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# First Lay-Down Heliostat with Monolithic Mirror-Panel, Closed Loop Control, and Cleaning System

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**Abstract.** The first lay-down heliostat with monolithic concentrator was erected at the Solar Tower Jülich. The main components and their main features are described: azimuth and elevation drive, concentrator, control, and the cleaning system concept. The dimensions of the elevation drive and the carriage already match the requirements of a 50 m<sup>2</sup> heliostat that shall be developed in a follow-up project.

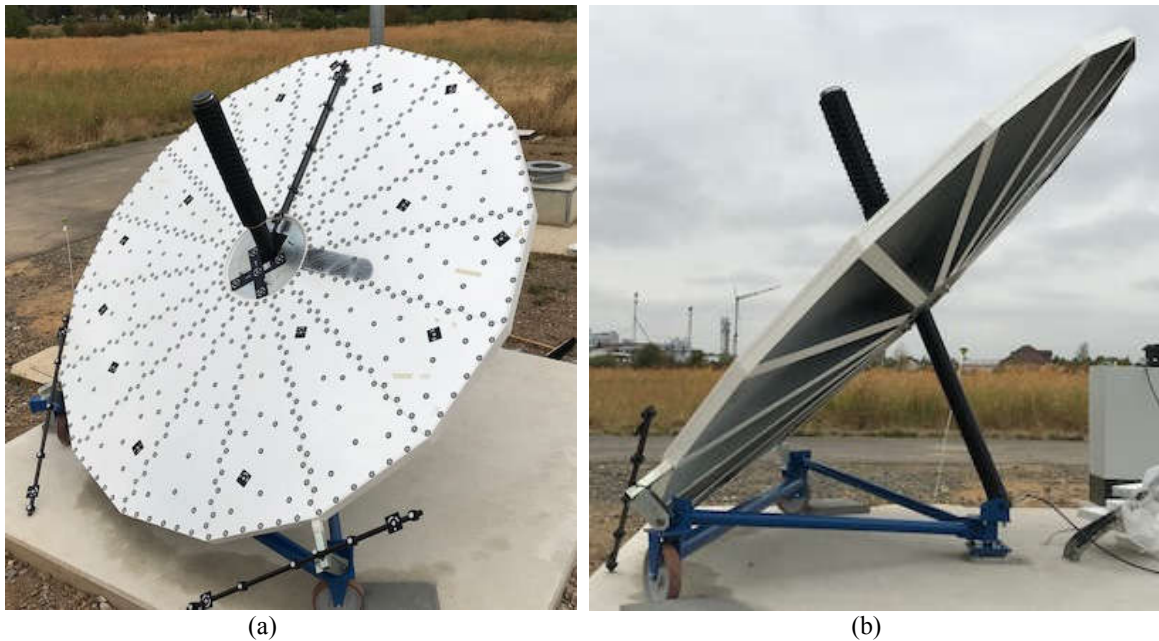
## INTRODUCTION

At SolarPACES 2017 conference, the concept for a lay-down heliostat with monolithic mirror-panel and closed loop control of extraordinary low cost was presented [1]: The concentrator combines the advantages of cantilever arm and sandwich structures and leads to 5% higher field efficiency due to its higher reflectivity and slope accuracy. It can be laid down for storm events to reduce the maximum wind loading. The elevation drive passes through the panel which significantly simplifies the design of the elevation and the azimuth drive. The azimuth drive is realized by a two wheel carriage with one driven wheel. The wheels are weighted against lifting and slippage and could run directly on stabilized soil or on a simple pavement. Only low accuracy demands on the mechanical parts are required due to a closed loop control by means of an optical sensor which detects the position of the Sun and of reference points of the surrounding. A first 8 m<sup>2</sup> heliostat prototype was built and the concentrator's deformation for different elevation angles measured.

