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A review of available methods for surface shape measurement of solar concentrator in solar thermal power applications

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ABSTRACT

The surface shape and optical quality of the solar concentrators have a great influence on the solar power plant efficiency, and there need an accurate, inexpensive and fast tool to do this measurement work at the plant start up and during operation. The development of the measurement methods of the solar concentrators over the past several decades was reviewed, and three types of the measurement methods: video scanning Hartmann optical test (VSHOT), photogrammetry and deflectometry were introduced in detail. A comparison of the different methods was made, and an outlook is also put forth.

Contents

1. Introduction

As global warming and an unbalance of the world energy system, solar thermal power plants will play an important role in future energy supply [1,2]. At present there exist three kinds of solar concentrating system in the world: parabolic trough system, power tower system and the dish/Stirling system. In all these systems the solar concentrator is the major cost component, and the optical quality in particular the geometric precision of the solar concentrators has a significant impact on the efficiency and thus on the performance of the power plant. Any deviation from the optimum shape can lead to optical losses, therefore it is important to have a tool that can measure surface slope errors with adequate precision. As the tested surface is specular, and requiring a quite high accuracy, then the measurement procedure must be a noncontact method, and this constraint excludes the various mechanical methods available. As we know, the interferometer is the most powerful tool to measure optical surfaces, but this standard interferometric method is also not suitable to measure the solar concentrators as following three reasons: firstly, the solar concentrator often has a large diameter, so it is inappropriate to use an interferometer to do the measurement work. Secondly, the optical errors of the solar concentrators are not fall in the measurement range of the interferometer, the larger surface slope errors would make the interference fringes too closely spaced and difficult to analyse. Thirdly, the interferometers are too complicated and expensive. All these reasons make it impossible to be used in the solar power system. In the year 1978, Smolka proposed a noncontact method for measuring the surface profile of a reflecting surface named two-pulse technique [3]. This method directly measures the phase difference between a reflected laser beam on surface and a reference laser beam. In this way the slope of the surface can be measured at various points. And the surface profile is then obtained by integration. This method yields a reasonably good accuracy, in

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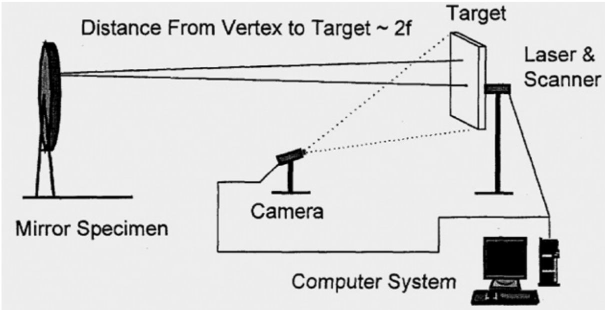

Fig. 1. Schematic of the VSHOT [4].

the 1–10 μm range. But the process to obtain data point-by-point makes it not suitable in the concentrating solar power system.

Usually, the solar concentrators have very large size, for example, heliostats in central receiver solar power plants can reach dimensions up to 150 m^2 with focal lengths up to 1000 m. And a heliostat field may consist of several thousand heliostats. It is a huge and difficult task to measure the optical quality of those specular facets both at plant start up and during operation. So we need a measurement fulfills the requirement to be accurate, inexpensive and fast at the same time. In the past three decades, many possible approaches have been put forward and applied in practical. They can be classified into three types according to their physical principle. The first kind is the so called VSHOT (Video Scanning Hartmann Optical Test) that is based on the laser scanning technique. The second and the third kind are the method based on image processing techniques and need a help of a camera to record the image, called photogrammetry and deflectometry respectively. The remainder of this paper is organized as follows: we will review the three types of surface shape measurements in detail firstly. Then a summary is put forth to analyse the advantages and shortages between the different methods. And an outlook for the development trend is also given at last.

