Canting heliostats with computer vision and theoretical imaging
Alberto Sánchez-González * , Adrián Lozano-Cancelas, Rodrigo Morales-Sánchez, José Carlos Castillo
Universidad Carlos III de Madrid, Av. Universidad, 30, 28911, Leganés, Madrid, Spain

A R T I C L E   I N F O

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A B S T R A C T

Solar Power Tower technology requires accurate techniques to ensure the optical performance of the heliostats both in commissioning and operation phases. This paper presents a technique based on target reflection to detect and correct canting errors in heliostat facets. A camera mounted on the back of a target heliostat sees an object heliostat and the target facets in reflection. The pixels difference between detected and theoretical distributions is analyzed to detect and correct canting errors in heliostat facets. A camera mounted on the back of a target heliostat sees an object heliostat and the target facets in reflection. The pixels difference between detected and theoretical distributions is analyzed to detect and correct canting errors in heliostat facets.

1. Introduction

Thousands of heliostats concentrate direct solar radiation onto a receiver in solar power tower plants (SPTP) [1]. Heliostats consist of an array of mirrors, called facets, slightly curved – focused – which must be appropriately oriented to concentrate sunlight in a receiver. The process of tilting each facet to aim at a single point is known as canting.

Proper heliostat canting maximizes the annual power intercepted by the receiver [2]. Off-axis canting at specific time instants seems to outperform on-axis canting (facets’ normal vectors intersect at the target when sun, target and heliostat center are aligned) [3]. Uncanted heliostats result into distorted flux distributions [4] with larger spot sizes, leading to increased spillage losses. According to Landman and Gauché [5], misaligned facets also increase astigmatic aberrations, which take place under defocus and high incidence angles [6].

The canting process must be performed both on heliostat field commissioning and throughout its lifetime to ensure an optimized operation of SPTP. In a recent report, issues related with the heliostat optical quality has been identified as one with the largest number of occurrences [7].

Several methods for heliostat facet canting have been developed, which are classified into three groups [8,9]: on-sun, mechanical, and optical. In on-sun alignment, the sun-reflected beam shape on the target is utilized to adjust the misaligned facets while the heliostat is in horizontal position. In these methods, commonly utilized in SPTP, the facets are manually adjusted to the pre-calculated angles in both axes, reaching canting errors below 1.5 mrad with careful measurements [8]. However, these processes are labor intensive, tedious and imprecise because of gravity sag and local slope errors [11].

In the optical category, seven methods can be identified: laser-based, backward gazing, flux map fitting, photogrammetry, deflectometry, camera look-back, and target reflection. In laser-based techniques, the heliostat facets reflect a collimated laser beam into the target. These techniques are very accurate but complex, they also require expensive equipment and are time-consuming [8].

The backward gazing method sees the sun image through its reflection on the heliostat. A mathematical procedure infers the local slope and canting errors [12,13].

The flux map fitting method utilizes a series of spot images in the target that is compared with computer-generated distributions. Canting deviations are quantified by fitting the synthetic distributions to the actual ones [14,15].

Photogrammetry methods infer the shape, size, and orientation of the facets from a series of images of the heliostat. In combination with edge detection, photogrammetry detects misaligned facets. Experiments showed around 1.6 mrad uncertainty [16], which is not enough to ensure heliostats optical quality. By increasing the number of cameras and target marks, a higher accuracy can be achieved, at the expense of greater complexity [7].

* Corresponding author.
E-mail address: asgonzal@ing.uc3m.es (A. Sánchez-González).

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In deflectometry, a fringe pattern reflected by the facets is viewed by a camera. The surface normal at each point in the mirror is then calculated, so that this technique can be used both for slope and canting characterization [17]. Precision below 0.25 mrad has been reached with the AIMFAST implementation [18]. Because of the complex experimental setup, this technique is currently reliable only in laboratory (or production line) environments, rather than in situ.

Camera look-back methods rely on the self reflection of the camera on the facets to detect canting errors. This technique is time-consuming and depends on the precision of the heliostat encoders [19].

Target reflection methods view the reflection of a known target on the heliostat facets [10]. The specific canting errors are computed by the pixels difference between actual and theoretical images. Depending on the position of the camera, Sandia National Laboratories proposed two implementations: in HFACET the camera is placed atop the tower [10], while in UFACET the camera is mounted on a drone [20]. In both cases, a neighboring heliostat is used as the target. Alternatively, the SPTP tower has been recently proposed as the target [21].

