QDec-M-Line: A Geometric Quality Control System to Assess Fully Assembled Parabolic Trough Modules in Series Production

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Abstract.

A new inline measurement system for automatic quality assurance of the concentrator shape of parabolic trough modules in series production has been developed. The applied deflectometry measurement technique is based on the iterative reflection of an illuminated movable pattern in the mirror surface and its distortion due to mirror surface deviations. The movable pattern can be realized conveniently by making use of a gantry crane typically utilized in parabolic trough module production workshops. The measurement system was built and extensively tested on laboratory scale. All relevant effects on the slope measurement accuracy, reliability and dependency on harsh ambient conditions were thoroughly analyzed. All required features for the upscaling to full parabolic trough module size and for flexible adaption to different geometries are available. The here presented progress in the development of the system and the results of the validation measurements demonstrate its readiness for an industrial scale implementation.

Keywords: Solar concentrator, shape accuracy, optical quality, quality control, optical measurement, deflectometry, trough

INTRODUCTION

The thermal output of parabolic trough solar fields is a result of the optical, geometrical and thermal properties of the installed solar collectors and their correct tracking of the sun. Besides a good collector design, appropriate quality control of the collector components and proper assembly and installation are key for high performances [1]. There are several commercial measurement solutions available to ensure the geometric quality of key components prior to assembly [2, 3]. However, only few solutions exist to assess fully assembled parabolic trough concentrator modules at the end of the assembly line, like the QDec-M measurement system [4]. A major drawback of this system is that it requires a large projection screen to display fringe patterns in a darkened measurement bay, which makes the integration in a production line challenging. To overcome this restraint a new system has been developed, complementing the existing quality control systems. The new deflectometry system replaces the projected fringe patterns with a narrow target line that is moved across the module during measurement. This technique supports ambient light conditions and thus enables inline automatic quality control of mirrored modules in the parabolic trough production line. For a straightforward and economic implementation, the system can use the existing gantry crane as a movable support for the target pattern, which consists of a single line with a certain profile to measure the surface slopes of the concentrator module line by line. Therefore, the new system is called *QDec-M-Line*.

MEASUREMENT SYSTEM

System Description

The newly developed system is inspired by two different measurement systems. Firstly, by the QDec-M deflectometry system, an optical measurement system for high resolution and high precision quality assurance measurements of the bidirectional slope data of completely assembled CSP parabolic through modules [4]. The *M* in QDec-M stands for *Module*, differentiating the system from the standard QDec system used for quality control of individual mirror panels in series production. Secondly, by the Trough Absorber Reflection Measurement System (TARMES) that measures the unidirectional slope data of parabolic troughs using the reflected image of the absorber tube [5, 6]. Both these systems and the new system use non-contact optical measurements and digital image processing techniques based on the deflectometry measurement principle (Figure 1a). While TARMES relies on the presence of the absorber tube and a rotation of the concentrator module, the QDec-M system uses regular stripe patterns that are projected onto a large-area screen. In the new QDec-M-Line system, a movable narrow target replaces the large projection screen that must be supported above the concentrator module and is complex to realize (Figure 1a and 1b). The movable narrow target carries a defined line pattern. By moving the narrow target and thus the position of the pattern, full module resolution is achieved by repeated picture acquisition, similar to measurements according to the TARMES principle.
From the position and deformation of the reflected pattern in the mirror, the deviations of the reflector slope perpendicular to the line pattern can be calculated. This is done by a specially developed evaluation software that controls the measurement and uses digital image processing to calculate the local normal vectors of the reflecting surface and their deviations to the design vectors. The positions of the camera, the mirrored module and the moving target relative to each other need to be known. More detailed descriptions of the principle of the measurement technique can be found in [1, 2].

