QFOTO: AUTOMATIC INLINE MEASUREMENT SYSTEM FOR PARABOLIC TROUGH STRUCTURES: EXPERIENCES AND DEVELOPMENTS

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Abstract

Digital close range photogrammetry has proven to be a precise and efficient measurement technique for the assessment of shape accuracies of solar concentrators and their components. The flexibility of photogrammetry to provide high accuracy 3d-coordinate measurements over almost any scale resulted in the development of the QFoto system for inline quality control of support structures in parabolic trough collector assembly lines before the mirror panels are attached. The paper gives an overview of the capabilities of the QFoto system, its layout and measurement adapters and a description of the employed in-situ camera calibration. Special attention is given to the internal quality control of the system and features like the statistical process control, and the evaluation of the angles of all mirror brackets within one single measurement using specific measurement adapters.

Keywords: QFoto, Photogrammetry, Quality Control, Concentrator Analysis, Space Frame, Assembly Line

1. Introduction

The optical quality of the collector field of concentrating solar power plants is an essential factor for their profitability. High optical quality can be achieved and guaranteed when the manufacturing process is continuously monitored and adjusted in its essential steps. As digital close-range photogrammetry proved to be an adequate measurement method for solar concentrator elements [1-3], the German Aerospace Center (DLR) developed the stationary and automatic photogrammetry system QFoto [4] to track the fabrication quality of space frames in parabolic trough assembly lines. The system uses a digital camera, automatically moving around the object, computer controlled automatic image evaluation, in-situ calibration and continuous checks of the measurement uncertainty. It has been designed to reach, maintain, and control the required high accuracy in the rough environment of an on-site production line [5]. Whereas the development and prototype test was done by DLR, the spin-off company CSP Services GmbH (CSPS) further developed the system and introduced it into the market in 2008. Since then, QFoto has been used to secure the quality of solar thermal power plants in Spain, Morocco, Algeria and Egypt with a total solar field size of more than 3.1 Mio m². Currently, it is in use in the buildup of additional power plants in Spain, Abu Dhabi and Arizona, USA. When these plants are finished, QFoto has secured the quality of solar fields with more than 7 million square meters of total mirror size. QFoto has demonstrated to measure accurately and operate reliably in diverse regions of the world. Highly skilled operators are not required and its components do not fail in rough and dusty climates.

2. System Description

The QFoto concept for photogrammetric measurement is used in the quality control procedure of the collector structure assembly line. The quality control station is integrated into the assembly line layout. The height of the camera positions can be adjusted to the workshop design. Fig. 1 shows possible layouts.