A preliminary study showed that confidence in the position of the camera is a key point in target reflection methods [22]. A camera position uncertainty in the order of 10 cm provokes a noticeable shift of the target-reflected image, undermining the comparison between real and theoretical images. For unmanned aerial systems, its position uncertainty might be an issue. On the other hand, if the camera is placed far from the object heliostat – e.g., atop the receiver tower –, very large zoom lenses are required to keep a high image resolution.

The present work proposes a new implementation based on the target reflection method that overcomes the drawbacks above. The camera is attached to a neighboring heliostat, used as target. This way, the camera position can be accurately measured using the heliostat itself as the reference. Moreover, the proposed method only requires neither expensive equipment nor extensive resources. The process is less time consuming (camera attachment and computation are fast) and can be performed by a single person.

This paper presents in detail the proposed methodology to detect canting errors in heliostat facets. Section 2 introduces the method and describes the underlying steps. To evaluate the performance of the technique, the manuscript offers extensive experiments both at lab-scale and in real heliostats. Section 3 presents the lab-scale testbed along with results on the technique’s accuracy. The experimental campaign carried out at a real SPTP, Plataforma Solar de Almería, is presented in Section 4. The manuscript ends up in Section 5 with the conclusions and the challenges addressed.

2. Method for canting heliostat facets

The proposed method uses a camera mounted on the back construction of a heliostat utilized as a target, pointing the camera toward an object heliostat (see Fig. 1). With both heliostats in vertical position, the camera views an object facet (or a set of object facets) as well as the target heliostat’s ones reflected. A theoretical camera model determines the ideal reflection of the target facet [22]. Then, it quantifies canting errors by comparing the camera image to the theoretical model. The method overcomes drawbacks from previous target reflection systems, such as camera location uncertainty and the use of long focal lenses, by mounting the high-resolution camera on the rear structure of a target heliostat, close to the object one.

To determine the canting errors of a heliostat facet, the technique follows seven steps1 (Fig. 2) divided into two main phases. The first phase consists of preprocessing the input image as well as measuring and estimating a series of features. In the second phase, those features are input into the modules that calculate the actual and ideal position of the reflected facet, which lead to the canting error calculation.

2.1. Extracting images data

This section includes the low-level steps that comprise the calculation of all of the necessary data used by the border detection and the theoretical model to calculate canting errors in Section 2.2. These processes correspond to steps 1–4 in Fig. 2.

The first step consists in the acquisition of images with a high-resolution camera mounted on the back of the target facet. The method requires two images from the object mirror: one focused on the mirror itself (see Fig. 3(a)), and the other focused on the reflection (see Fig. 3(b)). Both images must be taken with the same settings, such as position, orientation, and focal length of the camera, as well as the same positions of the mirrors.

The next step is the removal of distortions caused by the camera lens, provoking that straight lines appear curved in the images. The method rectifies these radial and tangential aberrations using computer vision algorithms. It uses a chessboard-like pattern with high contrast as a calibration reference. The distortion parameters are calculated using Matlab Camera Calibrator utility [23]. These distortion parameters are calculated from several images from different positions but the same camera focal length and focus distance.

Then, the system extracts the camera focal length from the image metadata and applies the appropriate distortion parameters, obtained from the camera calibration utility, to correct radial and tangential distortions as shown in the equations below, where x and y represent the horizontal and vertical pixel locations, respectively. Eq. (1) corrects radial distortion, with coefficients $k_1$, $k_2$, and $k_3$, where $r = x^2 + y^2$. Eq. (2) corrects tangential distortions, where $p_1$ and $p_2$ are the lens distortion tangential coefficients.

$$
x_{radial} = x \cdot (1 + k_1 \cdot r^2 + k_2 \cdot r^4 + k_3 \cdot r^6)
$$

(1)

$$
y_{radial} = y \cdot (1 + k_1 \cdot r^2 + k_2 \cdot r^4 + k_3 \cdot r^6)
$$

(2)

Calculating the camera orientation is another important step in the system. The camera orientation is defined by the normal vector of the camera, that is obtained from simple vector operations.

At this step, the geometric data – specific to each experimental setup – is loaded, which consists of: mirror facet dimensions and focal distance (or curvature radius), relative position of the facets (object and target), and camera position. Given a camera vector position, its normal vector is CO, where O is the image center point. Using as reference point, P, center of the object mirror facet, the camera normal vector is computed as: CO = CP – OP.