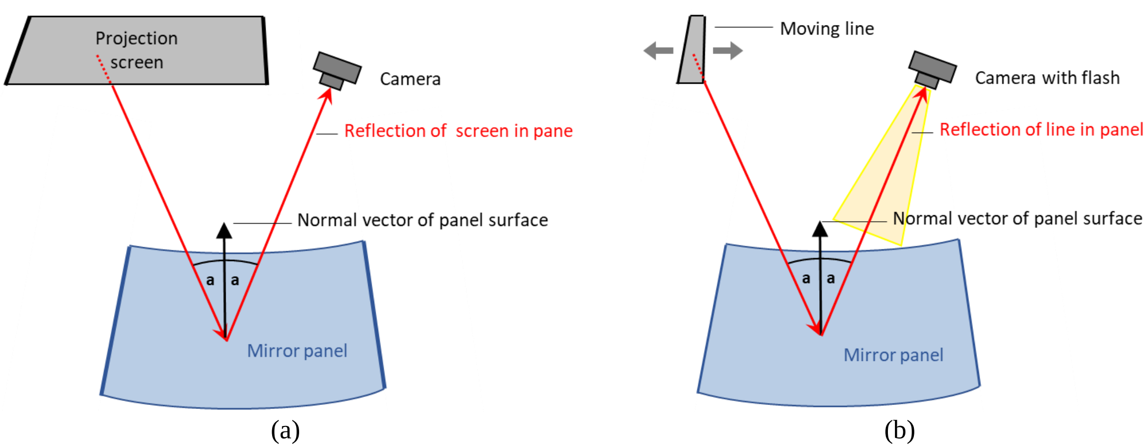


FIGURE 1: a) general measurement principle of deflectometry,
b) adapted measuring principle for the QDec-M-Line system measurement

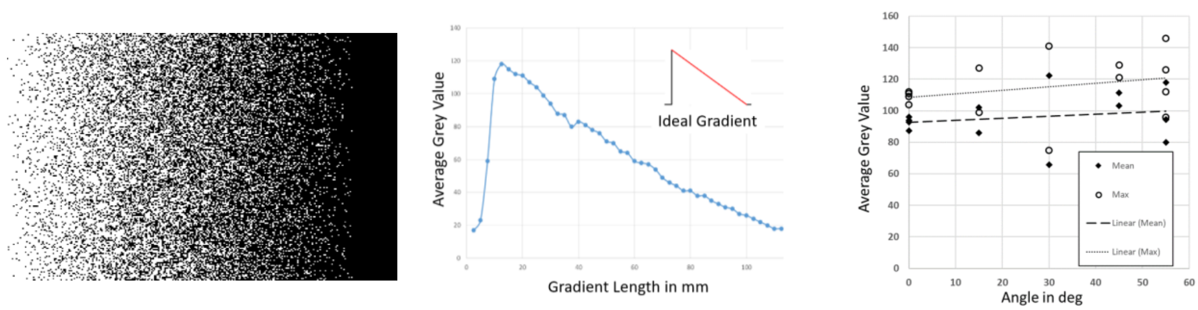
The new measuring system was developed with the vision of using the gantry crane typically available in parabolic trough production lines as the movable target support. To serve as defined line signal, the gantry crane must be equipped with a durable and well detectable pattern. This possibility gives the system clear advantages in terms of implementation. The installation effort and space requirements are reduced and no lateral extension to the production line is needed. It also allows for an easy integration in existing or pre-designed production lines. Using a high contrast line signal further enables the system to work under normal indoor light conditions, so no darkened measurement bay is needed.

Development and Laboratory Setup

In the new measurement system, a movable narrow element with a line pattern is used as target. As the visibility of the line is critical for measurement robustness, speed and inline capacities, several illumination concepts were studied (active LED strip, diffusely reflecting material, retroreflective material, constant illumination, flash light). Finally, a retroreflective foil with flash illumination was selected due to several advantages. Firstly, the retroreflective surface is a passive element that does not require electric power supply, which keeps the complexity of the mobile element low. Secondly, the concept allows for precise adjustment of the line profile in terms of gray value gradient by screen printing (Figure 2a). And thirdly, the flash illumination enables high contrast for low camera exposure times, which reduces image noise and motion blur during the imaging of the moving line. Additionally, the retroreflecting object stands out against a pitch-dark background, simplifying image processing and subsequent edge detection. Apart from the actual line signal, only direct reflections of the flash light or other bright light sources can appear in the measurement images, but can be automatically identified and cut out using background images taken before the measurement start.

