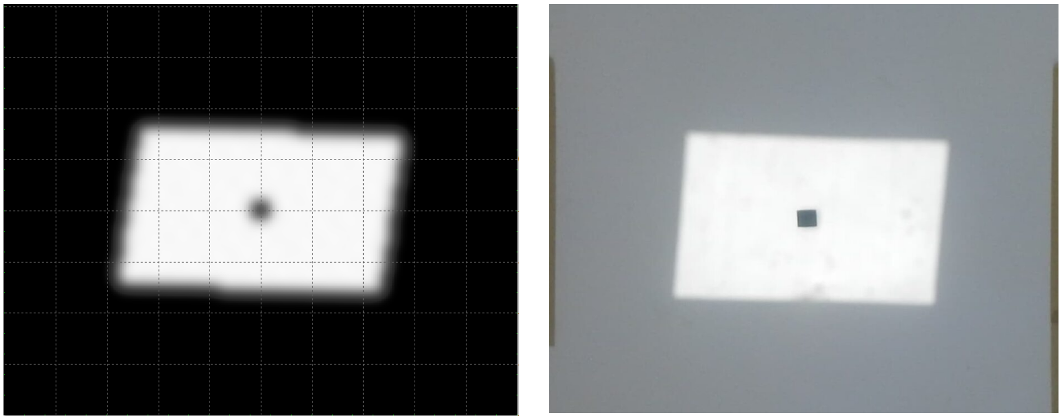
(a) **(b)**

Figure 5. Images obtained in both methodological processes for the same moment: (a) simulation in TracePro, and (b) physical experimental test.

Conclusions

This research materializes in the solid and credible validation of our approach through a consistent combination of simulation and physical experimentation. Valuable results have been obtained that allow us to understand the operation of the developed redirection algorithm and confirm its effectiveness. The surprising congruence between the simulation data and those obtained in the experimental test, with a significant 97.9% similarity as shown in the results section, validates the reliability of our approach and its ability to accurately capture expected behaviors. From this, it is inferred that the development of this algorithm contributes to the improvement of conventional systems such as those of Carvajal since many initial parameters are not needed in the map calibration mode (only the capture of the target vector R) and even less so in automatic mode. This leads to the elimination of redirection errors caused by the low resolution of the initial parameters and disparity in the reference systems.

Looking ahead, numerous opportunities for expanding and refining this study come into view. Firstly, there is an intention to enhance the resolution of the prototypes, specifically the solar tracker and the heliostat, to obtain more precise angle data at the tracker's output and allow for smoother movements in the heliostat. As a consequent step, the implementation of autonomous control of the heliostat is shaping up as a crucial second stage for future experimental tests. This expansion will enable the evaluation of the system's efficiency and adaptability in more challenging and dynamic situations, thus contributing to its robustness and applicability in diverse conditions.

Furthermore, it is imperative to shift the focus of simulation in future research. Instead of being limited to the validation of the redirection algorithm, the simulation could be redirected towards the precise quantification of the energy redirected by the field of heliostats. This would provide a more quantitative assessment of the system's performance and allow for even more rigorous optimization of its energy efficiency.

To conclude, there is a desire to transition from experimentation with a single heliostat to a full field of heliostats instead, as was done in this initial phase. This promises to provide a more comprehensive and applicable understanding of the interaction and coordination of multiple heliostats in a real-world setting. Consequently, this study is not only seen as a significant achievement but also as a solid foundation for more complex research and even deeper discoveries in the field of solar concentration technology and renewable energy.

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