From Research to Industry: Development of a High-Resolution Measurement System for Mirrored Heliostats in Series Production

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Abstract. A new measurement system able to measure the shape accuracy of complete mirrored heliostat modules in series production was developed. The applied deflectometry measurement method is based on the reflection of regular patterns in the mirror surface and their distortions due to mirror surface deviations. The measurement system's key features are its high spatial resolution, its low global measurement uncertainty of less than 0.2 mrad and its total measurement and evaluation time of few minutes. The measurement process is contact-free and completely automatic, which allows a 100% optical quality control of the production of the heliostat modules for a typical solar tower power plant. The system is validated by measuring a flat reference surface and by comparison to manual photogrammetry measurements. This makes the new measurement system, called QDec-M-Helio, a valuable tool for final geometric quality control of heliostats in series production, especially for new generation heliostats which obtain its final curvature during a bonding process between mirror and support structure from a precise jig.

Keywords: Heliostat, shape accuracy, optical quality, quality control, optical measurement, deflectometry.

INTRODUCTION

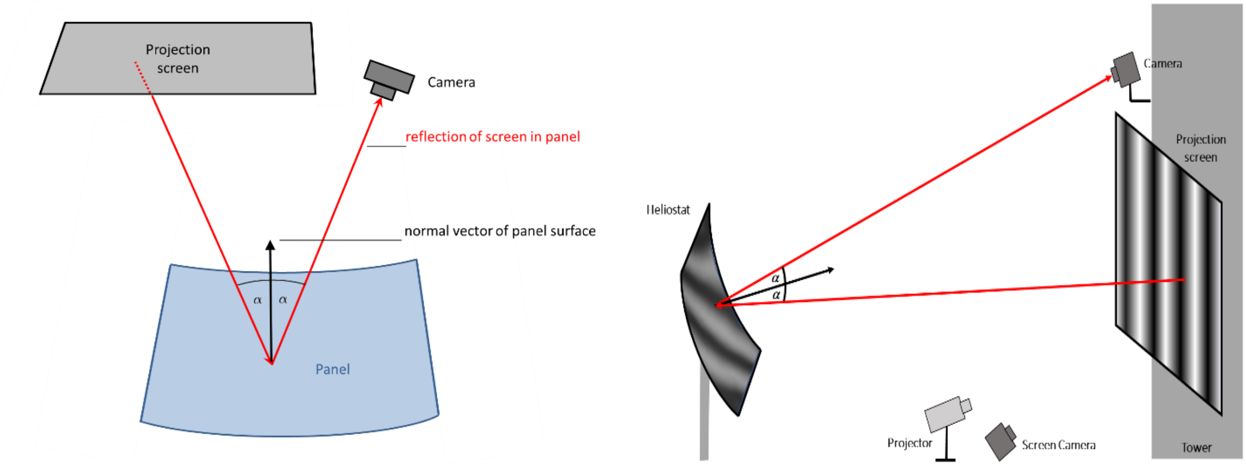
To further improve the optical quality of heliostats and decrease their manufacturing costs, economical and highly accurate measurement systems for quality control in series production are needed. At present, the geometric quality of heliostats is usually checked at the level of the steel support structures, while the shape of the mirror panels is separately controlled at the mirror manufacturer. It is generally supposed that if both components are within specifications, then the fully assembled heliostat is also within specification, but no final control in series production is feasible so far. New heliostat manufacturing concepts, where flat mirrors are glued to the steel structure and the heliostat obtains its final curvature during this bonding process from a precise jig, can achieve higher optical qualities at lower cost, but require a quality control of the fully assembled heliostat modules.

The only available measurement methods that could be generally used for this task in terms of accuracy and object size are photogrammetry, laser radar and laser tracker. But for use in a series production they are not suitable due to the required preparation of the measurement object, their time-consuming measurements or low resolution. A measurement technique, based on the principle of deflectometry, was initially introduced by the German Aerospace Center (DLR) [1,2] for measuring mirrored concentrators. As a result of the further development and commercialization of the system, called QDec, by CSP Services, it is now a widely established quality assurance method for mirror and concentrator shapes in the CSP sector. However, due to certain peculiarities of the measurement task, it was not possible to measure large mirrored heliostats during series production inside the assembly building with sufficient accuracy. In this paper, the development of such a deflectometric measurement system to measure the optical quality of already mirrored heliostat modules as final inspection of a heliostat production line is described. The software and hardware adaptions were developed by CSP Services and tested in two different applications within the research projects HelFer and TERRA.