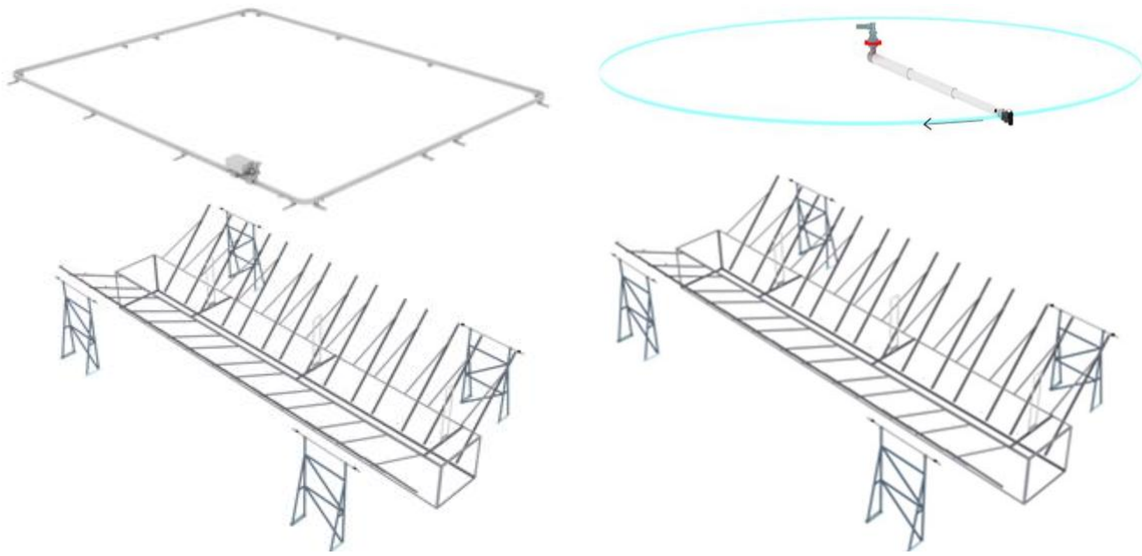

Fig. 1. QFoto setups with sketch of concentrator space frame and orientation bars on the ground. Left: camera on rectangular track (standard version), right: camera on rotating arm (alternative version)

QFoto currently uses a professional camera/lens combination on a pan tilt unit mounted on a rectangular closed track positioning system. It also includes the necessary software for automatic camera control and positioning, photo evaluation and data post-processing. Due to the use of the single, high-definition camera and camera self-calibration, the system allows for high measurement precision even under changing climate. This is advantageous over systems with stationary cameras that have to be calibrated individually.

3. Measurement Setup

3.1. Structural Setup and Camera Motion

As shown in Fig. 1 the QFoto system exists in two different configurations. In the standard configuration a shuttle-mounted camera stops at 14 positions along a rectangular rail track and takes a number of pictures at each stop position. The camera orientation on the shuttle in two axes via a pan tilt unit and the data acquisition is controlled by a wireless network connection. The size and height of the rail system can be adjusted to a variety of collector types and workshop layouts. For two parallel collector assembly lines in the same workshop, a dual QFoto system is available featuring one control cabinet and two rail tracks with two independent camera/shuttle systems.

The QFoto system with alternative camera actuator, which will be introduced into the marked shortly, is shown in the right of Fig. 1. Here, the camera positioning is done by a rotating arm and the camera can be oriented by three axes (pan-tilt-roll system). The third axis allows for an improvement of measurement accuracy and stability by canting the camera and fitting the collector better into the image pane. The images are taken “on-the-fly” without the rotating arm stopping its movement. The image transfer is done using a high-speed cable connection. The two last enhancements yield a significantly faster measurement combined with better stability. Table 1 gives some properties of the two systems.

<table>
<tr><th>Property</th><th>Standard QFoto system with rectangular rail track</th><th>QFoto system with rotating arm</th></tr>
<tr><td>motion type</td><td>rail track</td><td>rotating arm</td></tr>
<tr><td>camera path</td><td>rectangular</td><td>circular</td></tr>
<tr><td>number of cameras</td><td>1</td><td>1</td></tr>
<tr><td>number of camera axes</td><td>2</td><td>3</td></tr>
<tr><td>communication</td><td>wireless</td><td>hard-wired</td></tr>
<tr><td>measurement time</td><td>8-12 min</td><td>3 min</td></tr>
<tr><td>number of images</td><td>around 40</td><td>up to 80</td></tr>
<tr><td>ambient temperature range</td><td>-10 to +60°C</td><td>-10 to +60°C</td></tr>
<tr><td>number of supports for system mounting</td><td>≥ 16</td><td>1</td></tr>
<tr><td>measured quantities</td><td colspan="2">• 3d coordinates of all mirror support brackets
• 3d coordinates of all receiver support points
• angles of all mirror support brackets (optional)
• module length</td></tr>
<tr><td>features</td><td colspan="2">• complete automatic measurement (after preparation with measurement targets)
• contact-free measurement
• in-situ camera calibration with each measurement
• automatic compensation of module heat expansion to chosen reference temperature
• module rotation axis as reference
• calculation of mirror panel mounting angles
• calculation of deviations by comparison of measured values to nominal values
• comparison of deviations to allowed tolerances
• module quality report
• final “pass” or ”fail” signal
• statistical output (optional)</td></tr>
</table>

Table 1. Properties of the QFoto system with the standard and the rotating arm camera actuator