For the measurement accuracy, it is key that the detection of the line position is as exact as possible and that the assignment of all lines is unambiguous. For this reason, different line profiles were created and thoroughly tested. The most favorable profile turned out to be a sawtooth-like shape with a steep up-slope and a linear gradient down-slope (Figure 2b). Due to limitations in the printing on retroreflective material this gradient was achieved by linearly increasing the density of black spots along the gradient (Figure 2a). The fusion of tiny black and white pixels are detected by the camera from the distance as linear grey value gradients. The linear gradient profile enables robust edge detection at the steep slope side of the profile. This improves the accuracy of the system as well as the robustness of the software.

Several retroreflective foils were tested for their reflectivity at different angles of incidence. As the cameras are mounted at fixed positions and the line moves through the measuring bay, the incidence angles of the flashlight illumination and camera viewing angles vary during a measurement. The retroreflecting foil with the lowest angle dependence was selected, as it provides a rather constant gray response in all measurement pictures (Figure 2c).



(a) (b) (c)

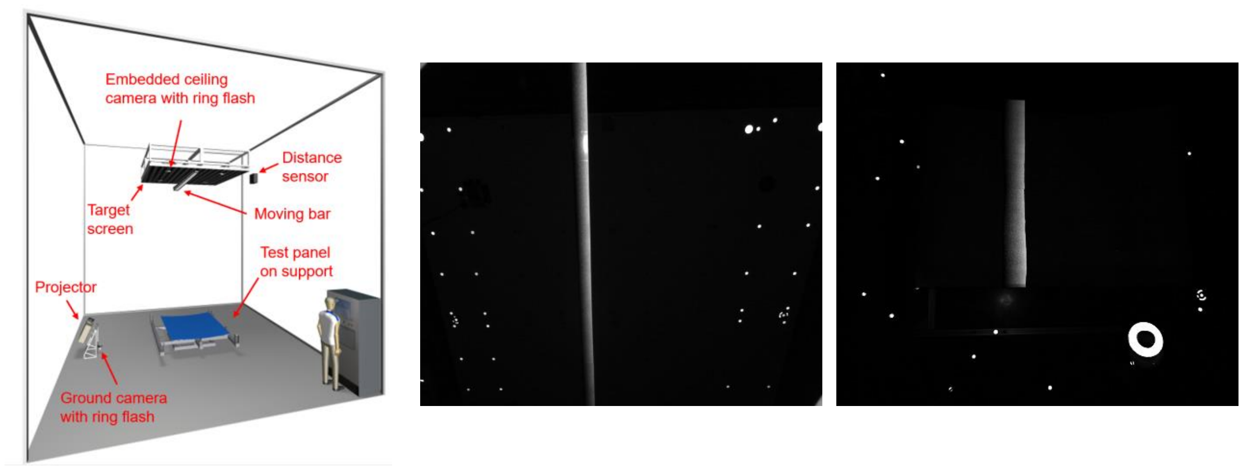
FIGURE 2: a) print pattern to create a linear gradient line, b) gray value gradient of a printed retroreflective foil, c) gray value homogeneity for chosen retroreflecting foil for different illumination/viewing angles

A ring flash was chosen for maximum alignment of the flash illumination with the imaging system. Additionally, diffuser covers are used to accomplish a uniform illumination of the line over the entire measuring range. The recharging capabilities of the flashes must support the desired picture acquisition rate that depends on the desired measurement time and resolution.

