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DESIGN AND EXPERIMENTAL IMPLEMENTATION OF AN AUTOMATED HELIOSTAT SYSTEM FOR SOLAR HEAT FOR INDUSTRIAL PROCESSES

Summary

The objective of this study is to improve the efficiency of solar thermal concentration through the design, automation, and experimental validation of a modular heliostat system. As a preliminary step to evaluate mirror geometries and field layout, a heliostat prototype with a 30 x 30 cm reflector was developed. A custom trigonometric control algorithm was established, utilizing a web interface for empirical data acquisition and manual calibration. Dynamic orientation data from an initial array of two heliostats were cross-validated with theoretical solar tracking data (NREL) and optical ray tracing simulations in TracePro. The preliminary vector analysis closely tracked the target alignment, identifying time-varying mechanical deviations at the center of rotation, thereby providing a fundamental framework for optimizing the future geometry of the heliostats and the accuracy of the structural tracking.

Keywords: Concentrated Solar Power (CSP), Heliostat Field, Simulation, Experimental Validation, SHIP

Field of application for the findings: 03. Sustainable Heat for Industrial Process

Addressed audience: Academic researchers and R&D engineers interested in the evolution of renewable energy technologies

1. Introduction

Globally increasing energy demand, driven by population growth and the urgency to mitigate greenhouse gas emissions, has positioned concentrated solar power (CSP) as a viable and sustainable technological alternative. Within these systems, heliostat are critical components whose function is to capture and precisely direct incident solar radiation toward a central receiver [1].

This sustainable approach is increasingly applied through Solar Heat for Industrial Processes (SHIP), a sector that reached a global thermal capacity of over 1 GWth by the end of 2024. As analyzed by Marzouk (2024) [2], while the current market is largely dominated by parabolic trough collectors, there is an anticipated shift toward more complex designs, such as solar power towers (SPTs). These systems rely on two-axis solar tracking and point-focused concentration to meet high-temperature industrial demands, a trend expected to align with large-scale deployment by 2026. Consequently, optimizing heliostat field efficiency and automation becomes essential for the continued expansion of high-temperature SHIP applications.

In light of this, this paper is structured as follows: first, the methodology for data acquisition and validation. Second, a mathematical and trigonometric control algorithm is established for tracking processing. Third, the system's performance is validated through experimental tests, culminating in an analysis of the results obtained.

2. Methodolgy

Autonomous heliostats employ continuous solar tracking data to achieve real-time dynamic realignment, ensuring consistent focal precision. Conversely, in manually calibrated heliostats, the mirror orientation requires iterative adjustments to maximize optical interception at the receiver. Two distinct methodologies are planned for data acquisition and validation. In the first empirical model, elevation and azimuth parameters are manually input into the actuator controllers via a local web interface, which is initialized by each heliostat at startup. This aligns the reflected beam with a static target, logging the precise angular coordinates required to maintain target interception over time.

The dataset derived from manual calibration is validated against solar ephemeris data provided by the National Renewable Energy Laboratory (NREL) [3]. By applying solar tracking geometry, the theoretical coordinates are transformed to align with the experimental reference frame. A comparative analysis is subsequently conducted in MATLAB to quantify the relative error between the empirical measurements and the calculated theoretical values.

For the second methodology, a computational simulation of the physical field is executed. Initial boundary conditions corresponding to the actual heliostat array are configured within a Python environment. Subsequently, TracePro software is utilized to conduct a rigorous ray-tracing analysis, allowing for the observation of optical behavior and the evaluation of deviations from the experimentally acquired data.

3. Algorithm design

Manual calibration is performed by orienting the heliostat toward a fixed target via a web-based interface. During this process, the system records the heliostats azimuth and elevation angles required to reflect the solar beam, along with the corresponding timestamps. This angular data defines the normal vector ($\hat{\mathbf{N}}$) of the heliostat surface, which in turn determines the direction of the reflected vector ($\hat{\mathbf{R}}$), representing the redirection of the incident solar vector ($\hat{\mathbf{S}}$) toward the target, as shown in Fig. 1. The vector ($\hat{\mathbf{R}}$) is assumed to be invariant, as

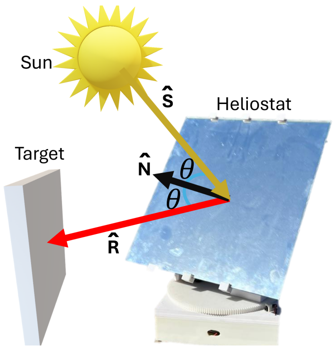


Fig. 1: Heliostat prototype and associated vector system.