## HELIOSTAT SYSTEM

The objective of the DLR project KOSMOS is to develop, build, and test a first prototype of the new heliostat concept. Figure 1 shows the 8 m<sup>2</sup> prototype equipped with retroreflective targets for photogrammetry measurements and a mirror protective foil. The azimuth drive was manufactured and the complete heliostat was installed by the company TEUPE Stahlbau GmbH, Dormagen.

Although the cost optimum size is presumably in the range of 50 m<sup>2</sup>, at first an 8 m<sup>2</sup> size was chosen for cost and handling reasons. However, the dimensions of the elevation drive and of the carriage including gear motor already match the requirements of the (later) 50 m<sup>2</sup>-heliostat (only with reduced lengths).



**FIGURE 1.** Front view (a) and side view (b) of first 8 m<sup>2</sup> lay down heliostat prototype installed at Solar Tower Jülich with temporary retroreflective targets for photogrammetry measurements and mirror protective foil; all dimensioned already for loads of 50 m<sup>2</sup> heliostat

### AZIMUTH DRIVE

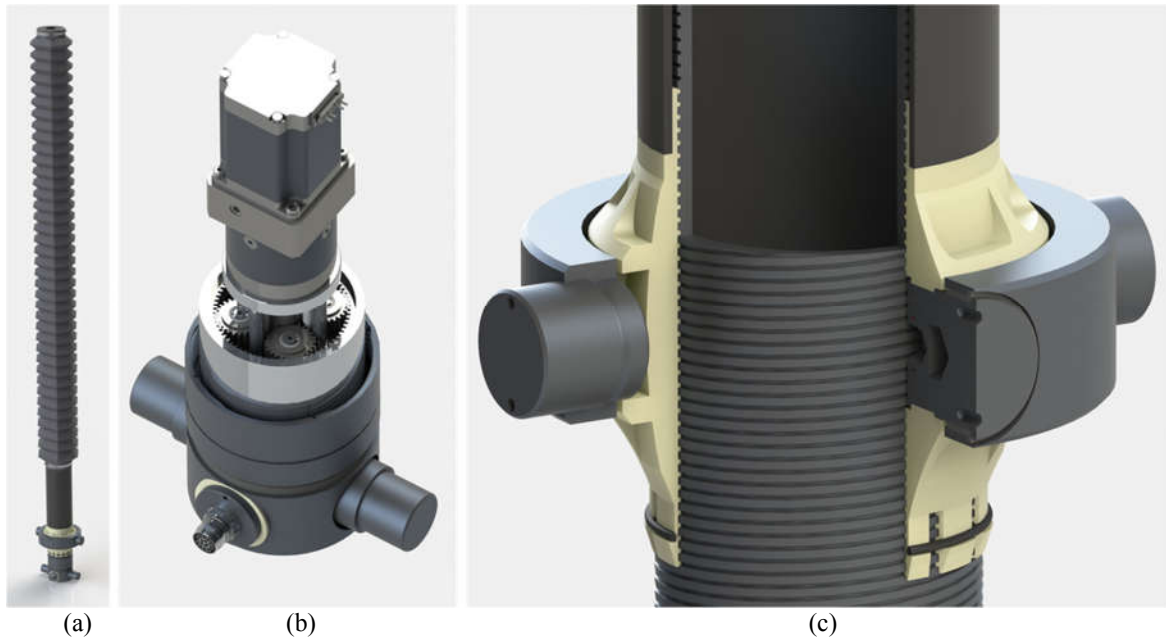
The carriage is very simple: It consists mainly of two wheels, three tubes, and the central bearing. One of the wheels is driven for the azimuthal movement. A cheap but precise chain gear allows the use of a small low cost gear motor [2]. The wheels are weighted to prevent the wheels from slippage and the system from lifting during wind gusts. The weighting is realized by filling the connecting rod between the wheels with sand. Due to the design, the tubes are almost not loaded by bending moments. Therefore, their dimensions can be small which reduces cost.