Further, to automate the measurements, a distance sensor was implemented to trace the movement of the line. The sensor is used to trigger the measurement start as soon as the line enters the measurement bay and continuously monitors the unidirectional movement of the line during the whole measurement procedure. All cameras are triggered simultaneously by the distance sensor for certain line advancements which can be programmed such that homogenous measurement resolution along the module is achieved.

While the distance sensor is used to trigger the picture acquisition, the exact target line position is obtained from pictures taken by additional cameras on the floor. All camera positions and orientations (via custom-made photogrammetric adapters) are determined by highly accurate photogrammetry measurements. In addition, systematic deviations from the plane in which the line moves are calibrated with a total station. These measurements together with the camera calibration parameters are stored as a system calibration. This enables the calculation of the position of the line signal from the target images with the required accuracy and makes it independent of eventual variations in speed and in planarity of the line movement.

For demonstration and validation purposes, the in-house laboratory QDec system has been extended with a narrow bar that supports the retroreflective gradient line and can be moved on rails. This corresponds to a measurement configuration at smaller scale, but generally with the same proportions and conditions. The general setup is displayed in Figure 3a. Integrating the system on a smaller scale (*QDec-Line* without *M*) into the laboratory setup offers the advantage to compare the results to the ones from the highly accurate QDec measurement system. Smaller dimensions have higher demands in terms of measuring accuracy in positions of cameras and mirror surface, as well as edge detection. Therefore, successful testing in this laboratory configuration ensures that the system works on a large scale. The laboratory system is capable of measuring about 2 m² large mirrors, which are placed on a custom manufactured metal support. This support allows to position and measure the mirrors in a highly repeatable manner. The moving bar with the attached gradient line is placed slightly below the about 4 m² large projection screen used for QDec standard measurements and can be moved along rails by a motorized pulley system. The bar can be moved outside the active measurement area to allow a standard QDec measurement. One industrial camera with ring-flash is placed on the floor close to the measurement object and two industrial cameras with ring-flashes are embedded into the screen, in parallel to the line. A distance sensor is integrated into the setup at the level of the horizontal line movement. The distance data is communicated via RS422 port to the software and is used as described earlier to check the movement of the line and trigger all cameras simultaneously according to its advancement.



(a) (b) (c)

FIGURE 3: a) laboratory setup of the QDec-Line system, b) example image of the gradient line on the moving support bar, c) example image of the reflected gradient line used for evaluation

Figure 3b and Fig. 3c show exemplary measurement images of the gradient line on the moving bar and its reflection in the mirror. The slightly visible distortions in the reflected line indicate local deviations of the mirror panel. An in-house software developed in MATLAB® evaluates the images, calculates the surface normal vectors and visualizes the results. It takes into account and corrects for all known systematic error influences such as lens distortions, perspective rectification, background lighting, inhomogeneous reflection properties of mirror and retroreflective material, as well as non-uniform speed and height deviations in the movement of the line. The graphs in Figure 4 visualize the exemplary evaluation sequence of a test measurement with 100 images per camera (synchronized acquisition of all cameras). Raw images (a) are merged into one image with non-overlapping individual lines to save computation time in the subsequent processing steps (b). Direct reflections of the flash light and other light sources are filtered using stored background images (c). The edges of the lines are detected and assigned to the corresponding picture number (d). Finally, all detected lines are merged into one matrix (e) and corrections for remaining systematic errors are applied. With this information and the combined information from the reflected lines in the subdivided mirror panel (f), the evaluation can be carried out by calculating the mirror surface normals.