2. Methods of surface shape measurement

2.1. VSHOT method

In 1996, Jones et al. developed a prototype Video Scanning Hartmann Optical Test (VSHOT) [4] which is an evolutionary step beyond the original SHOT [5] system. It is a laser ray trace device utilizing a video system to measure the optical quality of point-focus solar concentrating mirrors, providing higher speed testing and requiring less operator oversight. A schematic of the VSHOT is shown in Fig. 1.

The distance from Mirror Specimen to target is slightly greater or less than twice its focal length. And a laser beam is controlled by a 2-axis scanner. A laser beam strikes on the mirror and reflects back to the target. The CCD camera takes the image and the data digitized by a computer video board, and then centric location of the reflected spot is calculated. This method measures the slope of a reflector at many locations and compares that information to the mathematical simulation. Because the VSHOT was based on direct measurement of slope and provided a quantitative map of optical errors, it is proved to be suitable to characterize the optics of not only the dish-type solar concentrators but also any large reflector with a focal length over diameter ratio greater than 0.45, and RMS optical error in the 0.1–10 mrad range. And the VSHOT hardware, software, and operation are also described.

In the second year, Jones et al. studied the accuracy of the VSHOT measurement as well as its sensitivity to changes in test setup variables [6]. And not long after, in 1998, Jones used the VSHOT measurement to test the Distal II Dish/Stirling systems installed at the Plataforma Solar de Almeria (PSA) in southern Spain [7]. This is first use of VSHOT on a concentrator installed and operating in the field. The outdoor testing appears feasible and a number of suggestions to improve the VSHOT capabilities in outdoor testing have been provided.

2.2. Photogrammetry method

Essentially photogrammetry is the science of quantitative analysis of measurements from photographs. And in the early photographic processes this method was been used for qualitative mapping. But until the year 1996 when Shortis et al. wanted to assess the surface quality of the so called 400 m^2 "Big Dish" at the Australian National University (ANU), they developed the photogrammetric method to characterize the surface of solar concentrators [8,9]. In this method several cameras record from different viewpoints and a number of targets fastened over the surface to be measured. The image locations are connected to the corresponding points, and the object is then recreated in three dimensions using the principle of collinearity. Traditionally, we can use manual or semi-automated devices such as photogrammetric comparators or stereoplotters to help us. The number of camera stations and the number of photographs at each camera station is decided by the desired precision of measurement. And due to the requirement for a minimum level of reliability, the minimum number of camera stations is four. Photogrammetry has been successfully applied in a large range of mirror sizes (up to 400 m^2) with focal lengths up to about 13 m and it is proved to be available to assess surfaces of almost any size or orientation. But observation of the target images is a time consuming work and this technique does not provide surface normal information directly. What is more, the cost for commercial film-based photogrammetric assessment is relatively high. As this reasons, nowadays digital image based systems are becoming widespread.

In 2005, Pottler et al. used the digital close range photogrammetry method to measure a range of solar concentrator components [10]. Such as fabrication jigs, concentrator sub frames, trough mirror facet surface, small-scale mirror facets and so on. In order to ensure photogrammetric accuracy both the internal and external measures are used. And in the year 2008, Shortis et al. also described the use of close-range photogrammetry to solar collectors [11]. And later, Burgess et al. used the photogrammetry to control the assembly of a convex parabolic jig which used in the construction of a new designed solar concentrating dish called SG_4 [12]. The SG_4 has been constructed at the Australian National University (ANU) during September 2008. The evidence arising from these studies indicates close-range photogrammetry is an appropriate tool that aids both the design and quality control of the construction of solar concentrating systems.