For the first prototype, the wheels are running on a concrete slab. The wheels could run also on a less accurate pavement or even directly on the ground because of the quasi closed loop control system which does not require a precise runway. However, this shall be developed only in the next step.

### ELEVATION DRIVE

For the heliostat the elevation drive system RGT-100 (Fig. 2(a)) was developed by the company NEFF-Gewindetriebe GmbH. The gear motor drive unit (Fig. 2 (b)) is housed inside the spindle which simplifies the interface to the central bearing and avoids the cost of an extra motor housing.

Gimbal joints are used for the connection of the spindle to the central bearing (Fig. 2 (b)) and of the spindle nut to the central hub of the concentrator (Fig. 2 (c)). Thus, no moments are transferred to the spindle and it is loaded only by longitudinal forces which is important regarding lifetime of spindle and spindle nut. Furthermore, the accuracy requirements on the interfaces are significantly reduced. A segment scraper at the spindle nut wipes away dust and sand particles from the spindle. However, above the spindle nut the spindle is enclosed by a rubber bellow (Fig. 1) because otherwise particles could fall between spindle and spindle nut which would reduce the life time of the system. The spindle of low wall thickness is made of alumina and coated with PTFE and has a special five-start thread based on the trapezoid thread profile DIN 103. The spindle drive can be equipped with an adjustable integral lift limit switch.



**FIGURE 2.** Gear-motor drive unit with gimbal mount (a) and spindle nut with segment scrapers and gimbal mount (b)

## CONCENTRATOR

The new concentrator concept [3] developed by sbp-sonne GmbH in the joint BMWi project SPACE combines the advantages of structures with cantilever arms connected to the centre (high resistible loads at low weight) and of sandwich structures with thin glass mirrors (high reflectivity, shape accuracy, hail resistance, and low number of parts). Besides the hub and the bearings, the concentrator consists only of four different components: mirrors (front layer), bended metal sheets (back layer), foams between metal sheets (core layer I), and foams between mirrors and metal sheets (core layer II).

For high quantities, the sandwich segments would be produced by using liquid foam that hardens in high pressure molds. However, such molds are very costly and cannot be built for the production of only one single heliostat prototype. Therefore, rigid foam sheets were used instead. With them no parabolic shape could be realized. Nevertheless, the deformation of the shape for different inclinations can be investigated also for a plane concentrator.

Hence, the concentrator was built on a plane ground. The concentrator consists of the central hub and of 16 almost identical segments. For the gluing adhesive of Sika Deutschland GmbH was used. The main steps of the manufacturing were the following:

1. Rigid foam sheets of 20 mm thickness were glued on the thin glass mirrors.
2. Rigid foam sheets of 8 mm thickness were glued on one side of the metal segments.
3. One after the other, the metal segments were glued on the foams of the mirrors, to the central hub, and to the neighbouring metal segment (Fig. 3).
4. The gaps between the mirrors were sealed and the open sides of the foam cores protected with paint.

