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A Two-Stage Method for Measuring the Heliostat Offset

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Abstract. The conventional method of initial heliostat calibration by sequentially pointing the heliostats one by one onto a target is a very slow process. The use of unmanned airborne vehicles (UAVs) is a possible approach to developing a less time consuming procedure for the initial setup of the field control system and elimination of offset in light beam pointing. This paper presents a UAV based method for measuring the heliostat offset in two stages. The first stage, preliminary and less accurate, creates a three-dimensional model of the mirror facet corners in order to estimate the heliostat orientation. The estimated orientation from the first stage is a prerequisite for the second stage of measurement, in which the highly accurate heliostat orientation is derived from deflectometrically measuring the mirror shape. While work is still ongoing to fully implement the final steps of the second stage, the measuring principles has been demonstrated and partially validated for the first stage.

INTRODUCTION

Power tower or central receiver systems use hundreds to ten thousands of two-axis tracking mirrors, so called heliostats, which reflect and focus the sunlight onto a receiver on top of a tower during the day. After the construction phase, the initial setup of the heliostat field controls and elimination of offsets in light beam pointing can take various months before the plant is able to operate at full capacity. A fast ramp-up to nominal production values is an important factor in achieving low costs of electricity.

The classic approach for heliostat calibration is to focus them for different sun angles sequentially to a white target to measure the deviation between set point and aimpoint. As this procedure depends on the sun position and availability of a target, this sequential procedure takes too long for industrial-sized plants.

In this work, a new UAV (unmanned aerial vehicle) based method is outlined which allows the characterization of the heliostats' offset within days and without any requirement of having completed the construction of the central tower. Segments of the solar field can be calibrated as and when their control system becomes operational. This may result in power plants reaching their maximum performance months earlier than they would with conventional calibration methods.

Several research groups and industry have been tackling the topic of heliostat calibration. An overview of former calibration techniques and recent developments is given in Sattler et al. [1]. In the last years, the use of UAVs for this task has emerged and several R&D activities have been launched. In 2017, DLR started the HelioPoint project, pursuing a two-stage method for calibration, with a photogrammetric approach as the first step and deflectometric approach as a second step. NREL and Stellenbosch University also suggest deflectometric approaches. Whereas NREL uses the reflection of the tower edge [2], Stellenbosch uses the reflection of a target [3]. This paper presents the two-stage method suggested by DLR.

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TWO-STAGE METHOD FOR HELIOSTAT CHARACTERIZATION

The method presented here is divided in two separate measuring stages where the second stage depends on the completion of the first as outlined in figure 1 (left side). For full characterization of a heliostat the workflow described here needs to be carried out multiple times for varying heliostat orientations.

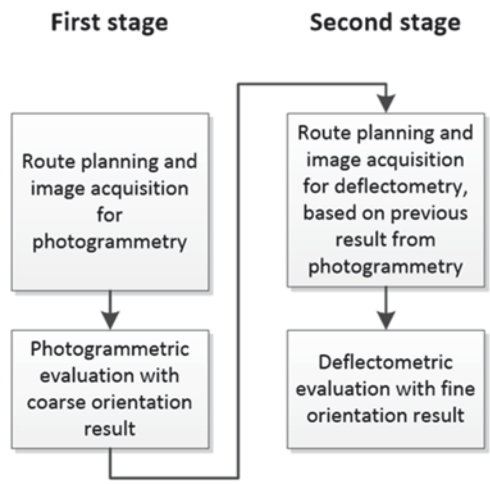

FIGURE 1. Left: The simplified overall process for measuring the heliostat position

The first stage of the process is the initial preliminary coarse measurement for which the heliostat orientation is determined by photogrammetric methods. Heliostat features such as mirror corners are recognizable for machine vision techniques and are used as reference points for calculation of the heliostats' orientation. This rough measurement is required as the basis for planning the flight routes and camera positions for the second stage of measurement, which uses deflectometry to achieve a higher accuracy for the initial characterization of the heliostat offset in the solar field. If a rough characterization of better than 10 mrad uncertainty is already available for the respective heliostats, it is possible to skip the first stage and start directly with the deflectometric measurement.

PHOTOGRAMMETRIC COARSE MEASUREMENT

This approach builds on methods used in Prahl et al. [4], where the underground contrasts strongly against the sky's reflection on the mirror surface and facet edges thus become detectable. The individual facet corners, here called features, are used as photogrammetric reference points. Thus, the key necessity is to identify each feature in images from multiple viewing angles as varied as possible and detect its accurate pixel location within the images. The involved steps in this stage are roughly outlined in Fig. 2. Flight routes were chosen in circular shape around various points of interest in order to have a relatively even coverage of the area while assuring a wide range of viewing angles. Once the images are obtained, the camera position needs to be determined in order to detect and identify correctly all heliostats and features within an image. Once the visible features in each image have been located and identified, the accurate 3d-setup can be determined via commercially available photogrammetry software. As a final step, the heliostat normal vector is determined by fitting the ideal heliostat geometry onto the measured 3d-model.