The whole measurement procedure including preparation, data-acquisition and evaluation of the traditional photogrammetry method usually takes up several hours, since the fetroreflective targets must be positioned on the object. In 2008, Röger et al. proposed a new photogrammetric measurement based on edge detection [13]. This new method uses the automatically detected heliostat facet corner points instead of the circular-shaped retro-reflective targets, and in this way, it extremely reduces the measurement time. A digital camera is mounted on the top of the central receiver tower offering visibility to all heliostats and providing the pictures. Combining with several standard images processing techniques, this method was tested on a 40-m^2 CESA-1 heliostat at the Plataforma Solar de Almerìa (PSA) and it exhibited an accuracy of 1.6 mrad for a single-facet normal vector. Of course compared to manual photogrammetry with retroreflective targets the accuracy

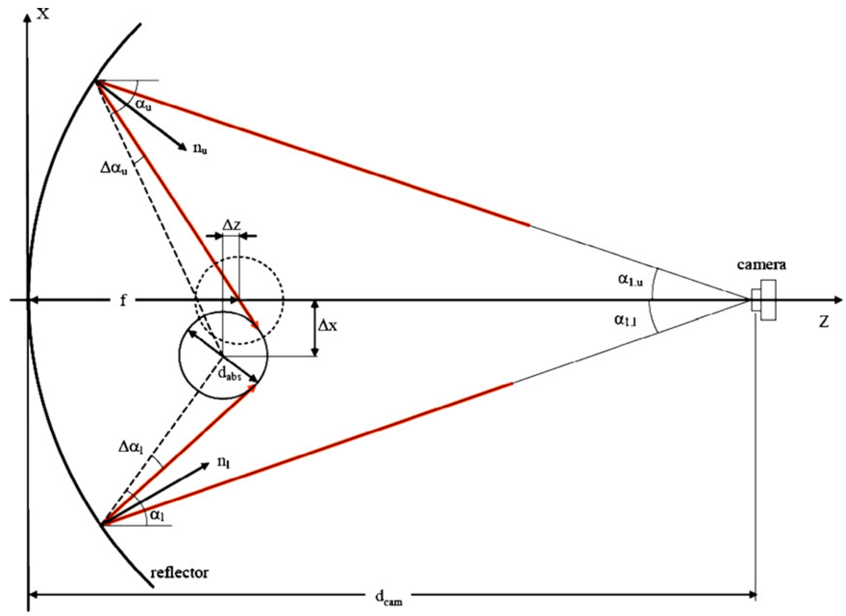

Fig. 2. Measurement set-up of the absorber reflection method [14].

is lower but it is still sufficient to detect facet misalignments in existing heliostat fields.

As the application and evaluation of many targets is a time-consuming task, another method to overcome this restriction is developed by Ulmer et al. in the year of 2006 [14]. It is called "absorber reflection method", as it uses the reflection images of the absorber tube in the concentrator which seen from some distance to measure the reflector slope of the parabolic troughs with high accuracy. And Fig. 2 shows a sketch of the used measurement set-up.

A digital camera is positioned on a tripod of about 100 times the focal length from the collector. A series of pictures is taken while tilting the collector from up to down. Due to the concentrating optics, the reflected image of the absorber tube is magnified. Then the position of the reflection within the concentrator and the shape of its outer edges are very sensitive to variations in surface slope. This new method has a simple set-up and the time-effort for slope measurements is drastically reduced. The drawback is that the measurements are limited to horizontal collector position.

As the above methods are not practical for the very large focal length system, a novel procedure for the optical characterization of solar concentrators is presented by Arqueros et al. in the year 2003 [15]. The method has been named SCCAN which stands for "Solar Concentrator Characterization At Night". It is based on recording at night the light of a star reflected by the mirror. A schematic of the SCCAN is shown in Fig. 3.

This technique relies in simple principles of geometrical optics. A point source (object at infinity) reflected by an ideal parabolic mirror will converge at the focus. Therefore an observer located at the focus would see the whole mirror surface "bright". But a realistic mirror is far from ideal, thus the images of a point source taken from its focal region have a finite size and these images allow the reconstruction of the slope map. The SCCAN method can be easily applied to heliostats of a central tower system, and the first tests carried out with a heliostat of the CESA-I field at the Plataforma Solar de Almeria have shown its feasibility. The uncertainty is about 1.0 mrad, and the data are taken in the night and in situ at usual working conditions which means it would not interrupt the energy production in the solar plant. In addition the cost of this method is extremely low.