3.2. Measurement Targets and Adapters

The measurement system utilizes custom-made measurement targets and adapters with retro-reflective surfaces to guarantee short measurement times and high precision. Different measurement targets and adapters are used for different collector types and measurement setups, according to costumers’ needs. Examples are shown in Fig. 2. Usually, the position of all mirror support brackets (112 pcs. in case of EuroTrough-like collectors), the position of the receiver supports, the reference rotation axis and module length are measured. Additional reference points, e.g. the direction of the x-axis , can be measured within the same measurement without extending the measurement time. It is guaranteed that the standard deviation of the measured coordinates (x, y and z) from the true coordinates is ≤ 0.5 mm (valid for EuroTrough-like modules). Special inclination measurement adapters (IMA) can be used to measure the inclination of the mirror support brackets in the curved direction of the parabola (γ-angle) with a maximum expanded uncertainty of 1.0 mrad. As a new feature orientation measurement adapters (OMA) can be used to measure both the position and the orientation of all mirror support brackets at the same time. As the OMAs are smaller than the IMAs, the uncertainty of the measured bracket angles (in curved and non-curved direction of the parabola) is increased to 2.0 mrad.

Fig. 2: Measurement adapters for the reference axis and the receiver supports (left) and measurement targets for the mirror support brackets (right) for a EuroTrough-like space frame

With the experience gained during the last years, the system and especially the targets and adapters are optimized for stability and reliability. In particular, the retro-reflective coating has been optimized for keeping the reflectivity high also under high temperature and dusty conditions. The measurement targets and adapters are manufactured and/or calibrated with high precision to ensure the required measurement accuracies. The targets on the last-generation measurement adapters can easily be replaced without the need of adapter recalibration. Furthermore, the targets and adapters keep their high precision when handled under normal production conditions.

3.3. In-situ Calibration of Camera and Lens System

Professional digital cameras and lenses are used for the measurement system. Currently, the Nikon D300 camera with specially chosen prime lenses (from Nikon or Zeiss) is used. However, the measurement system is operated at changing temperatures, usually between -10 to 60°C. Under these conditions, the distortion parameters of the camera and lens system change. Therefore, one and the same camera is used to take all pictures instead of using various fixed cameras for the photogrammetric measurement. With this approach, the distortion parameters can be calibrated within each measurement leading to reliable high measurement precisions.

4. Measurement Sequence and Data Evaluation

4.1. Measurement Procedure

After positioning of the collector structure in the measurement location and placement of the measurement targets and adapters onto the required locations, the measurement is started and the photos are taken from the different perspectives and locations of the camera trajectory. These digital images are evaluated automatically. The results are stored, and incorrectly mounted collector elements can be identified and adjusted. The required measurement time, including target mounting, analyzing, displaying or printing, and storing the data is (depending on the number of operators on site and the number of measurement points) 20 to 30 minutes, mere shuttle running time is 8-12 minutes (camera on shuttle) or 3 minutes (camera on rotating arm). In the standard system, crane crossing over the measurement location during the measurement is allowed in order to yield an uninterrupted production process.

4.2. Data Evaluation Report

The data evaluation is fully automatic. This includes the calculation of all point coordinates, camera calibration, scaling, precision check, computation of further outputs such as mirror mounting angles and deviations of coordinates, output of a quality report including all data in tabular and chart format, checks against the defined tolerances and a final “pass” or ”fail” signal for the whole module. This result is indicated to the operators by a signal light. Fig. 3 shows the overview page of the quality report, given as Excel-Sheet.