the target remains stationary in a fixed reference frame. Consequently, the only time-varying components are the solar vector ($\hat{\mathbf{S}}$) and the heliostats surface normal vector ($\hat{\mathbf{N}}$). Based on the manually collected samples, the instantaneous normal vector ($\hat{\mathbf{N}}$) can be derived. Concurrently, the solar vector ($\hat{\mathbf{S}}$) is retrieved from the NREL solar position algorithms for the exact timestamps associated with each measurement of ($\hat{\mathbf{N}}$). Finally, a reflected vector $\vec{\mathbf{R}}_{\mathbf{0}}$ can be determined according to the law of reflection as defined in Equation 1, and afterwards the directional unit vector $\hat{\mathbf{R}}$ is calculated with Equation 2.

$$\vec{R}_0 = 2(\hat{N} \cdot (-\hat{S}))\hat{N} + \hat{S} \tag{1}$$

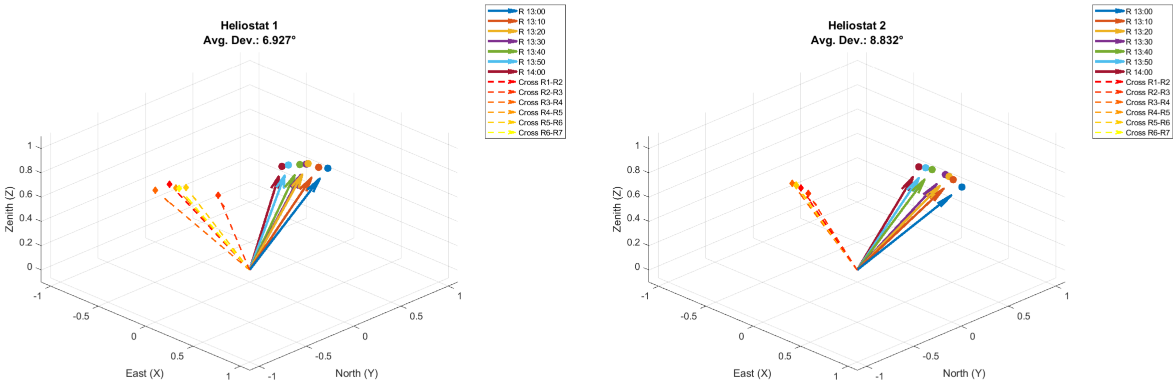
$$\hat{R} = \frac{\vec{R}_0}{|\vec{R}_0|} \tag{2}$$

4. Experimentation

Experimental tests were carried out with the heliostat prototypes on March 13, 2026, in the municipality of San Nicolás de los Garza, Nuevo León. The test began at 13:00 hours with a sampling frequency of 10 minutes over a one-hour period. It is worth noting that, at this initial stage of the study, the heliostat were operated electronically (in a non-autonomous manner) through a web interface. Throughout the experimentation, the rotation and inclination angles of each heliostat (γ_h, α_h) were recorded at every time step. Using this data, a vector calculation was performed in MATLAB by inputting the real variables required by the vector calculation algorithm in order to verify its operation and feasibility, as shown in Table 1 and its graphical representation of the Fig. 2.

Tab. 1: Tracking analysis for Heliostats

		Heliostat 1				Heliostat 2			
Vector	**Time**	**X**	**Y**	**Z**	**Dev. (°)**	**X**	**Y**	**Z**	**Dev. (°)**
$R(1)$	13:00	-0.0001	0.8244	0.5660	13.81	0.3186	0.7866	0.5289	15.20
$R(2)$	13:10	-0.1119	0.8390	0.5326	7.23	0.1995	0.8167	0.5415	8.12
$R(3)$	13:20	-0.2000	0.8184	0.5388	2.33	0.1487	0.8229	0.5483	5.20
$R(4)$	13:30	-0.2205	0.8203	0.5277	0.99	0.1011	0.8323	0.5451	2.41
$R(5)$	13:40	-0.2852	0.8139	0.5062	2.96	-0.0528	0.8447	0.5327	6.47
$R(6)$	13:50	-0.3811	0.7916	0.4775	8.83	-0.1189	0.8436	0.5237	10.30
$R(7)$	14:00	-0.4362	0.7765	0.4548	12.35	-0.1846	0.8388	0.5122	14.13
Target Vector $\hat{R}$:		-0.2361	0.8207	0.5203		0.0597	0.8388	0.5411	
Avg. Angular Dev.:			—		**6.93°**		—		**8.83°**



(a) Heliostat 1.

(b) Heliostat 2.

Fig. 2: Time evolution of the computed reflection vectors ($\hat{\mathbf{R}}$) for each heliostat

The algorithm also generates two three-dimensional plots (one for each heliostat) displaying each of the computed vectors. Since the target is a fixed element, the reflection vector ($\hat{\mathbf{R}}$) should ideally remain constant at every time step. However, upon analyzing the plots, a deviation was identified that varies over time. This observation suggests that the center of the mirror is not truly fixed; instead, it shifts as the heliostat's rotation and inclination angles are adjusted. Therefore, this physical displacement must be taken into account to analytically determine the theoretical heliostat positions at each instance of the experimentation. Additionally, future prototype designs could incorporate this consideration to enforce a fixed mirror center throughout the heliostat's motion.

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