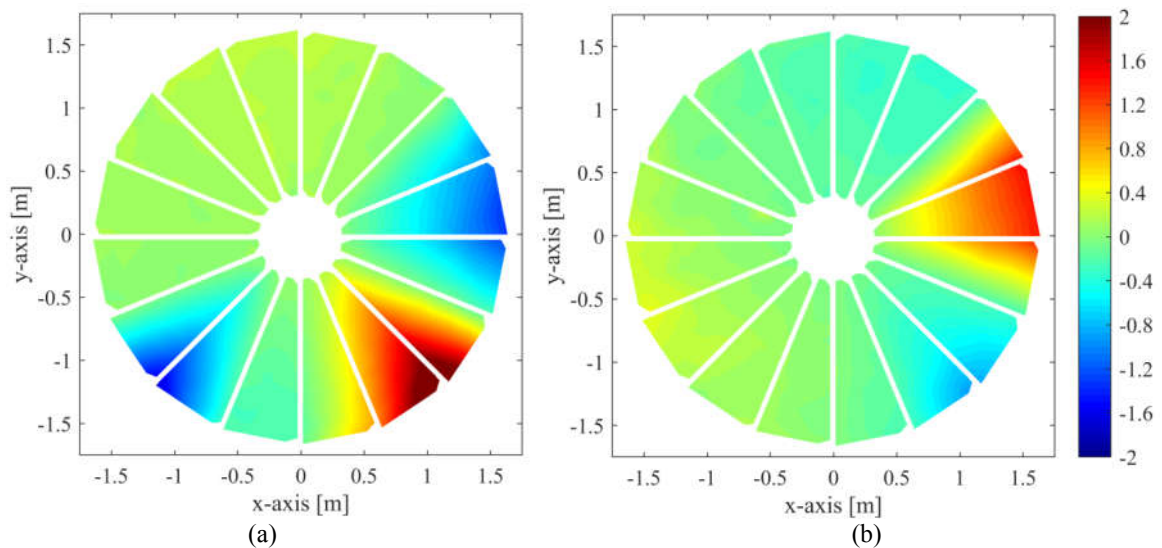
The stiffness of the concentrator is important not only regarding durability but also regarding its resulting shape and slope accuracy and thus regarding its optical efficiency. Deformation during heliostat operation at varying elevation angle can lead to significant energy losses [4]. Therefore, the system's deformation was characterized by photogrammetry measurements at different elevation angles.



**FIGURE 3.** Assembly of sandwich segments and central hub

Photogrammetry is the science of making measurements based on multiple photographs from different perspectives, especially for recovering the exact positions of surface points. To this end, the object of interest is equipped with coded and un-coded retro-reflective targets as well as calibrated scaling rods (Fig. 1, (a)) and high resolution photographs taken from the hemisphere above it. During post-processing the pictures are oriented with the help of the coded targets. Subsequently, the 3D coordinates of the measurement points are identified from bundle adjustment.

It is assumed that the concentrator will be shaped for optimum curvature at a mean elevation angle close to  $45^\circ$ . Therefore, the shape measured at an elevation angle of the prototype of  $45^\circ$  (Fig. 1) was used as a reference. The deformation of the horizontal concentrator ( $0^\circ$ ) and of the close to vertical concentrator ( $81^\circ$ ) compared to the shape of the reference orientation ( $45^\circ$ ) was determined. The results are shown in Fig. 4.



**FIGURE 4.** Deformation of mirror points in normal direction in mm for horizontal (a) and almost vertical (b) concentrator compared to the shape at  $45^\circ$  elevation angle

The results show relevant deformations at the lower segments at which the support rods of the concentrator are fixed. The deformations of the segments connected with the support structure seem to impact also the segments on the right. The other segments show almost no deformation. From this it can be concluded that with the new sandwich concentrator high stiffness and therefore accuracy can be reached. However, the support structure must be connected to the concentrator in a way that moments cannot be transferred from the support structure to the mirror segments.

## CONTROL

The vision based tracking control system uses a camera mounted on the moving heliostat frame. The camera image is used to detect the position of the sun and the receiver (or another suitable marker), relative to the mirror normal [1]. This control principle makes the tracking basically independent of the accuracy of the drive systems, as long as the drives are stiff enough and of low backlash to maintain the desired frame orientation. Position sensors are not required at the drives, and the azimuth movement with wheels can be even performed on uneven natural ground, fully tolerating changes with time. The concept can also result in reduced requirements on mechanical parts of the drives, simplifying manufacturing and installation and reducing cost. Systematic errors can be compensated by an appropriate heliostat calibration method, e. g. the target-based calibration method. The tracking accuracy is then mainly determined by the measurement accuracy of the camera system.