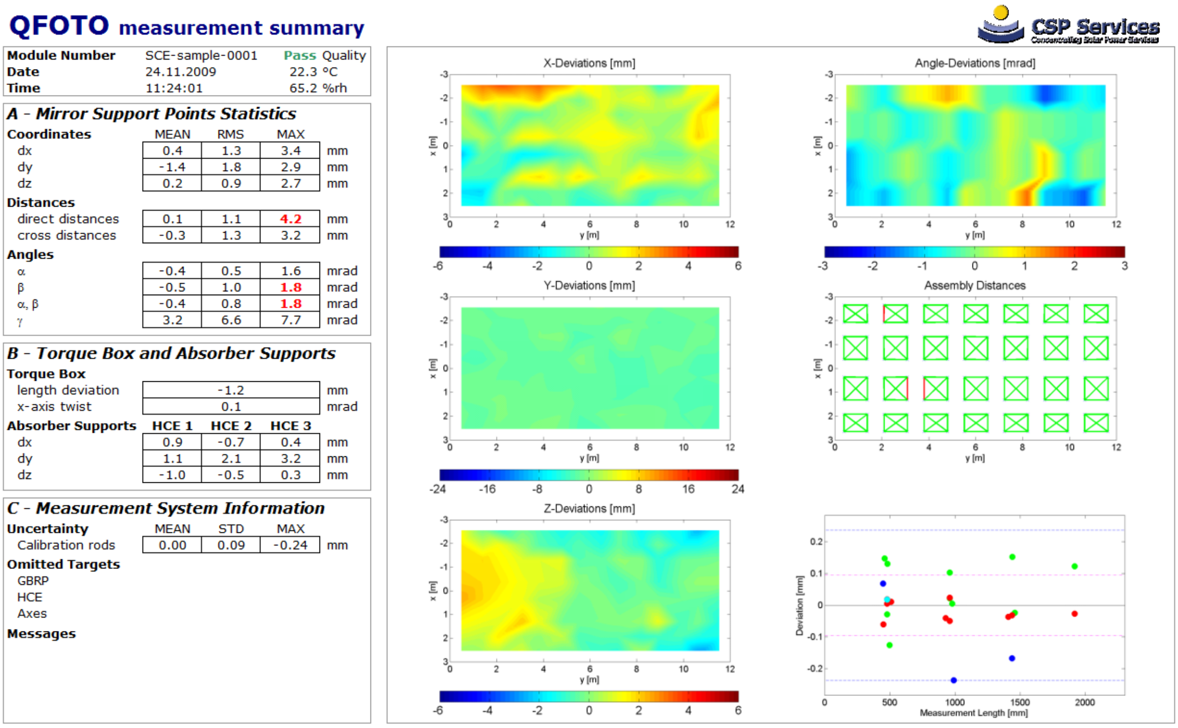

Fig. 3. Summary result sheet of module quality report (for imaginary data)

Fig. 4 left shows an exemplary plot from the data evaluation report, indicating the measured α- and β-angle deviations from nominal. The definition of these angles is shown in Fig. 4 right. The α- and β-angles are of high importance for the collector efficiency, as they directly influence the amount of light intercepted on the receiver. This visual information is of high value to optimize the production process. For example, in the plot, the red zone indicates that the respective cantilever arm is mounted too steep, i.e. the parabola is too narrow. In general, all the plots are also given in numeric table format, and statistic parameters are derived. These deviations and statistic parameters trigger a collector "passed" or "failed" quality control to the system operators based on the set warning and acceptance thresholds.

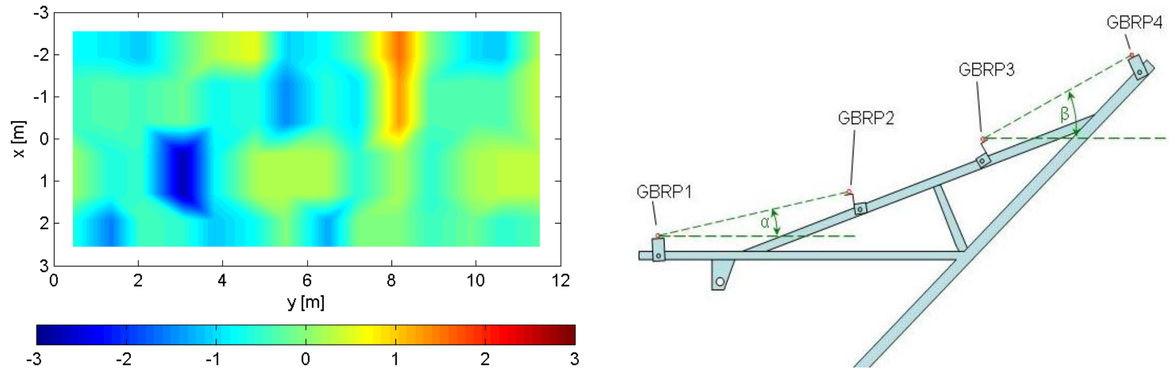

Fig. 4. Deviations of mirror tilt angles α- and β in mrad (left) and the definition of these angles (right) for imaginary data