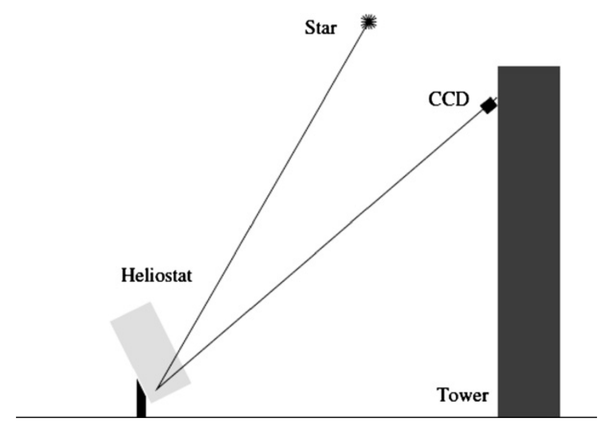

Fig. 3. Schematic of the SCCAN technique [15].

2.3. Deflectometry or fringe reflection technique

Deflectometry is an optical measurement technique originating in the car manufacturing industry, and it is virtually identical to "Fringe Reflection Technique" which is developed by BIAS (Bremer Institut für angewandte Strahltechnik) [16]. It is a projection technique based on structured light patterns which uses a camera for imaging and a video projector for target generation just like other projection methods do, such as triangulation. But there is a difference between the Deflectometry and the triangulation method [17] which is illustrated in Fig. 4 and Fig. 5.

Fig. 4 shows the difference of the images forming process between the two methods. In triangulation, the projector projects

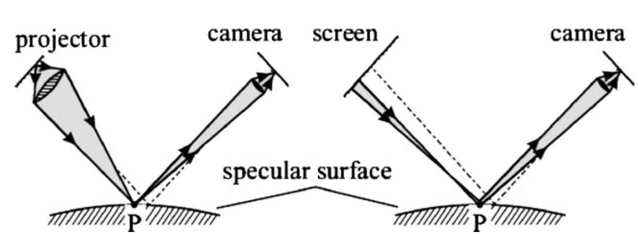

Fig. 4. Measurement principles: (a) triangulation; (b) deflectometry. [17].

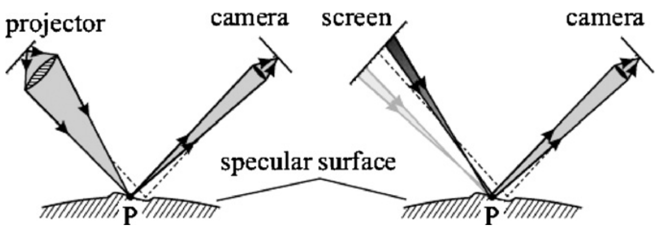

Fig. 5. Sensitivity to the surface slope: (a) triangulation; (b) deflectometry. [17].

patters on the surface directly. But in the deflectometry method, the camera views the image of a screen which displaying a certain intensity pattern. In this way the surface becomes a part of the optical system and it causes a different sensitivity compared with the triangulation method. For example if the surface is tilted at the point P just as Fig. 5 indicated, the camera still observes the same point of the pattern when projection method is used. But when we use the deflectometry method, the camera will observe a completely different area of the screen. Thus, the light rays are deviated depending on both the slope and the distance between point P and the patterns on the screen. So we can increase the distance to enhance the sensitivity. In 2008, Kammel et al. published a paper on IEEE transactions and introduced a deflectometric method to measure specular surfaces [18]. The method is exactly the same with the procedure they proposed in 2005 [17].