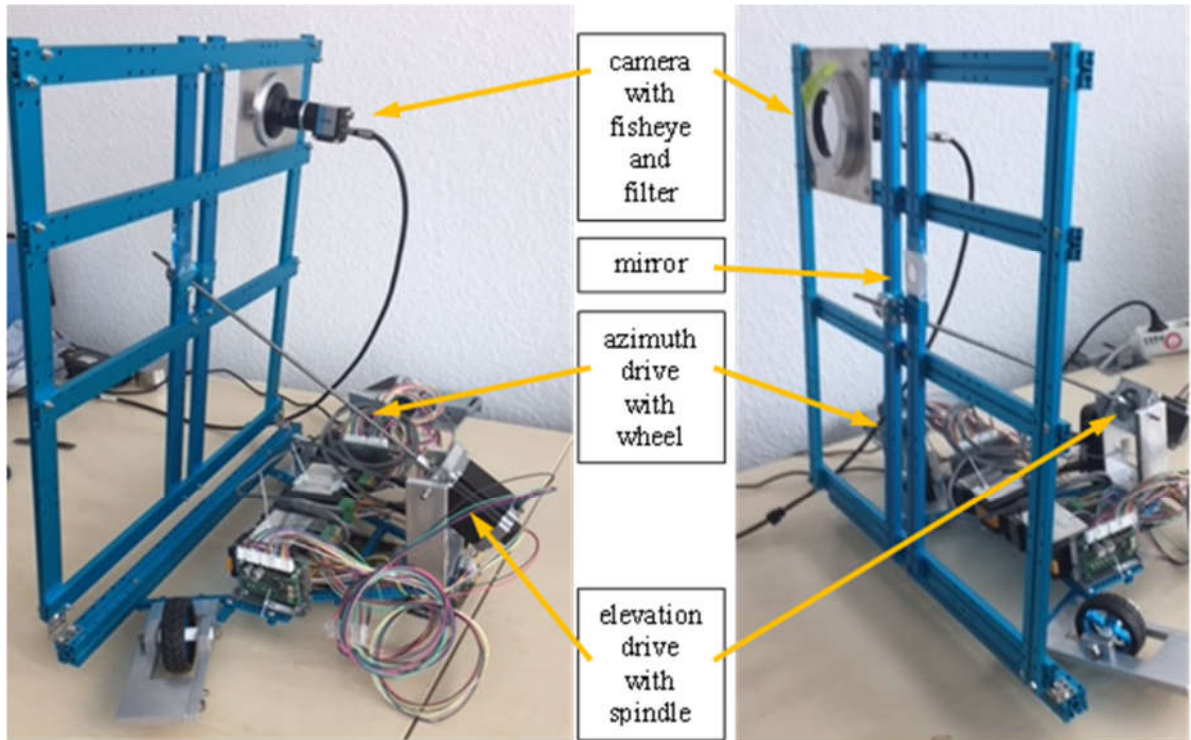
The optical sensor prototype consists of an 18 MP camera with a 1.8 mm fisheye lens and a strong attenuation filter in front (optical density 3.8, i.e. attenuation by a factor of 6300). The optical sensor is fixed to the concentrator and performs the same rotations as the mirror. The sensor detects markers with known 3D-position like the sun and features of the receiver/tower. For a camera with internal as well as external calibration with respect to the mirror, an algorithm reconstructs the pose (position and orientation) of the camera and hence of the mirror. Deviations from the desired orientation are controlled by moving the two drives.

Since the intensity of the sun is much higher than the intensity of the other markers, the camera must have a large dynamic range to capture both the sun and the surroundings. To enhance the marker detection, two subsequent images are taken with the camera. A first image with very short exposure gives a clear sun image, and a second image with longer exposure time allows detection of darker markers, while the sun image is overexposed. The images are taken right one after the other to represent a common pose of the heliostat. All in all a tracking accuracy similar to conventional heliostats is expected.

For the validation of the tracking control a fully operational small-scale demonstrator was built (frame size about 46cm x 46cm), Fig. 5. This demonstrator uses a duplicate of the optical sensor setup that will be used in the prototype heliostat, and also the stepper motors with the corresponding drives are identical. Only the mechanical setup after the motors is different. Instead of mirrors covering the whole heliostat frame, a small mirror piece with a diameter of about 1cm is placed near the center of the heliostat frame. This allows accurate evaluation of the position of the reflected image on a target.