Fig. 5 left shows an example distribution of γ-angles of the mirror support brackets from nominal. The definition of these angles is shown in Fig. 5 right. The γ-angle deviations usually indicate if a perfect mirror panel will be deformed during its installation onto the structure. Usually, non-proper γ-angles lead to local slope error deformations, which reduce the intercept. The measurement can be done with orientation measurement adapters (OMA) which allow both the control of all α-, β- and γ-angles in one measurement.

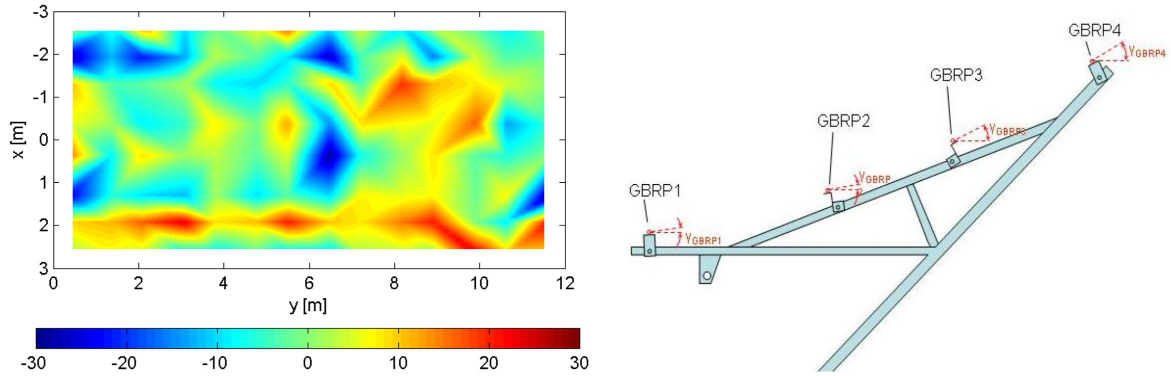

Fig. 5. Deviations of mirror support pad angles γ in mrad (left) and the definition of γ-angles (right) for imaginary data

4.3. Statistical Process Control

Production processes underlie changes. Some are obviously visible, others are not so easy to detect. Statistic process control helps to manage product quality and indicates when the process has to be optimized. The QFoto system stores all measured data in a raw-format database. An additional software module can be used to extract useful data, as exemplarily shown in this section.

Fig. 6 left shows a visualization of the RMS (root mean square) of α-angle deviations plotted over the modules produced. We can observe a step reduction in the deviations, i.e. an increase in optical efficiency. That means that the action taken, in this example a precise readjustment of the production jig, was successful. The software produces an automated, non-manipulable and traceable quality control report, containing quality control cards of the respective time periods which facilitate process control and process optimization. These quality control cards are also useful as quality tracking records. By application of warning and action limits, the production process can be controlled automatically. For example, the software gives a warning alert when the warning limits are exceeded and it gives an action alert, when the production process must be changed. The software also guarantees a fast and effective way to access and reduce the data produced by the QFoto measurement system over a specific period of time. In Fig. 6 middle, we can see that 97% of the modules passed, while 3% failed the quality control. Fig. 6 right shows why a collector module failed the quality control. This plot directly allows taking measures at the correct points, if necessary.