Fig. 4 shows the OP vector defined by the mirror’s center (red target) and the image’s center (white target). The point P is calculated as of crossing the diagonals of the mirror, once the mirror corners have been manually selected in the undistorted image. Using photogrammetry, the method converts OP pixel distance into real-world measurements.

Camera focal length is the distance between the camera pinhole (optical center of the lens) and the camera sensor. However, the focal length of the camera fluctuates slightly when focusing on different distances, and the length extracted from the image metadata is imprecise. In order to keep the model consistent and accurate, the method needs to perform an estimation of the effective camera focal length ($f_e$), both when focused on the mirror ($f_{e,m}$) and the reflection ($f_{e,r}$).

To estimate the effective focal length when focusing on the mirror ($f_{e,m}$), the model searches focal lengths around the metadata one. As long as the dimensions of the mirror are known, $f_{e,m}$ is found when the mirror area by the model matches the actual area in the undistorted image.

The previous procedure cannot be used to estimate the focal length when focused on the reflection because the area of the reflection

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1 From now on, when mentioning steps 1–7 of the method, we will be referring to the indices shown in Fig. 2.
depends on the mirror curvature and its slope error. The optical magnification formula in Eq. (3) helps us in this regard [24]. This formula establishes the relation between the effective focal length \( f_e \) when the camera is focused on distance \( d \) and the camera focal length \( f_c \) when
focused on infinity.

\[ f_e = f_s(1 + \frac{f_c}{d - f_c}) \]  

(3)

The camera focal length \((f_c)\) can be solved from Eq. (3) for the previous case: camera focused on the mirror (\(f_{e,m}\) and \(d_m\) are known). With the resulting \(f_e\) and the distance to the reflection (\(d_r\)), the effective focal length when focused on the reflection \(f_{e,r}\) is solved from Eq. (3). This mathematical procedure is summarized in Eq. (4), where \(f_{e,r}\) is obtained from \(f_{e,m}\), \(d_m\) and \(d_r\).

\[ f_{e,r} = \frac{f_{e,m} \cdot d_m \cdot d_r}{d_m \cdot d_r + f_{e,m} \cdot d_r - f_{e,m} \cdot d_m} \]  

(4)

As an example, following the preceding procedure, the effective focal lengths, for the metadata 130 mm camera focal length in Fig. 3 images, are \(f_{e,m} = 128.5\) mm (Fig. 3(a)) and \(f_{e,r} = 127.6\) mm (Fig. 3(b)), respectively.

### 2.2. Canting error detection

This section shows the steps necessary to calculate the differences between the mirror reflection characterized in the images and the ideal reflection from the theoretical model.

To build the **ideal model**, the method uses all the information from previous steps: camera orientation (step 3) and focal length focused on the reflection (step 4), together with the geometric data. This model supposes an ideal canting of the facets (e.g., on-axis, equinox noon, parallelism) to build the theoretical image that the camera should capture in such ideal conditions.

The ideal model is based on the perspective projection model, often known as the pinhole camera model as proposed in [22]. To construct the theoretical images, the method projects the corners of the object mirror and the target-reflected mirror into the simulated camera sensor. The transformation from global to camera system of coordinates makes use of the camera normal vector (step 3) and the effective focal length (step 4). The determination of the reflection points in concave spherical mirrors, known as Alhazen’s problem, is solved with the mathematical formulation in [25]. Fig. 5 shows an example of a theoretical image generated by the model, with the blue polygon representing the object mirror edge and the yellow one the target-reflected edge shaded in gray.

Using the undistorted image (from step 2), the method uses a quasi-automatic technique for the **border detection** of the target-reflected mirror. This process may run in parallel to steps 3, 4 and 5 in Fig. 2.

For each edge of the reflection, the user creates a region of interest by drawing a bounding box around one of the edges (ROI) (see Fig. 6(a)). This is the last manual operation in the pipeline and does not need to be precise, but it must include the entire edge. The step results in a cropped image containing the edge (see Fig. 6(b)). Next, the edge extraction process performs a preprocessing of the ROI to reduce noise and isolate the edge candidate pixels. To lessen the influence of image noise, the procedure entails converting the region to grayscale and applying a Gaussian blur [26] (see Fig. 6(c)). The edge pixels are then isolated from the rest of the crop using an adaptive threshold, and the Canny edge detector [27], which uses a first-order derivative to find the edge local orientation, identifies pixels that are candidates for belonging to an edge (see Fig. 6(d)). The ROI preprocessing finishes by applying a morphological opening operator [28] to remove noisy pixels (see Fig. 6(e)).