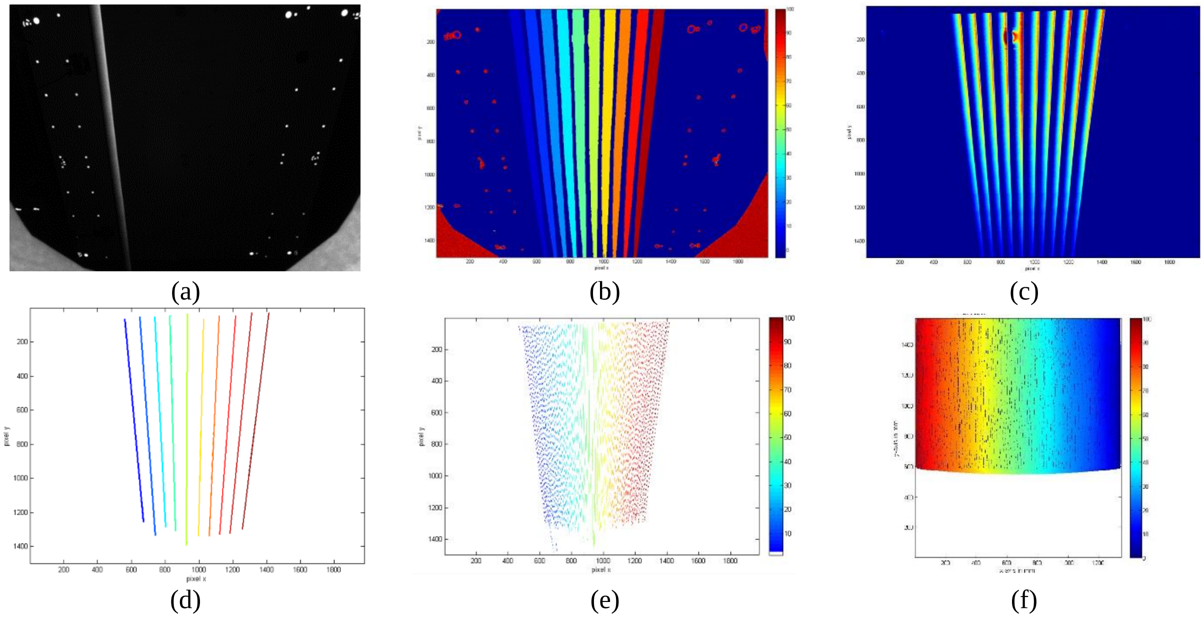


FIGURE 4: a) raw image, b) non-overlapping lines merged for each camera, c) filtered image, d) detected edges, color corresponds to picture number, e) complete result of all detected edges, f) result of all detected edges in one mirror section (a-e: ground camera, f: a ceiling camera)

MEASUREMENT RESULTS AND VALIDATION

For demonstration and validation purposes an about 2 m² large RP2 test panel was used in the laboratory QDec-Line setup. Presented results and quality parameters are therefore just representative for a single panel and not an entire module in series production quality.

The measurement results are surface slope deviations in measurement direction (curved direction), the corresponding mirror height deviations, focus deviations as well as local intercept results. Since slope deviations can only be obtained perpendicular to the line signal, the line extends along the non-curved direction and moves along the curved direction, to get the slope deviations in the performance relevant curved direction (x).

For validation with the standard QDec, which measures in both directions, only the slope deviations in the curved x direction of the test panel are considered. The test panel is measured with the QDec-Line system with different image resolutions (100 and 50 images per camera) and compared to the results of the standard QDec system. The measurements are performed directly in sequence and the panel is not touched in between to avoid any differences in the measurement object itself.