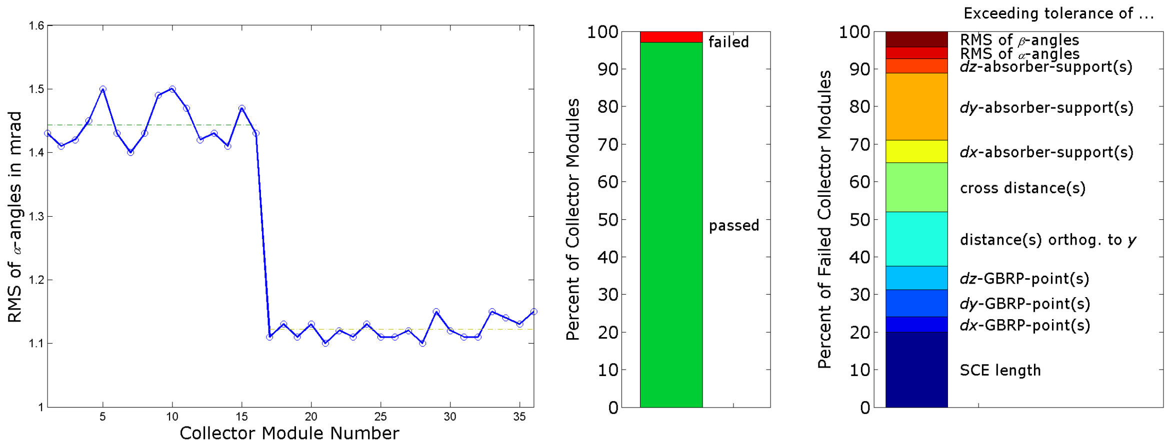

Fig. 6. Statistics over a period of time: Observation of a re-adjustment of a production jig leads to desired reduced deviations of mirror tilt angles (left). Share of collectors with failed quality control (middle), Reason of failed quality control (right). The underlying data is imaginary

5. Assurance and Confirmation of the Measurement Precision

The first step to ensure the specified accuracy of a measurement system is a proper system layout. An in-house photogrammetric simulation tool has been developed that analyzes possible geometrical layouts in a phase before real photogrammetry measurements are done. With these simulations, the optimal combination of camera/lens itself and defined camera positions and orientations can be found before the installation of a measurement system at the site. The distortion parameters of the camera/lens and the retro-reflectivity of the targets for the respective incidence angles are taken into account. Thus, a realistic model for the measurement setup is used.

Further methods to inspect the quality and stability of the camera and lenses are applied. For example, the distortion parameters and the uncertainties in these parameters are measured by means of photogrammetry in the CSPS laboratory with a calibration frame. A setup with similar camera orientation to the later use in the measurement system is chosen (camera always looking slightly downwards). Furthermore, pictures with different canting are made to determine the influence of the gravitational force on the camera/lens system. The uncertainties in the calibrated focal length, principle point and the distortion parameters (inner orientations) characterize whether this combination of camera and lens is suitable for photogrammetric measurements. High uncertainties indicate that the combination of camera and lens could be mechanically instable or that the camera model used in the photogrammetric evaluation does not fit the true distortion pattern. Fig. 7 shows the total radial distortion resulting from the calibration of three different lenses. The total radial distortion of lens 3 is much higher than for the other two lenses (left graphic). This alone is no criterion for exclusion. However, the uncertainty in the total radial distortion of lens 3 is significantly higher than for the other two lenses, too (right graphic). Thus, lens 3 is less applicable for high precision photogrammetric measurements. Other quality criteria are the position and the uncertainty of the principal point, the lateral distortion with its uncertainty and the uncertainty of the calibrated focal length.