The candidate pixels after the morphological filtering are then used to estimate the edge. The algorithm seeks out the straightest line that comes closest to the boundary. The filtered ROI is divided into regions or sub-ROIs (Fig. 7(a))². The approach creates a pseudo histogram for each of these sub-ROIs, calculating the number of white pixels per row as illustrated in Figs. 7(b) to 7(e) (see the left side of each subfigure). The row with the highest value in each pseudo-histogram corresponds to the line that best approximates that part of the edge. To join all of these lines, the method represents each one of them with a single point.

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1. For the sake of simplicity, Fig. 7 shows 4 sub-ROIs although in real cases, the number can be adjusted depending on the sensibility required. In our tests, the ROI is divided into 11 sub-ROIs.
In the example of the figure, the red line gives the $y$ coordinate of the point, while the middle point of each sub-ROI gives the $x$ coordinate (see Fig. 7(f)). For vertical edges the process is similar but switching rows with columns.

To approximate the ideal edge, the method divides the previous points from the sub-ROIs into two sets depending on whether they are to the left or to the right of the midpoint of the original ROI. Then, the method can use two different techniques to approximate the edge. The first one uses the points from each of the sub-ROIs from the previous phase to fit a linear regression model. In certain situations, facets with irregular deformations (due to faults in the mirror surface) might cause the edges to shift, lowering the precision of this procedure since it produces a line that accurately approximates the edges in the image but not in reality. If this happens, the method integrates a second approach that calculates the median for each set of points and, with the resultant two points, calculates the line that connect those points. Unlike linear regression, the estimated edges produce a less abrupt slope and a less irregular polygon, which better defines the facet true shape. Finally, if the deformations in the mirror do not allow an accurate edge detection, the user can manually label each edge in the image. After calculating all four edges, the method finds the intersection points of the lines to find the reflected mirror’s corners (see the green line in Fig. 8).

Comparing the observed borders (step 6) with the theoretical ones (step 5) it is possible to calculate the canting errors. Fig. 8 shows the detected borders (in green) and the ideal borders (in yellow) overlaid over the undistorted image focused on the reflection (step 2). In general terms, there is no canting error if both bounding boxes overlap, and the larger the difference, the greater the canting error. The figure
also shows the model’s edge of the object mirror (in blue), which corresponds to the actual mirror edge.

To calculate the canting error, a certain canting deviation in both axes (e.g. 1.0 mrad) is introduced in the model. Such canting deviation provokes a specific pixel shift of the reflection. As long as the proportionality principle applies [22], the pixel difference between the ideal and the detected borders in x and y directions is converted into angular canting errors. When the object mirror reflects the entire target, the center of its reflection is taken to compute the pixel difference between the theoretical and the actual images.

For instance, in the case shown in Fig. 8 (named as case 1 in the following section), the pixel difference of the detection (green) with respect to the ideal (yellow) in x and y directions is −52 (to the left) and 64 (downwards). On the other hand, a 1.0 mrad deviation causes a displacement of 29.64 pixels, according to the model. Therefore, applying proportionality, the resulting canting errors are \( \delta_x = -1.718 \) mrad and \( \delta_y = 2.136 \) mrad.

3. Experiments in the testbed

Before moving to a real facility, a series of experiments were conducted in a lab-scale testbed to verify the accuracy of the proposed technique. This section describes the testbed, the experimental methodology, and the results and conclusions reached from this phase of testing.

3.1. Testbed description

The experimental setup emulates two facets of two neighboring heliostats in a field. To reproduce field conditions, our installation comprises two structures, one has a square 1 \( \times \) 1 m mirror (object facet), while the other contains a metallic plate (target facet) of equal size with a camera mounted in the center (see Fig. 9). The object mirror is slightly curved with a curvature radius of 250 m, so that its focal distance is 125 m. In this setup, both facets must be aligned with zero elevation so that the object facet reflects the back of the target facet. This design is flexible, allowing for various camera positions and relative positions between the two structures. The goal is to be able to replicate a wide variety of real-world field conditions.