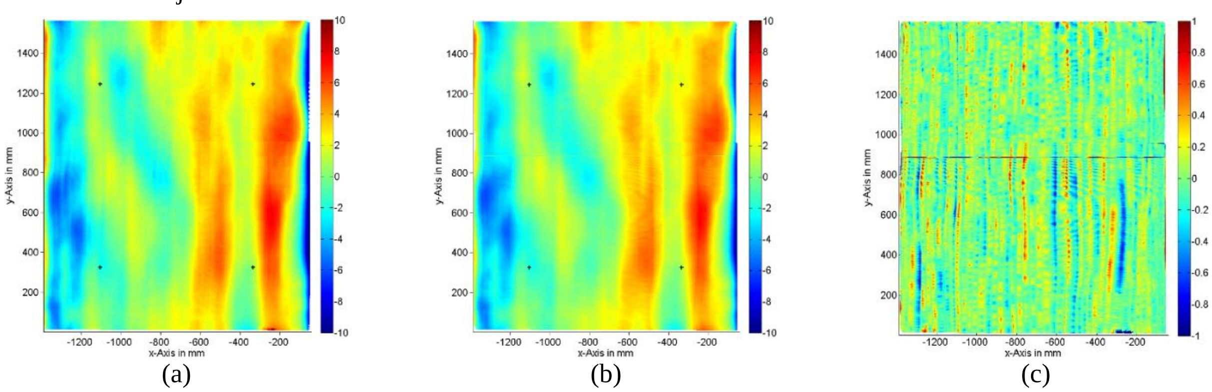
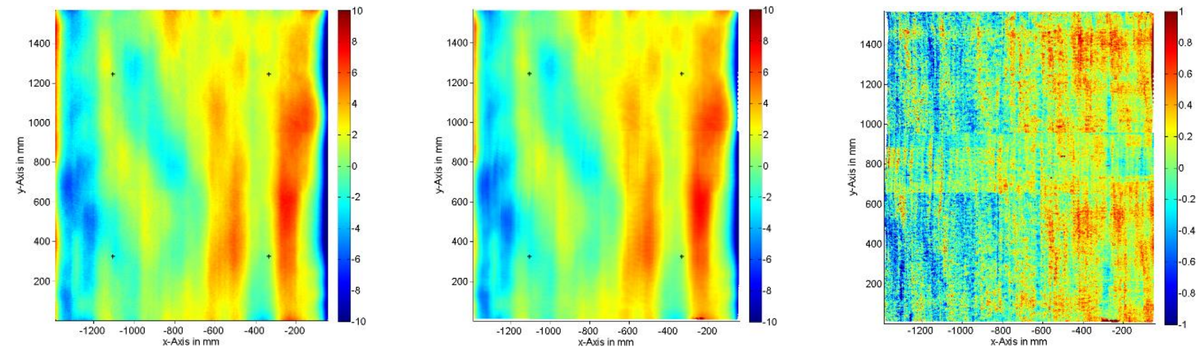


FIGURE 5: a) measured slope deviations in mrad in x direction for a line measurement with 100 images per camera, b) measured slope deviations in mrad in x direction for a line measurement with 50 images per camera, c) comparison of the two measurement results in reduced scale

Figure 5a shows the measured slope deviations in x direction of mirror panel with a set of 100 pictures, while Figure 5b shows the results for a reduced number of 50 pictures. Note that the sign convention is such that angular deviations are positive for deviations that cause reflections of ideal incoming rays above the focal line and negative for deviations that cause reflections below the focal line. Both results show the same characteristic waviness of the slope deviations for the individual panel along the curved x-direction. While the results are very similar, local deviations occur when the integration for the lower resolution does not match the measured slope of the 100-image measurement. The local differences of the measured slope deviations are displayed in Figure 5c in a reduced scale by a factor of 10. The standard deviation as well as the RMS of the local differences of the slope deviations are 0.22 mrad and therefore in a still tolerable range. Tests showed that a lower number of pictures than 50 leads to noticeable local deviations and therefore should be avoided. During the test phase and validation measurements, no influence of ambient illumination and soiling of the mirror panel on the measurement results could be detected.



(a) (b) (c)

FIGURE 6: a) measured slope deviation in mrad in x direction with a line measurement of 100 images per camera, b) measured slope deviation in mrad in x direction with a QDec standard measurement, c) comparison of the two measurement results

Figure 6 shows the high-resolution line measurement in comparison to the measurement results of a standard QDec measurement. The graph in Figure 6c shows the differences of both measurements in a reduced scale. Differences are slightly lower in the central area of the panel along the x axis, which corresponds to the area where redundant measurement information from both cameras is available. The areas towards the panel corners show slightly higher measurement differences. There is a general trend from slightly negative values in the left half to slightly positive values in the right half, which could be still improved. However, as can be seen in Table 1, the differences in the measurement results are generally very small: the global values of the panel quality (SDx) differ by less than 0.1 mrad for the scan with 100 lines and by less than 0.2 mrad for the scan with 50 lines. With values of 0.3-0.4 mrad the standard deviations and RMS of the local differences are also very low. As mentioned before, these results are very encouraging for the scale-up to full module size, since for larger measurement setups systematic errors like the spatial system calibration have less influence on total measurement uncertainty.