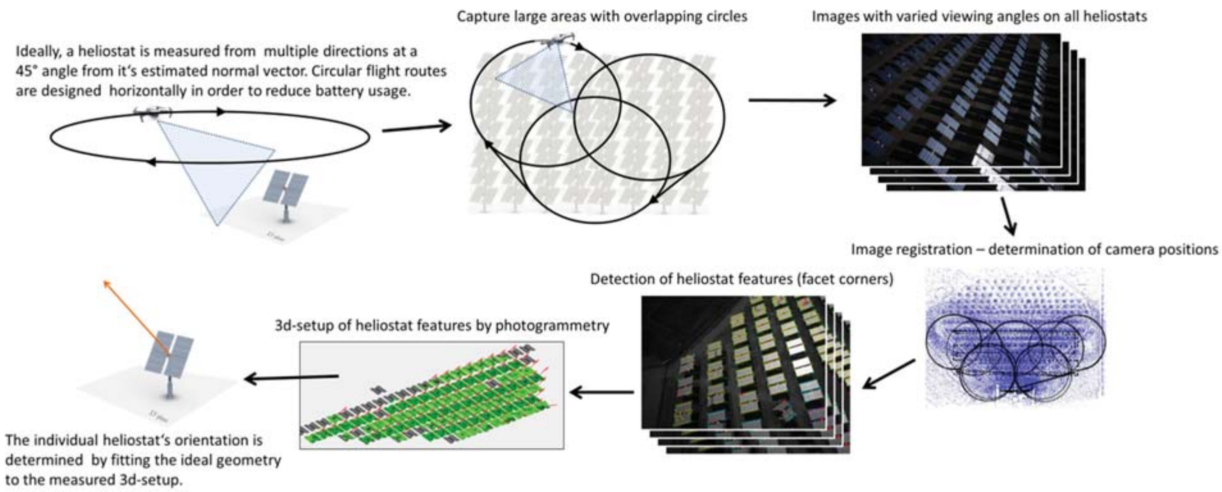

FIGURE 2. The photogrammetric first stage of measurement. The exemplary images were taken at the PSA (Plataforma Solar de Almería) owned by the Spanish CIEMAT

A first validation campaign for this stage of measurement was carried out at the end of 2018. Three samples of reference data were obtained using the traditional method of measuring the flux spot centroid on the calibration target and knowing the sun position. The left side of Fig. 3 displays the 3d-model of the heliostat field obtained from the photogrammetric measurement. Measured features are plotted as green dots. The resulting normal vectors are plotted as red arrows. While the all other heliostats were oriented with 180° azimuth and 60° elevation, the orientation of the three heliostats used for the validation measurement (marked in yellow) differ notably from rest of the field since they had to reflect light beams onto the calibration target. The right side of Fig. 3 presents the corresponding uncertainties of the measured 3d-coordinates displayed on the left side. The histogram shows that the 1 sigma uncertainties for two third of all obtained 3d-coordinates are below 5 mm and is below 10 mm for approximately 90 percent of all 3d-coordinates. The mean sigma of all 3d-coordinates is 6.35 mm. Table 1 presents the validation result as concentrator normal vector deviations between the UAV-based measurement and the reference. A root mean square deviation of 5.9 mrad was calculated from these values.

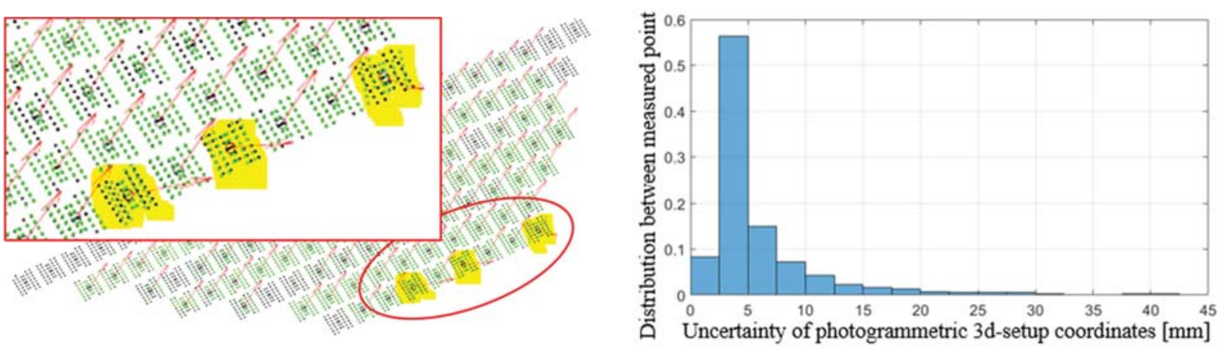

FIGURE 3. Left: Measured 3d-model and concentrator normal vectors in the first test arrangement for the photogrammetric step. The measured normal vectors are red; black dots indicate the assumed location of features for the initial preset model of heliostat orientation; green dots are features whose 3d-coordinates were successfully measured. The three reference heliostats in the first row are indicated by a yellow background. Right: Estimated uncertainties of the photogrammetrically determined 3d-coordinates (green dots on the left side).