The testbed includes as acquisition device a Sony Alpha 7R II [29], a high-resolution camera with 42 Mpx resolution (5304 \( \times \) 7952 pixels) and a sensor size of 24 \( \times \) 35.9 mm that delivers a large number of pixels per unit of length in the focusing plane. A 70–200 mm zoom lens is included with this camera [30]. The testbed includes a 10 mW and 640 nm (red) laser to align the object and target facets and vary the degree of parallelism between them [31]. The micrometer screws [32] allow accurate adjustment of the mirror’s canting angle in the three axes after the facets have been aligned. To facilitate alignment, the mirror rests on a ball joint. These instruments and their location on the testbed are illustrated in Fig. 9. To level the camera, we use an inclinometer with 0.05° precision and 0.01° resolution. Finally, the distance between the mirror and the metallic plate is measured using a digital laser telemeter.

3.2. Methodology

To ensure parallelism between the object and the target facets, the testbed must be calibrated (i.e. aligned) for reference canting using the laser system. A small flat mirror affixed to the object mirror is the target of the laser positioned in the target facet (see Figs. 9 and 10). Both facets are parallel when the reflected beam collides with the laser’s aperture. Furthermore, the laser point impinging on the small flat mirror is used to measure the relative position between the two facets, which is critical to the technique’s success. The ball joint and three micrometer screws attached to the object facet construction allow controlled adjustment of the facet orientation in three axes. We can incorporate deviation angles of hundredths of a mrad in the current configuration because one turn (0.5 mm linear movement) equals a 1.11 mrad canting angle. It is possible to create specific canting deviations in this manner in order to test vision-based error correction techniques.

Using the laser calibration system, an initial canting condition is established. This reference (parallelism) case is \( \delta_x = \delta_y = 0 \) in terms of angular error. Starting from here, we can introduce controlled or random errors, uncanting the mirrors in one or both (x and y) axes. Then, the method finds the canting errors, also outputting the angles that the micrometer screws need to be turned to correct those errors. Based on the position and characteristics of the micrometer screws, one mrad canting error amounts to 0.45 mm of linear movement, equivalent to 0.9 screws turns. After that, the images are taken and evaluated again to check the correctness of the method.

3.3. Tests and results

We run different scenarios to test the accuracy of the method, varying both the relative distance between the structures and the canting errors. Table 1 shows the results of the previous methodology at the different distances and camera positions. The first column shows the experiment number, the second the distance between the testbed’s two structures, and the third the camera’s offset with respect to the target mirror’s center in the x-axis. The canting errors (mrad) after uncanting the mirror are shown in the column Uncanted, whereas the ones found after fixing the position of the object mirror are shown in the column Canted. In the last row are the average absolute values of these last errors.

As can be seen in the column Canted, the error stays below 0.36 mrad (\( \delta_x \), case 6), with a minimum error of −0.003 mrad (\( \delta_y \), case 1). The average errors obtained during experimentation are 0.158 and 0.151 mrad in x and y axes respectively. It is noticeable how the model is able to correct large errors (e.g. cases 4 and 6) and small ones (e.g. case 3), showing a bit of difficulty when dealing with very small errors such as \( \delta_x \) in case 5.

Since canting errors are measured as the pixel difference of the reflected target center between ideal model and image, Table 2 displays the positions of these pixels to demonstrate the model’s accuracy. First column refers to the same experiments as in Table 1, second and third columns correspond to the uncanted and canted values, respectively, and the fourth column shows the ideal positions of the centers. The last column offers the difference between the canted mirror and the
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Fig. 9. Testbed configuration. Object facet on the left, supporting the mirror (seen from the back). Target facet on the right, supporting the metallic plate, the camera and the laser.

Fig. 10. Configuration of the calibration laser.

Table 1
Testbed experimental results. Canting errors before and after correcting in experiments with different distances between object and target facet and distances between camera and target centers in x-axis. In last row absolute average values of errors after canting.