TABLE 1. Statistical values of the QDec-line system validation on laboratory scale

SDx Results	**QDec standard**	**QDec-Line**		**Difference**		**Statistics of local differences (see Figure 6c)**		
		100 images	**50 Images**	**100 images**	**50 images**		**100 images**	**50 images**
STD in mrad	2.82	2.75	2.63	-0.07	-0.19	STD of ΔSDx in mrad	0.33	0.36
RMS in mrad	2.89	2.85	2.75	-0.04	-0.14	RMS of ΔSDx in mrad	0.33	0.36
Total evaluated area in m²	2.10	2.08	2.07	-	-		-	-

IMPLEMENTATION INTO A TROUGH PRODUCTION LINE

QDec-M-Line is designed to be installed within the assembly line of the collector module manufacturing and to perform a measurement of each individual collector module before leaving the assembly hall. Essential components include a movable target that is slightly longer than the module, a total station to control the module positioning, multiple cameras at the ceiling (number is depending on module geometry), two cameras on the ground and an electric control cabinet (see example in Figure 7). Depending on the number of cameras, evaluation complexity is increased due to the required merging of the partial module results. However, the feasibility has been demonstrated in the laboratory system tests and validated in former publications [4] based on the same underlying algorithms. When utilizing the gantry crane as moving element, a distance sensor is used to monitor its movement and trigger the picture acquisition for maximum automation and measurement homogeneity (equidistant stripes). The measurement system layout is adjusted to the available space in the measurement bay, the distance of the gantry crane from the module, and the parabolic trough module design and size. The mirror installation station itself can be used as the measurement bay if certain requirements are fulfilled.

In parabolic trough production lines, gantry cranes are typically used to transport the concentrator modules between the different production stations. Since the gantry crane is longer than the module length and is usually moved in the curved direction of the module, it is highly suitable to be utilized as the support of the movable target. For this purpose, the bottom side of the gantry crane is equipped with the measurement pattern. Details like the number, width and length of the crane girders, bottom side properties, obstacles that affect the line of sight of the cameras, and mounting height as well as minimum moving space to the side and height clearance must be considered. The movement speed of the bridge limits the measurement speed but is not considered critical. Typical speeds are in the order of ten meters per 30 seconds, which does not constitute a bottle-neck for full module control. Achievable spatial resolution is about 1000 points along the line and the number of pictures taken during the scan in curved direction, which corresponds to about 100.000 measurement points. For a EuroTrough type concentrator this is then typically interpolated to a 10 mm x 10 mm grid. For a scan with 50-100 images per camera, the fully automatic measurement, evaluation and reporting can be achieved within a time span in the order of 7 minutes.