MEASUREMENT SYSTEM

Deflectometry uses images of reflected regular stripe patterns, which are recorded with a digital camera, and digital image processing to match the reflection to their origin on the projection screen. The positions of camera, projection screen and mirrored surface have to be known to determine, by vector geometry, the local normal vectors of the reflective surface. A schematic view of the principle is shown in Fig. 1a. The deviation between local normal vector and the nominal local vector is commonly designated as slope deviation (SD). A more detailed description of deflectometry and its applications especially as shape measurement method in the CSP sector can be found in [2,3,4]. The development of the new measurement system is based on two existing concepts for deflectometric measurements of solar concentrators:

1. To measure fully assembled heliostat modules, which are already mounted on their pylons and set-up in the field, the QDec-H system was developed [2]. A single camera on the solar power tower is used to take pictures of the reflected stripe patterns which are projected on a white screen on the tower (Fig. 1b). This screen is usually available as it is used for tracking and focal tests. For a continuous production quality check this system is not suitable, because these measurements can only be performed in darkness and at a very late stage for quality assurance (tower needs to be built, heliostats need to be completely operative). In an assembly hall neither the size of the projection screen nor its distance to the mirrored surface can be realized to achieve the accuracy needed for such a system.
2. For quality assurance of the geometric quality of parabolic trough modules the optical measurement system QDec-M was presented in 2012 [3]. The measurement set-up was designed to be small enough to fit in a regular assembly hall. To reduce the required screen size, it uses three cameras along the non-concentrating direction, inserted in the projection screen to measure whole parabolic trough modules with a size of approximately 6 m x 12 m. Because of the geometric characteristics of parabolic troughs with their relatively short focal length, the screen size can be minimized at a convenient measurement distance of about 5 m. The stitching of the measurement results along the non-concentrating direction is not critical as deviations in this direction do not have a high influence on the optical efficiency. Also, the requirements on measurement precision of this method are generally lower for parabolic trough than for heliostats.



(a) (b)

FIGURE 1. Schematic view of deflectometric measurement principle (a) Schematic view of QDec-H measurement set-up (b)

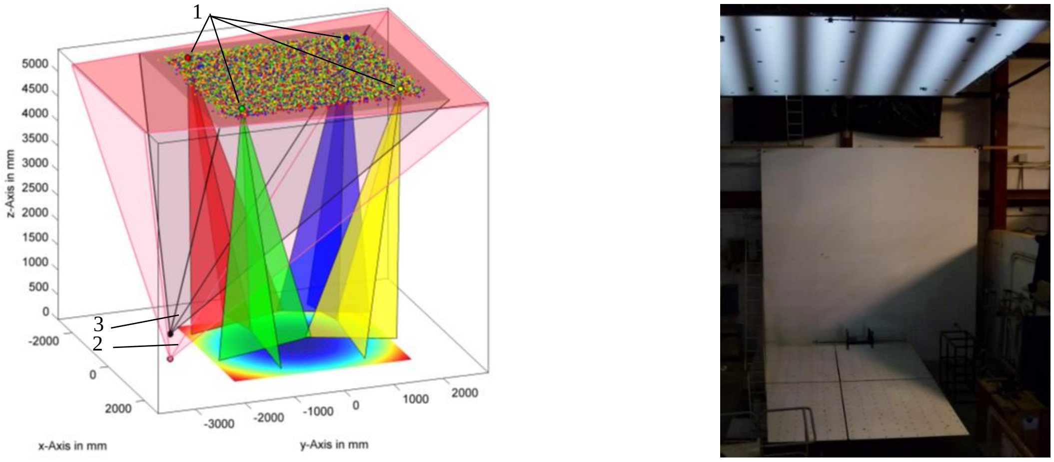
Heliostats can have a reflective surface size of more than 150 m² and have long focal lengths of several hundred meters, which results in an only slightly curved or nearly flat concentrator shape. Designing a deflectometric system for large heliostats, combined with the limited space available in an assembly hall and the high requirements on accuracy, is a challenging task.