<table>
<thead>
<tr>
<th>Case</th>
<th>Distance [m]</th>
<th>Camera offset [m]</th>
<th>Canting error [mrad]</th>
<th>Uncanted</th>
<th>Canted</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.618</td>
<td>0</td>
<td>−1.718 2.136</td>
<td>−0.068</td>
<td>−0.003</td>
</tr>
<tr>
<td>2</td>
<td>9.610</td>
<td>0</td>
<td>−2.624 0.896</td>
<td>0.049</td>
<td>0.047</td>
</tr>
<tr>
<td>3</td>
<td>12.428</td>
<td>0</td>
<td>−0.814 −1.284</td>
<td>−0.225</td>
<td>−0.049</td>
</tr>
<tr>
<td>4</td>
<td>12.428</td>
<td>0</td>
<td>4.133 1.737</td>
<td>0.161</td>
<td>0.236</td>
</tr>
<tr>
<td>5</td>
<td>13.016</td>
<td>0</td>
<td>−0.197 0.553</td>
<td>0.177</td>
<td>0.069</td>
</tr>
<tr>
<td>6</td>
<td>13.016</td>
<td>0</td>
<td>1.993 −1.868</td>
<td>0.166</td>
<td>−0.294</td>
</tr>
<tr>
<td>7</td>
<td>13.016</td>
<td>−0.098</td>
<td>3.451 1.886</td>
<td>0.258</td>
<td>0.360</td>
</tr>
</tbody>
</table>

Absolute average 0.158 0.151

ideal model. In both axes, the average pixel difference is 6.86 pixels. Considering that the images used in the experiment were 7952 × 5304 pixels, it can be appreciated the level of accuracy that the model is able to achieve.

Fig. 11 shows a qualitative comparison before and after the canting process. These images correspond to case 6 in Tables 1 and 2. Although the canting error is small (less than 2 mrad), it is visible how the rectification of that error is correctly performed.

4. Experiments in a real solar plant

After verifying the performance of the method in the lab, a series of tests were conducted in a real-world facility to assess the effectiveness of our method in real conditions. This section contains a description of the test setting and the experiment methodology, together with the problems discovered, and the results achieved.
4.1. Test environment description

This series of experimental tests were carried out in Plataforma Solar de Almería (PSA), a facility of the Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), located in Tabernas (Almería, Spain). The PSA is the largest concentrating solar technology research, development and test center in Europe, and includes different facilities, each with a type of concentrating solar power technology.

Among these facilities, CESA-I is a 330 × 250 m south-facing solar field consisting of 300 heliostats distributed in 16 rows. Each heliostat has a total reflective surface of 39.6 m², distributed in 12 mirror facets. The receiver is placed atop a 80-m-high tower, and its maximum thermal power is 7 MW at a typical design irradiance of 950 W/m², achieving a peak flux of 3.3 MW/m². To assess the beam quality of the heliostats, an image acquisition system takes pictures of the flux distribution reflected by the white Lambertian target located at 34 m from the base of the tower.

Fig. 12 depicts a scheme of CESA-I field layout, highlighting the 5 focal distance groups in which heliostats are grouped. The two heliostats highlighted in black are the ones used during the experiments, with the target heliostat on the right and object heliostat on the left. They are located at 230.2 m from the tower and their mirror focal distance is 220 m. Each heliostat consists of 12 rectangular facets, as mentioned before, of 3015 × 1120 cm each, arranged in two columns of six facets (Fig. 13). The heliostat has a total dimension of 6932 × 6770 mm. In the tests, a letter and number are used to refer to the heliostat facets. The letter corresponds to the column where it is located, “f” and “r” (left and right) and a number from 1 to 6, with 1 being the highest facet and 6 the lowest.

4.2. Methodology

The methodology follows a similar process as in the testbed experiments: detecting the errors with the method, adjusting the facets to correct these errors, and testing again to check if the facets are correctly canted. During the experiments, the model was set for ideal canting at equinox noon (i.e., off-axis canting).

To attach the camera to the back structure of the target heliostat, a specific clamp with the camera mount was built. The attachment was performed manually, using a boom lift to get closer to the attachment points (except for the lower facets in row 6, see Fig. 13). The process of camera attachment and position measurement took around 5 min on average.

The camera was connected to a laptop computer (located at ground level) via a USB cable. The image acquisition was made from the computer, previewing the images on the screen. A custom hardware mechanism was built to remotely control the camera zoom and focus so that the two required images (focused on the object and the reflected target) could be remotely acquired. The computation of the canting errors is almost instantaneous; therefore, the majority of the time is spent on the manual attachment of the camera.

The tests performed at PSA can be organized into three states.

- **State 1** consisted in measuring the whole heliostat to detect the initial canting errors. Fig. 14(a) shows a qualitative example of the comparison between the reflected target (green) and the ideal model (yellow) in facet 5. Table 3 summarizes the errors found in the heliostat mirrors. In the next steps, a series of representative facets with great errors, i2, i5, i6 and i5, was selected to test the performance of the method in the next states.