A measuring principle based on Deflectometry which called 'Phase Measuring Deflectometry' (PMD) was developed by Horneber et al. [19]. A sinusoidal pattern was generated on the screen by a fringe projector. And a camera captures four images of the object while the sinusoidal pattern is shifted each time by $\pi/2$. Then using the phase shift algorithm we can directly compute the slope perpendicular to the fringe direction. And in 2004, the same research group used this new PMD method to measure specular free-form surfaces [20], the experimental setup is illustrated in Fig. 6.

A projector generates fringes on a rear projection screen and a camera observes the pattern, using the specular surface as a 'mirror'. They discussed the method's diffraction-theoretical limits and used various photogrammetric methods to solve the calibration problem. At the same time they applied this measurement to measure the local curvature of progressive eyeglass lenses and analysed the experimental results.

In 2005, Fontani et al. proposed a measurement principle called Reflection Grating Moiré Method [21]. And they applied the method to measure the curvature of a deformable mirror of 1-m diameter for a heliostat plant. The schematic setup is showed in Fig. 7.

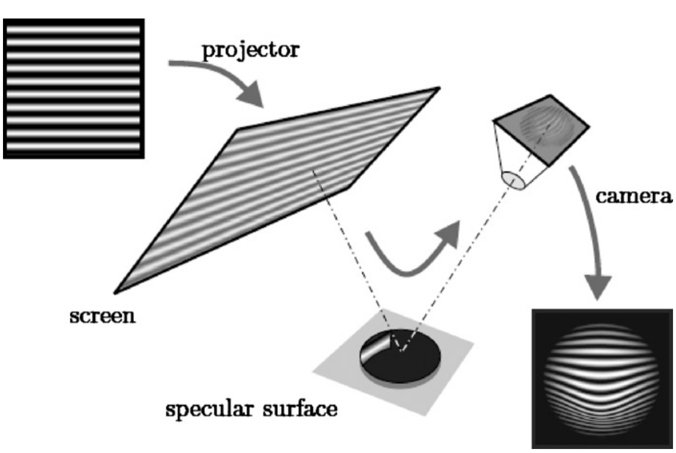

Fig. 6. Schematic setup of a sensor based on PMD [20].

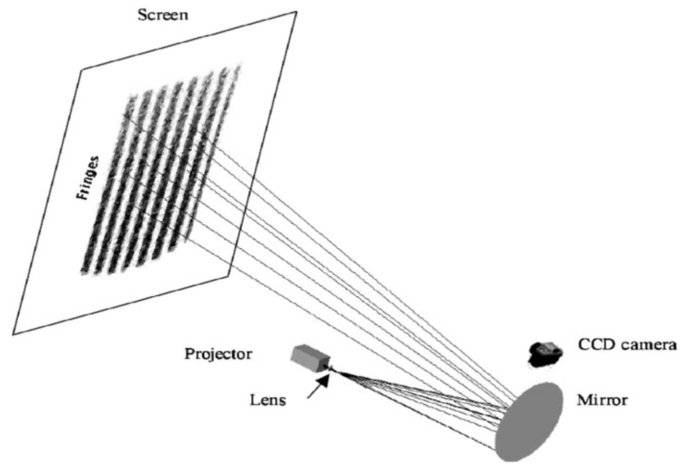

Fig. 7. Measurement optical system of Reflection Grating Moiré Method [21].

A grating is projected on the mirror to be tested and reflected, then arriving on the screen. The image of the grating before and after the deformation of the mirror is recorded. The local slope of the surface can be obtained by comparing the image with mirror deformation and the reference image. This method performs high sensitivity measurement and uses two different approaches. The first one is a surface reconstruction technique to provide quantitative curvature assessment and the other one is a study of the Moiré fringe pattern to provide a qualitative validation of the procedure.

Soon after, Heimsath et al. adapted the fringe reflection technique to large solar mirrors for Linear Fresnel Collectors [22]. The set-up in the laboratory is showed in Fig. 8.