New Developments

At the SolarPACES conference 2013, various improvements for the deflectometric system developed by CSP Services were presented [4]. The use of multiple cameras with an enhanced calibration method, as well as a better determination of their positions with a combination of photogrammetry and total station measurement, led to new possibilities for a QDec system capable of measuring large heliostat modules with long focal lengths in an assembly hall. The size and geometry of the mirrored heliostat surface demands a very large projection screen of more than twice the size of the heliostat in both directions. To keep the projection screen smaller and feasible, multiple cameras are needed. They are directed to different, overlapping parts of the mirror surface to take pictures of the stripe patterns of the same projection surface. By design it is often possible to reduce the size of the required projection screen to about the size of the heliostat. The reduced projection screen can be more easily implemented in a separate, dark enclosure which is required for the measurement process. Temperature of the measurement room can be controlled, so that temperature effects can be reduced to a negligible level and the calibration is stable over longer time. The pictures taken by each camera are evaluated separately and the results are stitched together to cover the entire heliostat surface. This approach requires a precise referencing of the positions of the components and an advanced algorithm for controlling and evaluating the cameras and their pictures. The positioning of the measurement object / mirror surface in the measurement volume has to be highly repetitive.

Test Applications

One task of the German Aerospace Center DLR during the German research project HelFer (Cost-optimized Manufacturing of Heliostats for Solar Tower Power Plants; partners: DLR, Heidelberger Druckmaschinen AG, Kraftanlagen München) was to develop feasible solutions for measuring the quality of the mirror shape at the end of a heliostat production line. It was required to be fast and highly accurate to give a direct feedback for automatic adjustment of the heliostat shape during the manufacturing process. A deflectometric measurement system was proposed and a conceptual procedure elaborated. As a first test of such a set-up, an existing deflectometry measurement system at DLR's research facility in Tabernas, Spain, was modified to measure a prototype of the heliostat developed in the project, with a rectangular surface of about 4 m x 3 m. In the horizontal projection screen, located about 5 m above the heliostat panels, four cameras were implemented to take pictures of the reflected patterns, each camera observing a different quarter of the heliostat surface.



(a) (b)

FIGURE 2. Schematic set-up of multi-camera heliostat measurement in confined space (a)
Picture of realized set-up at DLR facility (b)

In Fig. 2a a schematic view of the measurement set-up is shown. The four cameras in the screen at 5 m height are represented by small circles (1) and their viewing extension by attached triangles. At 0 m z-height, in the origin, the heliostat is shown. The skewed upside-down pyramids are representing the projector's projection (2) and the screen camera's view (3). The exact 3D position of the components (camera, screen, measurement object) were determined with a combination of photogrammetry and total station measurement. For verification of the set-up's functionality and uncertainty, a measurement of a water surface as absolute reference was performed. Furthermore, four flat mirror panels were installed in the system and measured in parallel with deflectometry and photogrammetry. The picture in Fig. 2b shows the realized set-up. Results of the water surface measurement and the comparison between both measurement methods are given in the chapter 'Validation'. To characterize a possible influence of thermal expansions of the measurement set-up on the measurement results a day-long repeatability test was performed.

In the Spanish research project TERRA (New Concept for a Solar Thermal Tower Power with Open Receiver), led by TSK and with participation of CSP Services, one subtask was to develop and demonstrate a verification system suitable for final checking of heliostat geometry after complete heliostat assembly. Special focus was set on getting a viable and robust system for industrial applications. Apart from a detailed analysis and further reduction of measurement uncertainty, the development included the automatization and optimization of the measurement process considering the general boundary conditions given by an industrial fabrication process. An advanced prototype system with the selected industrial components was installed in the laboratory of CSP Services. The distance between the mirrored surface and projection screen was just 2.2 m. This reduced distance made the set-up easier for development and tests, but more demanding in terms of measurement accuracy, as the influence of several error sources increase with shorter distances. This circumstance helped to analyze and further reduce the remaining measurement uncertainty. For verification, also a water surface measurement and a comparison to a photogrammetric measurement of four mirror panels were performed (see Fig. 3 a/b). Results are given in the following chapter. Several additional tests to quantify the influence of background illumination and dust on the reflective surface were performed. The in-house software code was enhanced to operate up to 10 cameras at once, allowing all kind of measurement set-ups for heliostats with complex geometries at the upper end of the size range.