- The next state (**state 2**) consisted on correcting the previous misalignment of the four selected facets. At this point there were two significant problems. The first one was caused by the bolt and nut arrangement to adjust the facet canting in each axis. With some basic maths, and knowing the pitch and the position of the nuts, it is easy to calculate the necessary nut turns needed to correct the error. However, the nuts were very tight and, sometimes, the facet would not move until the nut had turned halfway around and, therefore, it was impossible to guarantee an accurate movement of the facets. The second problem was the large slope errors present in the mirrors, mainly in the horizontal axis, because of its size and how the curvature of the mirror was created. Fig. 14(b) shows how the error in facet i5 decreases with respect to the previous state.

- The goal of **state 3**, was to eliminate or reduce the impact of previous issues. To do so, we implemented two solutions: (i) To remove the bolt and nuts uncertainty, a laser was attached next...
to the camera, pointing at the object heliostat, in such a way that the laser beam bounced back to the target heliostat. The displacement that the laser beam would have to make in the reflection for a certain turn of the facet was then measured. And (ii) to reduce slope error uncertainty, the camera was put in four distinct positions and measurements were taken in each of them. The average of the four values was then used to calculate the final canting error. Fig. 14(c) shows the final qualitative result in facet \( l_5 \) after reducing the canting errors.

Besides the two aforementioned issues, the method accuracy relies on the precise measurement of the heliostats’ orientation. Zero elevation and equal azimuth of both heliostats was ideally pursued in all the states, but slight tracking uncertainty did not ensure exact accuracy.

<table>
<thead>
<tr>
<th>Facet</th>
<th>( \delta_x ) [mrad]</th>
<th>( \delta_y ) [mrad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l_1 )</td>
<td>-1.50</td>
<td>-1.02</td>
</tr>
<tr>
<td>( l_2 )</td>
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<td>-5.44</td>
</tr>
<tr>
<td>( l_3 )</td>
<td>-1.96</td>
<td>-0.37</td>
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<tr>
<td>( l_4 )</td>
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<td>( l_5 )</td>
<td>-3.13</td>
<td>-2.07</td>
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<tr>
<td>( l_6 )</td>
<td>-0.39</td>
<td>-1.42</td>
</tr>
<tr>
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<td>0.96</td>
</tr>
<tr>
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<td>( r_6 )</td>
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</table>

Table 3

Initial canting errors (state 1) in the object heliostat. Highlighted facets \((l_2, l_5, l_6\) and \( r_5 \)) presented large errors and were selected to test the performance of the method in states 2 and 3.

To overcome such oscillation, an object facet with low enough canting error, namely \( r_6 \), was taken as reference, keeping it intact throughout states.

4.3. Tests and results

Table 4 shows the results of the canting errors in the three states for the four selected facets. The canting error of facet \( l_2 \) in \( y \)-axis was reduced from 5.44 mrad (the highest detected) to 1.52 mrad, after the first adjustment, and up to 0.21 mrad in the final state. In facet \( l_5 \), previously shown in Fig. 14, the canting errors were reduced in around 1 mrad in \( x \) and 2 mrad in \( y \). In facet \( r_6 \), \( \delta_x \) was decreased in about 1 mrad, while \( \delta_y \) was slightly increased from 0.39 to 0.74 mrad, even though there was no adjustment in the \( x \) nut. For facet \( r_5 \), originally with a high deviation in the \( x \)-axis, its canting error was reduced in 2.69 mrad. From the application of the canting methodology, it is worth mentioning that the final error in the four selected facets is below 1 mrad, being 0.76 mrad the largest one.

To check the impact of the canting adjustments on the flux distribution, heliostat images on the Lambertian white target were taken after each of the state tests. For proper comparison, images were taken at the same local time, 15:00, in successive days (i.e. states). Figs. 15(a), 15(b) and 15(c) show the experimental images for the three states. From the experimental images, contours of flux concentration were extracted as shown in Figs. 15(d), 15(e) and 15(f) (solid lines). These contours represent the normalized concentration ratio, from 1 (peak flux) to 0 (no flux) in steps of 0.1.
Fig. 14. Object facet 15 (blue border) reflecting its corresponding target facet. Comparison between the detected edge (green) and the ideal model (yellow) in the three states.