TABLE 1. Concentrator vector deviation of the photogrammetric coarse measurement from the reference data obtained by the flux spot centroid based method

Heliostat	Deviation of concentrator normal vector [mrad]	Azimuth deviation [mrad]	Elevation deviation [mrad]
#1	6.2	-7.3	-1.2
#2	4.2	4.7	1.6
#3	6.9	7.3	-3.0

DEFLECTOMETRIC MEASUREMENT

After completion of the photogrammetric coarse measuring process and once the heliostat controls have been adjusted to the rough offset, it becomes feasible to carry out the deflectometric stage of measurement as initially described in [5]. The UAV is equipped with mounted LED light sources which serve as a deflectometric target. Figure 4 describes the process of using this setup to measure local normal vectors on the mirror surface. The goal is to obtain a detailed profile of the heliostat shape by measuring at various points distributed over its surface. The overall orientation of the heliostat can then be determined by intelligent weighting of the sampled normal vectors. The measuring principle as presented in Fig. 4 begins with the positioning of the UAV near the previously roughly determined normal vector of the heliostat.

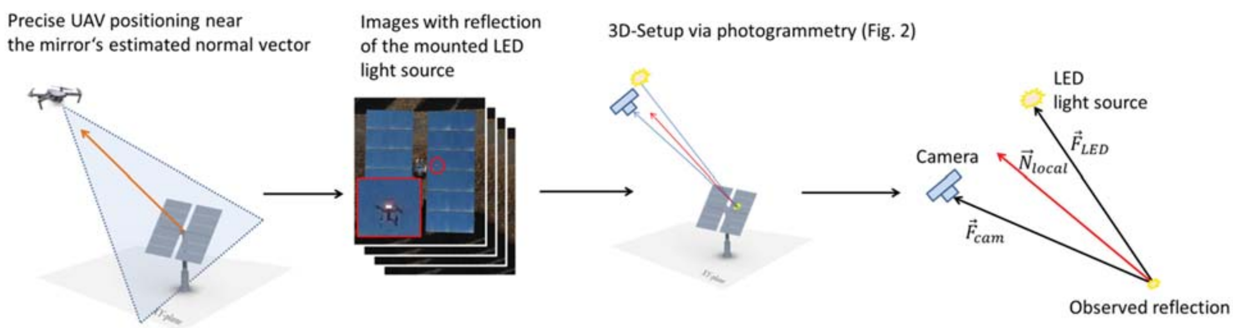

FIGURE 4. Deflectometric measuring principle. The local normal vector can be derived from the 3d-setup of camera position, light source position and the point where the reflection is observed on the surface of the mirror. The exemplary image was taken at the PSA owned by the Spanish CIEMAT.

The UAV positions for image acquisition need to cover a sufficiently fine grid in a wide enough area perpendicular to the estimated normal vector in order to obtain images with UAV reflections in different parts of the mirror surface where the camera sees its own reflection as well as the attached LED as in Fig. 5. The size of the area to be scanned depends on the accuracy of the results of the first photogrammetric step, the distance from the heliostat surface, the focal length, the expected heliostat slope errors, and the GPS based positioning of the UAV during the flight, for example. The grid to be scanned inside the area has to be defined sufficiently dense to produce sufficient LED reflections on the individual heliostat facets. Several adjoining heliostats can be oriented in a way, so that the areas the drone has to be placed coincide. Like that, in one image, we can capture LED reflections of several heliostats in parallel.

By application of photogrammetry, the 3d-setup of camera position, light source position as well as the location of the observed reflection on the mirror can be obtained. The local normal vector $\vec{N}_{local}$ at the point where the reflection is observed is the angular bisector

$$\vec{N}_{local} = \left| \left(\frac{\vec{F}_{LED}}{|\vec{F}_{LED}|} + \frac{\vec{F}_{cam}}{|\vec{F}_{cam}|} \right) \; / \; 2 \right| , \tag{1}$$

where $\vec{F}_{LED}$ is the vector between the observed reflection on the mirror surface and the respective light source and $\vec{F}_{cam}$ is the vector between the observed reflection and the camera lens (Fig. 4). In order to obtain the overall orientation of the heliostat, the mirror surface needs to be scanned with sufficiently dense and sufficiently even distributed local normal vectors.