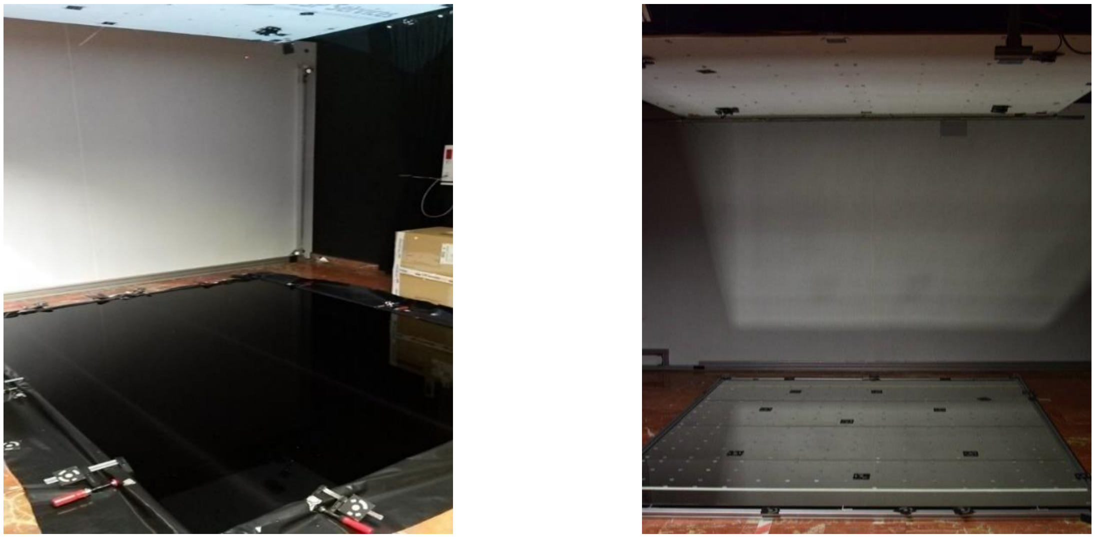

(a) (b)

FIGURE 3. Measurement of water surface (a), set-up with panels already equipped with photogrammetry targets (b)

Validation

Measurement of Reference Water Surface

For validation, a water surface is used as absolutely flat reference surface, which equals the mirrored surface in approximate total size and distance to screen, and is therefore a well comparable measurement object. Measured deviations from flat indicate remaining measurement uncertainties that can be similarly applied to the heliostat measurement. Figures 4 and 5 show the results of the local slope deviations of the two set-ups in an amplified scale. In the upper left corners of the graphs in Fig. 4 higher local deviations in form of parallel line patterns can be observed. The reason was found to be too much and slightly changing ambient light during the measurement process. Also, an effect from uneven projection screen panels can be seen, especially in the left part of Fig. 4 right. The main reasons for missing data points are due to the cameras fixed in the screen or from photogrammetry points on the screen or from dust on the water surface. In Fig. 5 the effects of an uneven projection screen could be mostly eliminated by implementing an internal correction of the measured shape of the screen.

The statistical results of the deflectometry measurements of the water surfaces at the DLR facility and in the CSP Services laboratory show similar good values, with slightly higher SDy values in the case of the HelFer set-up (Table 1). Considering the significantly shorter measurement distance, the wider camera view angles, and the proportionally larger water surface the result of the TERRA project is notably better.

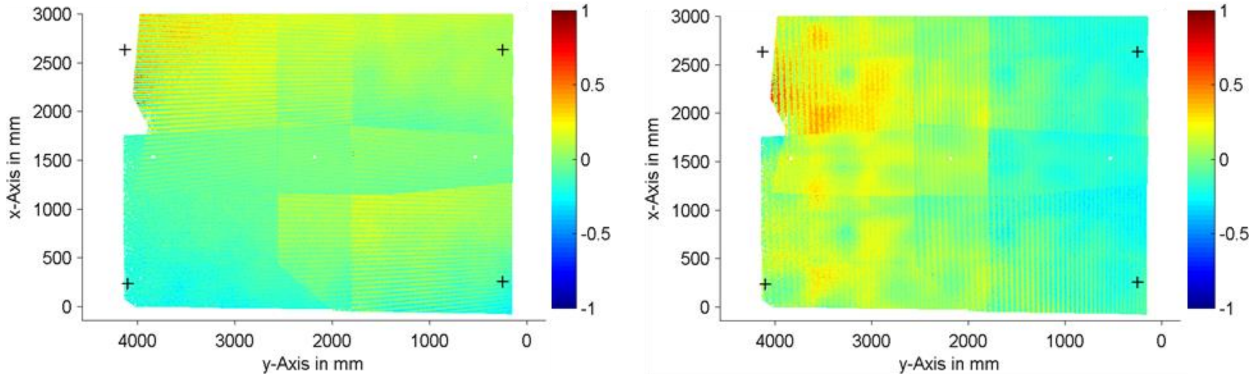


FIGURE 4. Slope deviations of water surface measured in HelFer set-up in x- and y-direction in mrad