Initially, indoor tests with a fixed position torch light and a white target with markers were carried out to verify appropriate tracking function, by evaluating the center of gravity of the torch image reflected by the demonstrator mirror. These indoor tests have shown a very good repeatability, typically well below 0.1 mrad tracking error.

Outdoor tests with real sun and representative geometry conditions are currently under preparation. Once completed, the inclusion of the receiver marker will be the next step, allowing validation of the accurate tracking on uneven ground.



**FIGURE 5.** Demonstrator unit with mirror, camera, and drive system

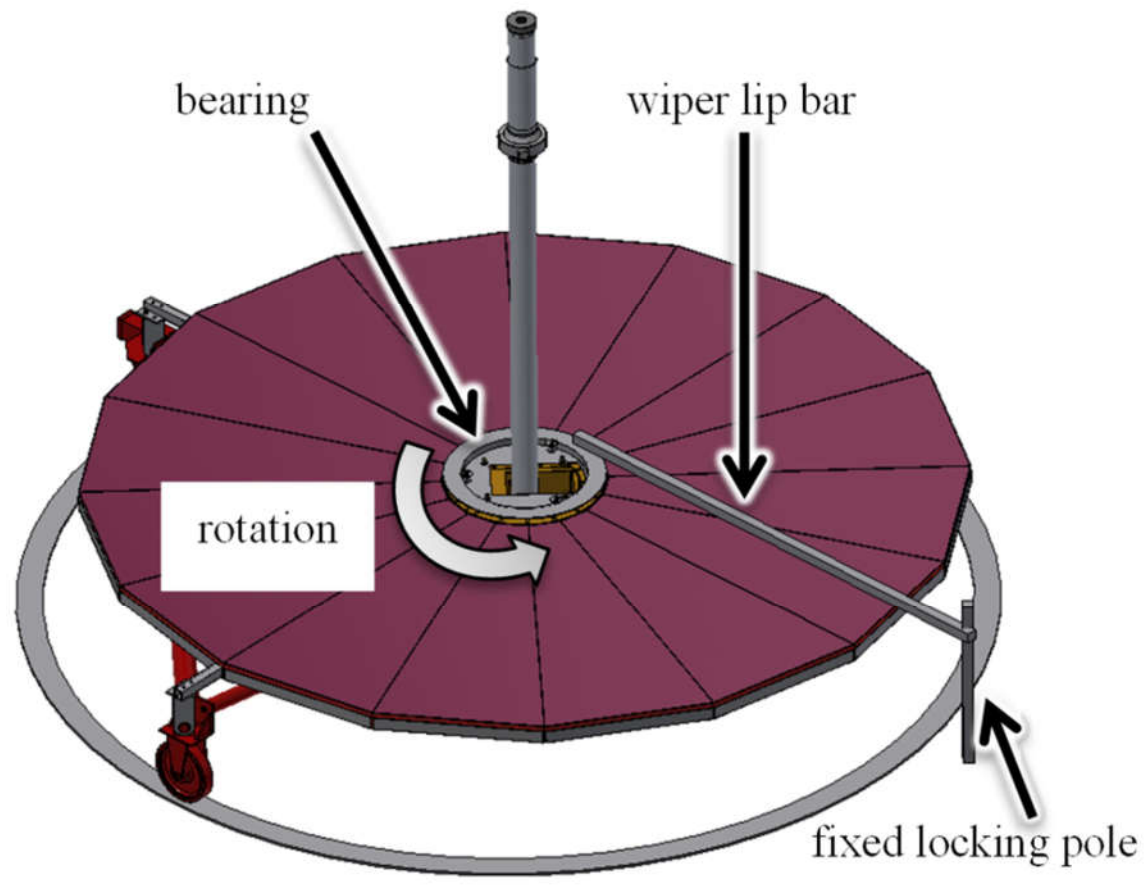
## CLEANING SYSTEM

Previous studies [5] have shown that water-soluble particles are cemented onto the surface of solar reflectors during alternating dry and humid periods as encountered in desert areas. The cleaning effort and water consumption to remove cemented particles is significantly higher than cleaning a surface with not cemented particles. From this point of view it seems desirable to clean the mirrors after every dew formation or rain. Then simple cleaning methods with low water consumption like wiper systems can be applied. To avoid high labor costs automated systems would be required.

In the EU project WASCOP a cleaning system for automatic mirror cleaning is under development. The new heliostat concept is particularly suitable to realize a wiper cleaning system of low cost. When in stow position, the horizontal concentrator can simply be rotated under a fixed wiper lip by the azimuth drive. The wiper lip can be located

1. on the concentrator itself or
2. next to the heliostat with an extra actuator for positioning it on the concentrator during cleaning.

The disadvantage of the first option is a reduction of the effective reflective surface. Assuming a 50 m<sup>2</sup> heliostat, the reduction is less than 0.3%. With the target heliostat cost of 80 \$/m<sup>2</sup> [1] the reduction is equivalent to 12 € extra cost per heliostat or 0.24 \$/m<sup>2</sup> (for the required additional heliostats). This amount is negligible compared to the cost of an extra active actuating system for positioning the wiper system. Therefore the first solution was chosen. The concept is illustrated in Fig. 6. The wiper lip is fixed on a bearing in the center of the heliostat. During cleaning, the bar holding the wiper lip is stopped from rotating with the concentrator by a pole positioned next to the heliostat. Thus, the concentrator rotates under the fixed wiper lip and is cleaned. If the wetness caused by dew or rain is not sufficient additional water is sprayed on the mirrors through the wiper lip bar or from the pole besides the heliostat.