As mentioned above, the UAV positioning and image acquisition has its own complexity due to diverging objectives required for a successful measurement. Under ideal theoretical circumstances, camera positions at distances near twice of an ideal heliostat's focal length would obtain images with UAV reflections in all facets of the same heliostat. Similarly, at such distances, it is conceivable to measure large groups of heliostats simultaneously. Another argument for using the largest possible distances between camera and the observed reflection on the heliostat (Fig. 4) is the mitigation of error propagation from in the photogrammetrically determined camera position to the local normal vector $\vec{N}_{local}$ during the final evaluation.

However, with increasing distances (being still below twice the focal length), the requirement for exact UAV positioning on the heliostat's normal vector becomes more challenging, since the area in which a camera would see its own reflection becomes continuously smaller. Furthermore, the assumed heliostat normal vector at this point of the measuring process can rather be described as a cone with a widening angle determined by the vector's uncertainty. In summary, at large distances, it is thus required to obtain images from a smaller area whose exact location is uncertain and only known to be within an estimated much larger area defined by the widening cone. Therefore, with increasing distance, it is required to cover the larger estimated area with an increasingly fine grid of UAV positions from which pictures are taken. A third aspect to be considered in this context is the relatively large inaccuracy of the UAV's GPS (Global Positioning System). For the current proof of concept stage of this measuring technique it was therefore chosen to measure at relatively shorter distances below twice the focal length of approximately 20 to 40 meters where the complexities of image acquisition are reduced at the cost of increasing the error in the obtained local normal vectors $\vec{N}_{local}$. The overarching long-term goal is to progressively increase the measuring distance and to achieve simultaneous measurement of larger clusters of heliostats.

Figure 5 shows examples of different setups and prototypes which are being tested. The common characteristic between these different prototypes are the mounted LED light sources at a known distance from the camera. These light spots are then detected and distinguished by their colors which allows measuring multiple $\vec{N}_{local}$ at once. On the left side of Fig. 5 three separate LEDs in different colors were used. The consumer level UAV in the middle image has a single much brighter light source which is part of its standard equipment provided by the manufacturer. On the right side multiple heliostats were measured simultaneously using two LEDs in red and green. The latter simultaneous measurement of multiple heliostats is a much more efficient mode of operation and intended as the standard approach during the UAV based field calibration.

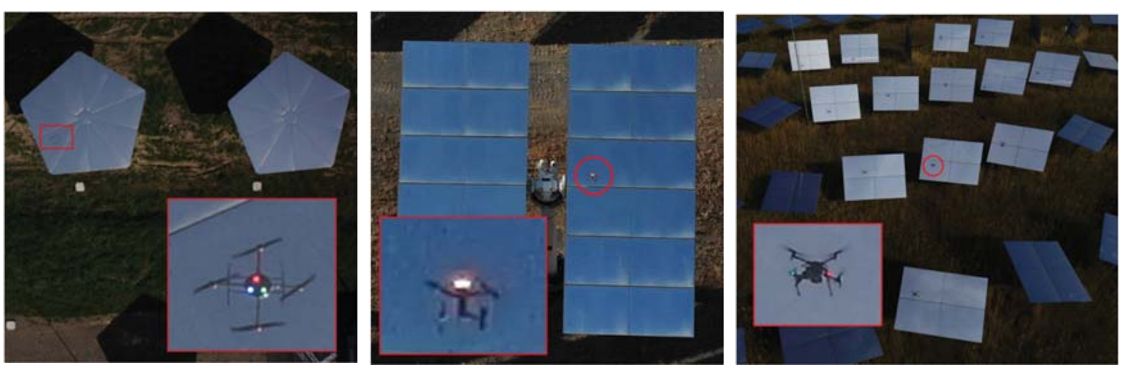

FIGURE 5. Left: First successful proof of concept (in Jülich, Germany). The reference targets are red, green and blue LEDs arranged around the camera. Middle: Tests with a consumer drone with a single mounted light source at the PSA (owned by CIEMAT, Spain). Right: Simultaneous measurement of multiple heliostats with two LEDs in red and green (in Jülich, Germany).

CONCLUSIONS AND OUTLOOK

The overall measuring process has been implemented and first campaigns have been carried out for testing. The photogrammetric first stage of measurement was fully implemented and was validated with a root mean square deviation of 5.9 mrad from three samples of reference data. A more detailed validation with recent and larger data sets is currently being worked on. The past measuring campaigns revealed, that for larger fields the after-flight processing time becomes critical and further optimizations of code and workflow are needed. For the deflectometric second stage, the last step of calculating the heliostat vector by intelligent weighting of sampled local normal vectors is to be implemented and validated in the near future. Furthermore, the concept for the parallel measurement of several heliostats in a cluster has to be refined.

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