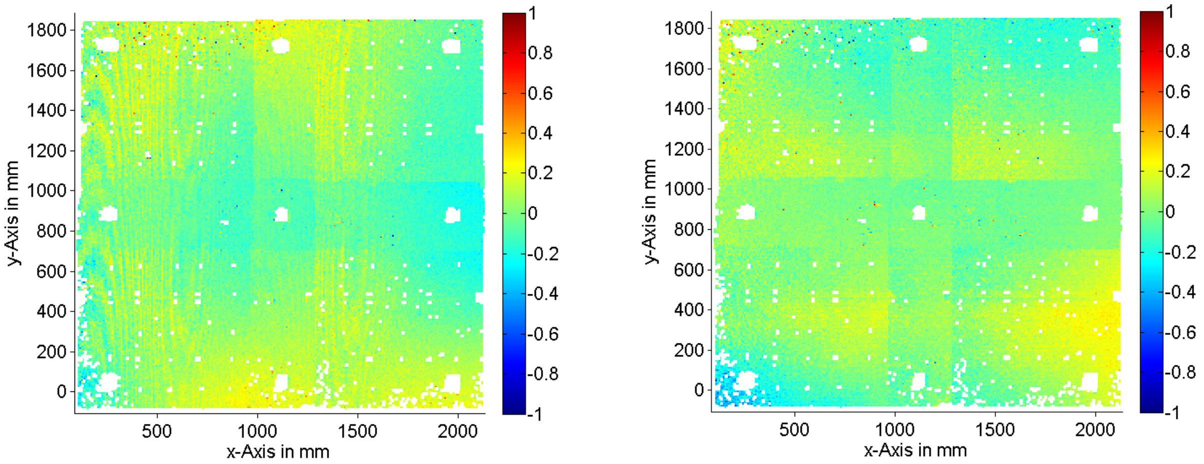


FIGURE 5. Slope deviations of water surface measured in TERRA set-up in x- and y-direction in mrad

TABLE 1. Statistical result of water surface measurements

	Meas. Distance	**Approx. Size**	**SDx (RMS)**	**SDy (RMS)**
HelFer	5 m	3 m x 4 m	0.12	0.16
TERRA	2.2 m	2 m x 2 m	0.12	0.11

Comparison to Photogrammetry

Additional to the water surfaces, mirror panels mounted on a structure were measured to perform a validation of the measurement of a mirror object with real curvature and slope errors. For comparison of the measured mirror surface, a manual photogrammetric measurement was used. The use of photogrammetry to determine the shape and possible deformations of solar concentrators is a commonly used and accepted measurement technique in CSP applications [5]. Being an independent measurement principle and an industrial standard tool, it can serve as a valid cross-check for the deflectometry method. However, the measurement resolution of the photogrammetric measurement compared to deflectometry is very low (in the present case about 300-400 points per heliostat) and the measurement usually does not cover the outermost borders of the mirror panels. In both set-ups such a comparison of a photogrammetric measured panels with deflectometry was performed. For photogrammetry, the area between the measured coordinates has been interpolated and slope deviations have been calculated. Figure 6 and 7 show the differences between the measured slopes of deflectometry and photogrammetry for both set-ups, respectively, and is further referred to as “DF-PG”. No systematic errors are observed, only the local differences due to the waviness of the panels which the photogrammetric measurement is not able to resolve. Figure 7 shows high deviations close to the borders of the panels. These differences are due to the fact, that the borders of the panels were not included in the photogrammetric measurement grid. Table 2 and Table 3 show the statistical results of the comparisons. As expected from the local waviness, the standard deviations of the differences within the facets are with about 0.3 mrad for HelFer and 0.9 mrad for TERRA not negligible. However, the mean values of the slope differences are very low, indicating a good comparison of the facets surface orientation, without systematic deviations between the two measurements.