**FIGURE 6.** Wiper lip bar fixed at a central bearing and stopped from rotating with the concentrator by a fixed locking pole

The system will be installed and tested on the 8 m<sup>2</sup> heliostat prototype. To achieve a significant cost reduction the cost aim for the complete cleaning system was set to < 8 €/m<sup>2</sup>. The cleanliness factor shall be > 98 %. The benefits of the cleaning system are that labor cost is reduced significantly and that it could thus be run more often than common cleaning systems. Hence, the average cleanliness and consequently the efficiency of the solar power plant would be increased.

## SUMMARY AND OUTLOOK

The first prototype of a new carousel heliostat with lay down option for storm conditions and monolithic sandwich concentrator was erected at the Solar Tower Jülich. All components lead to significant cost reductions:

- The azimuth drive is realized by a simple carriage with one of the two wheels driven.
- The gear motor for the spindle elevation drive is located in the spindle itself. Gimbal mounts of the spindle protects the spindle and the spindle nut from lateral forces and reduces the accuracy demands on the interfaces.
- The sandwich concentrator consists of a low number of different parts. The manufacturing comprised only four main steps. The results of photogrammetry measurements showed a high stiffness of the concentrator. To avoid deformations of the concentrator caused by deformations of the support structure the connection between both must exclude the transfer of moments.
- The optical quasi closed loop control was tested with a lab system and showed sufficient accuracy.
- For the carrousel heliostat a very simple wiper cleaning system can be realized.



The next steps will be the following:

- Tests of the drives, the optical control, and the cleaning system will be performed.
- In the project “Heliomaroc” two 9 m<sup>2</sup> heliostat prototypes will be built by Moroccan companies and tested.
- In a follow-up project the following shall be improved:
  - Upscaling to 50 m<sup>2</sup>
  - Development of a suitable rigid foam system for the core of the sandwich concentrator
  - Simplification of pavement and development of suitable wheels
  - Simplification of spindle protection
  - Development of low cost ground anchor

## ACKNOWLEDGMENTS

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