The experimental contours are compared with the theoretical ones, considering ideal canting at equinox noon. The ideal flux distributions were generated with SolTrace software [33] by tracing 100 million sun rays. For proper comparison, the actual solar position was taken at the three instants, and the heliostat aimpoint was retrieved from the experimental weighted centroid. The resulting ideal contours are plotted in dashed lines in Figs. 15(d), 15(e) and 15(f).

State 1 image (Fig. 15(a)) shows some deformations attributed to the misalignment of the facets. Such a slight deformity is evident in the comparison with SolTrace ideal contours (Fig. 15(d)). For instance, the experimental contour at the highest concentration ratio (0.9 level) is less rounded and encloses a larger area than the ideal contour level. After analyzing the results, the selected facets to be calibrated in the next steps were $l_2$, $l_5$, $l_6$ and $r_5$.

At state 2, after the first canting adjustment, the heliostat beam quality is slightly improved. From Fig. 15(e) can be seen that the number of borderline protuberances is reduced, as compared to state 1. However, the aforementioned issues (uncertainty on the nuts rotation and large slope errors in the mirrors) prevented from a better result. Those issues were tackled in the second canting adjustment, leading
to state 3. As a result, the flux distribution shows closer to the ideal one (Fig. 15(f)), even though a slight protuberance emerges in the right hand side, which is attributed to one of the facets not adjusted during the experiments.

Table 5 shows two metrics that quantify the heliostat beam quality in each of the states. The area of the spot provides an indicator of the optical concentration and, ultimately, the canting quality. The lowest concentration ratio (0.1 level) is taken as the outer boundary within which the area is calculated. Table 5 lists the areas of the experimental spot both in pixels² and m². At state 3, the spot area is decreased by 9% with respect to the initial state.

On the other hand, the comparison with the SolTrace’s ideal flux distribution can be quantified in terms of the Root Mean Square Error (RMSE). In general, the lower the RMSE is, the better is the match between experimental and theoretical flux maps. This figure of merit is shown in the last column of Table 5. At the final state, the RMSE is decreased by almost half compared to the original state.
The highest detected canting error, $\delta$, is around 0.15 mrad.

Minimum errors below 0.05 mrad. On average, the final canting error obtained results confirm the accuracy of the method. The peak error in a specifically tailored testbed, and in a real SPTP. In both scenarios, only the zoom. In reality, changing the focus also changes the focal distortions in raw images. Then, it obtains an exact measurement of the target heliostat after bouncing on the object facet and made sure that displacement coincided with the desired one.

Finally, the mirrors in the real field, PSA, showed a large slope error, uneven along the surface. Facets with irregular deformations (due to faults in the mirror surface) might cause the edges to shift, lowering the precision of this procedure since it produces a line that accurately approximates the edges in the image but not in reality. Also, this caused that the measurements of the canting errors varied depending on the camera position. Since obtaining an optimal camera position was not possible, the option taken was to perform different measurements on each facet (four per canted facet) and to average the error results. The bolts and nuts problem and this slope one were the main additions between State 2 and State 3 in our field tests, showing a reduction in the canting errors.

The operation time in PSA experiments was around 5 min per facet if a single measurement, and around 15 min when taking four measurements per facet. Since the algorithm is fully automated, most of the time is mainly devoted to manual tasks: boom lift operation, camera attachment and position measurement. Thanks to the custom-made camera control system, plenty of time has been saved in the adjustment of the camera zoom and focus, which is made remotely. The remaining manual tasks still have potential to be automated, for instance integrating the hardware into a robotic platform.

### 5.1. Lessons learned

During the extensive experimental phase, we faced a number of challenges arising from the peculiarities of both our hardware and the elements we were interacting with. First, using commercial optics for the camera is a good choice in terms of quality and cost, but in contrast, some of the metadata provided was not accurate enough. In particular, the focal length provided by the metadata only varied in integer numbers and did not take into account the focus of the lens, only the zoom. In reality, changing the focus also changes the focal length and obtaining that parameter accurately is important for our method. For this reason, the pipeline includes a specific step for refining the camera focal length.

The system was also adapted to consider the characteristics of the bolts and nuts on the facets for canting. Thus, given a certain error, the method calculates the amount of rotation to be performed on the nuts in order to achieve the ideal canting. Nevertheless, the tightness in the nuts causes not completely accurate turns when exerting force at first and, therefore, the final displacement of the facet is not exactly the target one. To overcome this limitation, we attached a laser next to the camera and also measured the movement of the beam on the target heliostat after bouncing on the object facet and made sure that displacement coincided with the desired one.

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References