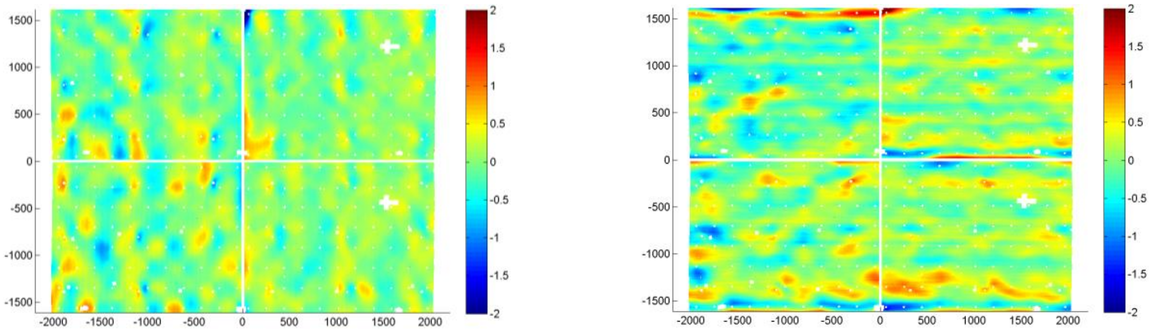


FIGURE 6. Maps of the difference in local slope deviation between deflectometric and photogrammetric (DF-PG) measurement of the HelFer heliostat in x- and y-direction in mrad

TABLE 2. Results of comparison in project HelFer in mrad

	Facet 1	**Facet 2**	**Facet 3**	**Facet 4**	**mean**	**std**
DF-PG SDx (std):	0.31	0.21	0.28	0.24	0.26	0.04
DF-PG SDy (std):	0.36	0.33	0.37	0.31	0.34	0.03
DF-PG SDx (mean):	0.01	0.04	-0.06	-0.00	-0.00	0.04
DF-PG SDy (mean):	0.05	0.10	-0.11	0.04	0.02	0.09

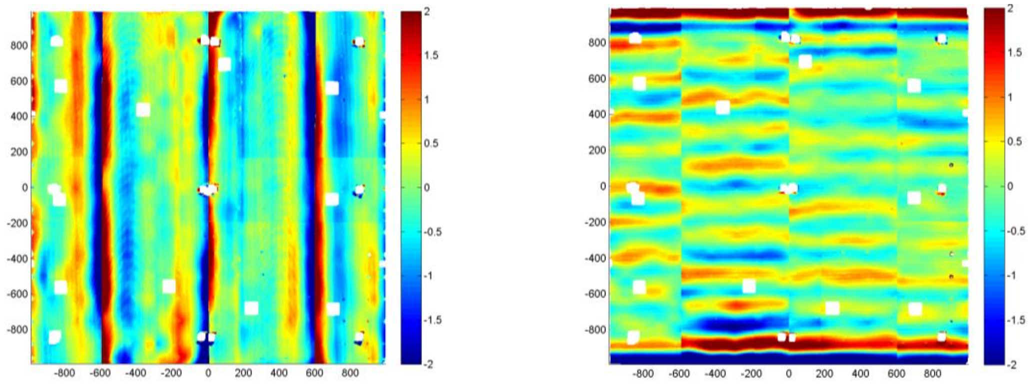


FIGURE 7. Maps of the difference in local slope deviation between deflectometric and photogrammetric (DF-PG) measurement of the of the TERRA heliostat in x- and y-direction in mrad

TABLE 3. Results of comparison in project TERRA in mrad

	Facet 1	Facet 2	Facet 3	Facet 4	mean	std
DF-PG SDx (std):	0.84	0.81	0.80	0.77	0.80	0.03
DF-PG SDy (std):	0.93	1.09	0.87	0.82	0.93	0.12
DF-PG SDx (mean):	-0.03	-0.05	-0.13	-0.01	-0.05	0.05
DF-PG SDy (mean):	0.11	0.02	0.03	0.03	0.05	0.04

Further Tests

As part of the HelFer project, a repeatability test was performed. Overall 61 measurements were made regularly over a period of 12 hours. From Table 4 it can be seen, that the process is very stable (very low standard deviation of the absolute values). The calculated local differences of these measurements - local subtraction of a representative measurement from result matrices - show low variation in statistical values. Over the measurement period the temperature in the measurement hall was registered. With a variation of 5 degrees temperature change no significant correlation with the result values could be identified.