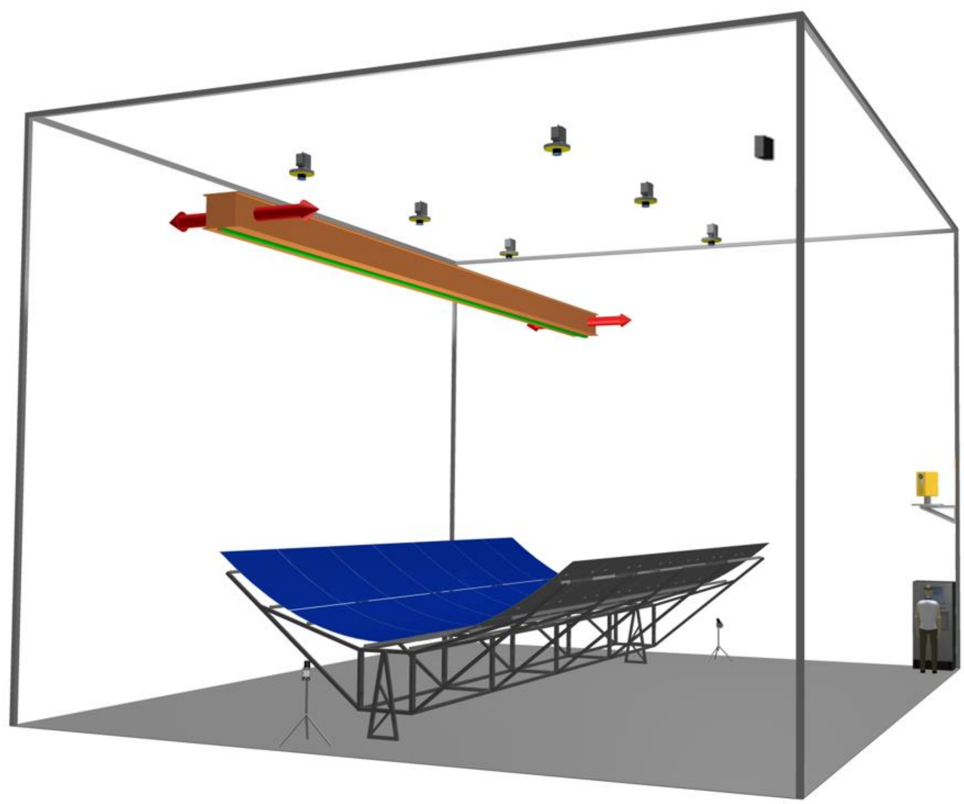


FIGURE 7: Layout of an industrial QDec-M-Line system for EuroTrough module type

Figure 7 shows an exemplary layout of the QDec-M-Line system for a typical parabolic trough module (EuroTrough dimensions: length ~12 m, aperture width ~6 m). The mirrored concentrator module is positioned horizontally on two supports, allowing the module to hang freely similar to its field installation on two pylons and providing a reproducible measurement position. The gantry crane from the production line is used to position the modules on the supports, as well as the movable element for the measurement. In this case, the gradient line with retroreflective surface is installed at the crane bottom side and moves in the curved direction of the trough as indicated by the red arrows. In this layout six cameras below the ceiling and two cameras on the ground are used to image the moving line reflected by the concentrator module. Each ceiling camera covers about one sixth of the module area, providing sufficient overlap for merging. The two ground cameras for the synchronized measurement of the gradient line are positioned lateral to the collector module on the ground. All cameras are equipped with high-power ring-flashes to provide stable illumination for the measurements. If exact module positioning and alignment is not completely controlled, a total station and custom-made prism adapters as in the QDec-M system can be used to measure the module position and automatically communicate it to the control cabinet. The system would be typically integrated within line (e.g. within mirror installation station), requiring only 1-2 meters of space above the gantry crane and around the module.

SUMMARY AND OUTLOOK

A new inline measurement system for automatic unidirectional mirror slope measurements of mirrored parabolic trough modules in series production has been successfully developed. Similar to the former QDec-M system, the new QDec-M-line system offers high spatial resolution and high measurement accuracy. New key features of the measurement system is the capacity to work under normal indoor lighting conditions and the possibility to make use of a gantry crane typically utilized in parabolic trough module production workshops, enabling a straightforward inline implementation in the assembly line. This makes the new measurement system suitable for final geometric quality control of parabolic trough concentrators in series production and for continuous optimization of concentrator optical quality and prototype development. The system was validated under laboratory conditions by comparison to highly accurate standard QDec system measurements. The QDec-M-Line system is ready for full commercial size implementation in existing or planned module parabolic trough collector module assembly lines.

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