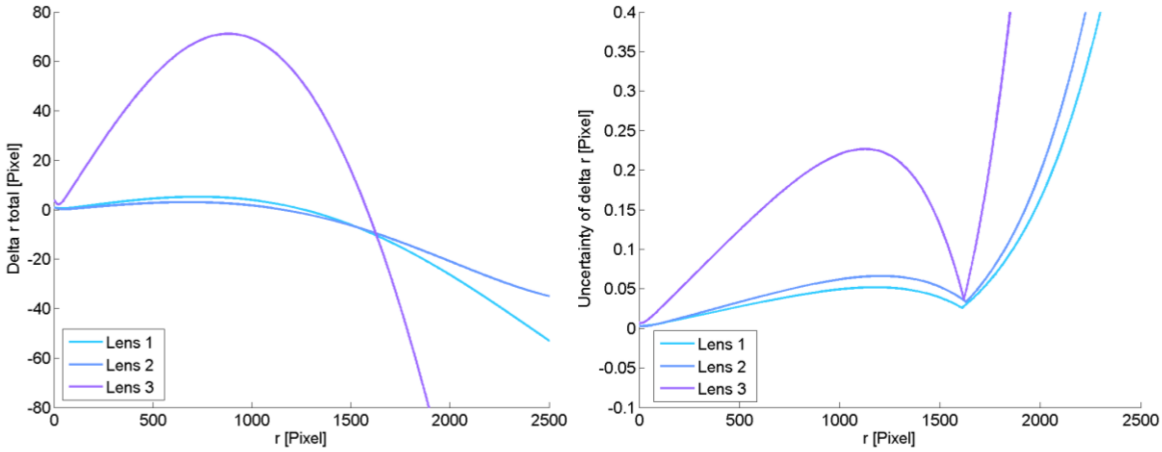

Fig. 7. Total radial distortion of three different lenses (left) and its standard deviation (right)

The used measurement targets and adapters are manufactured with high accuracy. Depending on the type of adapter, they are calibrated and/or adjusted applying optical as well as geometric measurement techniques (including photogrammetry, calipers or inclinometers).

During the commissioning of the measurement system, several checks are made to verify the measurement accuracy of the installed system. Amongst them is a manual photogrammetry done with a Nikon D3X and a Nikkor 24mm MF lens whose properties are well known from several high precision close range photogrammetry measurements. Pictures from many different camera positions and with different camera orientations are taken. The resulting 3d-coordinates are compared with the results of the measurement system. The results must coincide within the proposed measurement uncertainties. For the scaling of the resulting 3d-coordinates carbon fiber bars with retro-reflective targets are used whose distances are calibrated with high precision close range photogrammetry. As reference lengths DKD-calibrated carbon fiber bars are used. The coefficient of thermal expansion is very low for carbon fiber bars (approximately -0.2 µm/m/K). Thus, scaling for a large range of workshop temperatures is sufficiently accurate. During commissioning, the distances between the reference targets on the carbon fiber bars (approximately 300 distances in a range from approximately 200 mm to 4000 mm) are measured with the QFoto system and compared to similar reference bars which are situated and oriented in different positions within the measurement area. The calibrated distances are not only used to scale the measurement results but also to track the present measurement accuracy which could be diminished (e.g. due to a cover of dust on the targets or not utilizable pictures). Additionally, long distances may be checked with complementary measurement techniques (e.g. with calibrated tape measure or a total station). The angle measurement precision is confirmed with a test where the same angles are measured with the adapters rotated by 180°. If possible, deformed or otherwise corrupt adapters are detected automatically in the evaluation of the measurement. Furthermore, a subset of the commissioning tests is repeated during periodical maintenance visits to identify and replace or repair corrupt adapters. Appropriate instructions are automatically displayed to the operators on the screen. In addition to on-site maintenance visits, remote support and maintenance from the CSPS office via broadband modem using a secured connection allows rapid and efficient software updates and fast reaction times in case of troubleshooting. Amongst other, software updates can be deployed remotely in this way. Also whole sets of measurement pictures can be transferred for checking the correctness of the automatic on-site evaluation in case of special events or changes in the concentrator design.

6. Conclusion and Outlook

QFoto has proven its effectiveness in reaching and maintaining a high-quality production while delivering a solution for the issue of a traceable quality control in the assembly workshops of many CSP plants worldwide. A QFoto system with rotating arm camera actuator has been developed to reduce the effort of installation and maintenance as well as the measurement time. The deployment of the standard QFoto system with the camera on a shuttle or the rotating system has to be selected depending on the measurement task to be solved (e.g. kind of space frame) and the design of the assembly workshop. QFoto is widely used for the measurement of parabolic trough collector structures. It can be applied in the same way for dishes and heliostats.

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