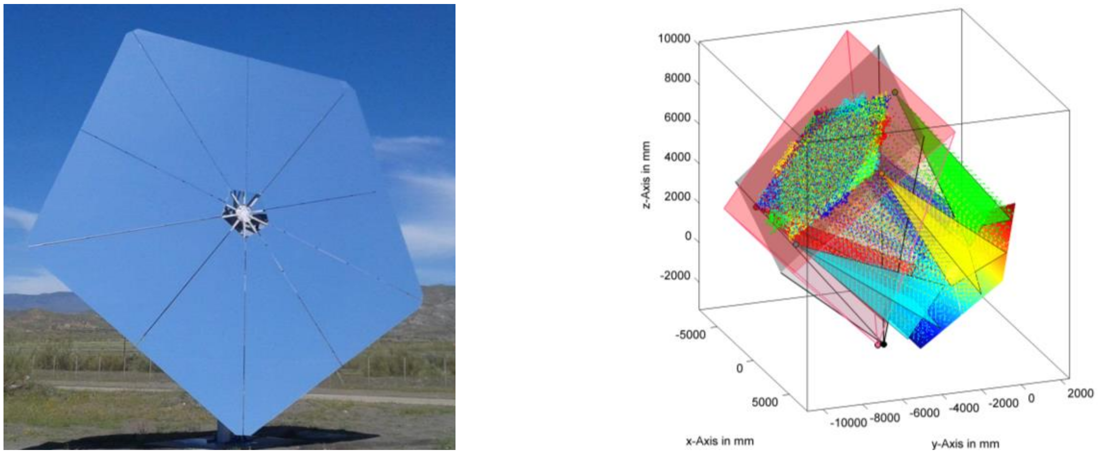
TABLE 4. Statistical results of repeatability test of 61 measurements and 11 local comparisons

	Mean absolute	Std absolute	Mean local diff	Std local diff
Number of measurements	61	61	12	12
SDx (RMS)	1.44	0.01	0.10	0.03
SDy (RMS)	0.92	0.02	0.09	0.03

An illumination test to check the limits of external light influences was performed during the development project TERRA. Especially the combination of dust loads and external lighting conditions can lead to failures in stripe detection and evaluation. Different dust loads that influence the reflectivity of the mirrors were tested (20 %...90 % reflectivity) in different lighting conditions (30…300 lux direct and indirect light). As a result, in a dark measurement room (< 5 lux) dust contaminations that reduce the reflectivity of the mirror to 30 % do not influence the measured values. In an environment with ambient light up to 100 lux, dust pollution can only lower the reflectivity down to 50% without affecting the result. Static illumination of only about 50 lux on the screen surface leads to alterations in the pattern detection and results in local systematic error of up to approximately 0.5 mrad. Dynamic changes of the light conditions in the room during the projection of the pattern series (< 1 minute) can lead to errors in the detection of the patterns characteristics and have to be avoided by all means.

Industrial Application

The final step was to elevate the functional and validated small prototype system at the CSP Services laboratory to a real industrial application. This step was done by realizing and implementing a geometric quality assurance system for the production line of the new Stellio heliostat [6] (Fig. 8a), which is currently being built for a 50 MW molten salt solar tower plant in China. The unique and innovative pentagonal Stellio heliostat has a diameter of about 8 m and a reflector size of about 48.5 m^2. Optimization of the measurement set-up for this geometry led to an implementation of 5 cameras in the screen for a minimum screen size and an equally distributed view onto all facets. See Fig. 8b for the schematic set-up of the system components. Optimum measurement distance was determined to be approximately 8 m, which was no problem to be integrated in the assembly hall. As a special requirement it was demanded to measure heliostats in several elevation angles which can be switched by the operators for different production periods. This will allow to account for different average operating angles of the heliostats in the field and thus for optimized optical accuracy. For this unique solution a movable screen was designed. The low-tolerance, accurate positioning of the measurement object demanded by the measurement method was solved by newly determining the object's position for each measurement with a high-accuracy laser tracker measurement. Special adapters were designed which have to be fixed to the heliostat corners before the measurement. With the heliostat in measurement position, prisms on these adapters can then be measured automatically with a fixedly installed laser tracker. This allows higher tolerance in the measurement object's initial position without losing accuracy in the measurement process. The requirements for production cycle time with < 15 minutes are met easily even with additional measurement time of the laser tracker. After each change in the position of the projection screen, the coordinates of screen and cameras have to be newly measured with the laser tracker. This improves the overall accuracy of the system's calibration and keeps the measurement uncertainty low. In Fig. 9b an example result of a deflectometric measurement in the newly developed system is shown. 99.3% of the surface could be evaluated with about 750.000 data points.



(a) (b)

FIGURE 8. Picture of Stellio heliostat (a)
Schematic set-up of multi-camera Stellio measurement with angled projection screen (b)

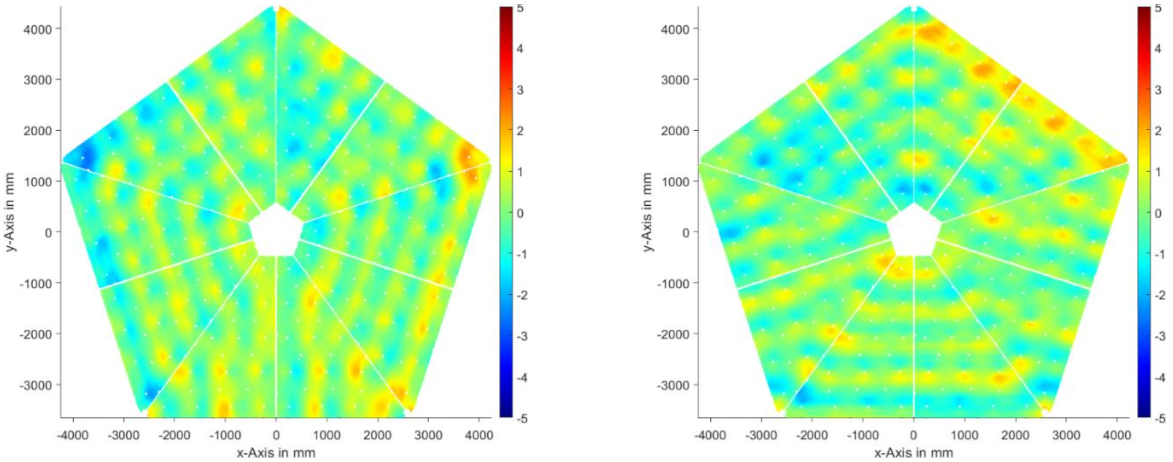


FIGURE 9. Measured slope deviations of Stellio heliostat in x- and y-direction in mrad

SUMMARY AND OUTLOOK

A new measurement system able to automatically measure shape accuracy of large mirrored heliostats in series production has been successfully developed. Key features of the measurement system called QDec-M-Helio are its high spatial resolution of about 1 million points per module, its low local uncertainty of less than 0.5 mrad and its low global measurement uncertainty of less than 0.2 mrad. Its measurement time of less than 1 minute and evaluation time of less than 5 minutes easily meets the typical cycle time in industrial production of about 15 minutes. The system was successfuly validated by comparison to photogrammetry and by measuring a flat reference surface. Tests showed that the system has a very high repeatability, low sensitivity to temperature changes, and the measurement process is very robust concerning dust on the mirror surface and static ambient light. If required, the measurement position can be changed in different phases of heliostat production to optimize optical quality for different average operating angles. With the new development, CSP Services achieved a solution suitable for industrial environment and commercial application. It is currently being installed as key quality control system for the Stellio heliostat production in a 50 MW solar power tower project in China.

Further development steps are the implementation of automatic determination of facet heights relative to concentrator origin, thus reducing the required heliostats pre-alignment accuracy. This would make the system application even more flexible to measure different heliostat designs with pad-mounted mirrors or unknown sub-structure tolerances of the heliostat.

ACKNOWLEDGMENTS

Financial support from the German Federal Ministry for Economic Affairs and Energy (HelFer, contract 0325458A) and from the Spanish CDTI through the program FEDER-INNTERCONECTA (TERRA, contract ITC-20151145) is gratefully acknowledged. The contributions of all involved colleagues not included in the list of authors, such as Markus Well and Benjamin Brix from CSP Services are also gratefully acknowledged.

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