The numbers in the schematic represent: (1) CCD camera, (2) coordinate plane with fringe pattern, (3) mirror, (4) projector, respectively. The measurement theory is similar to other deflectometry or fringe reflection system. A projector generates phase-shifted sinusoidal fringe patterns, a camera records the reflected pattern from the mirror under investigation, the fringe distortions and surface normal are calculated by phase measurement method. This technique can be made outdoors in the solar field and the results for the linear Fresnel collectors shows it is possible to achieve an accuracy of more than 0.1 mrad for surface gradients.

In 2009, Andraka et al. reported a new characterization system based on fringe reflection technique named SOFAST (Sandia Optical Fringe Analysis Slope Tool) [23]. This method is shown schematically in Fig. 9.

The target is an LCD screen used to display sinusoidal fringe patterns and a camera views the image of the fringe pattern reflected from the facet being measured. Through the fringe analysis, the return location at the target of each pixel can be determined. Using geometry and ray tracing method, we can calculate each point on the facet, and then the surface normal on the facet

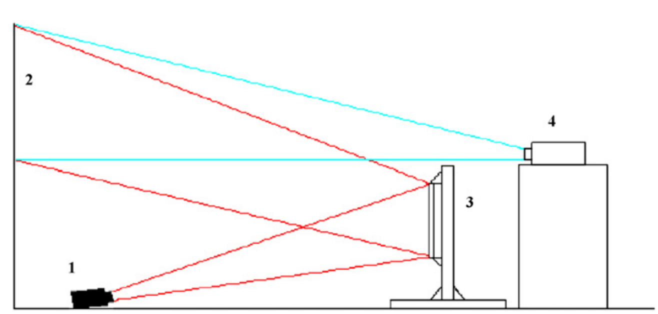

Fig. 8. Measurement set-up of fringe reflection technique in the laboratory [22].

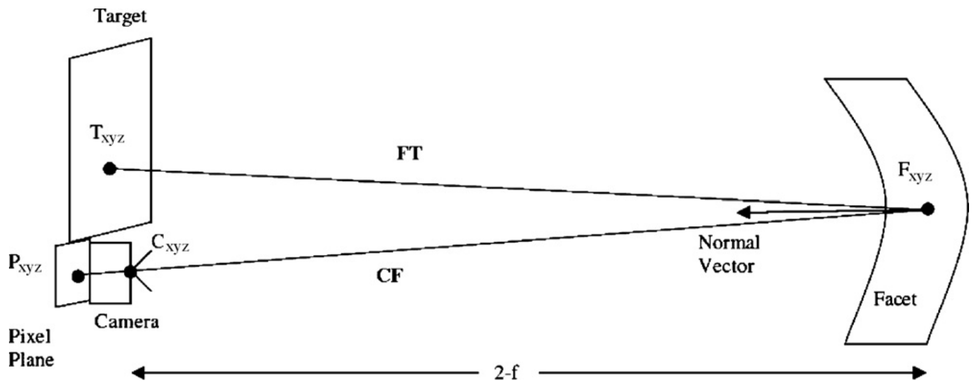

Fig. 9. Schematic of SOFAST system [23].

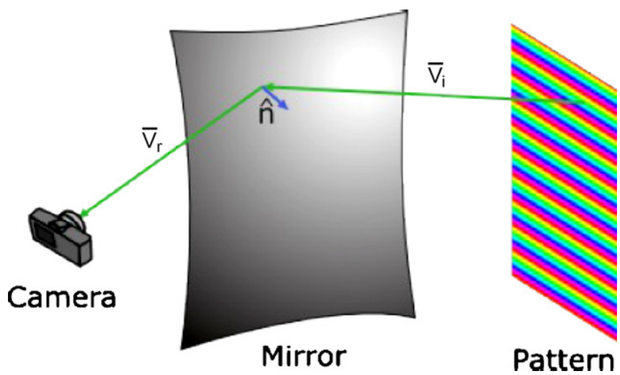

Fig. 10. Basic setup of the CPD method [24].

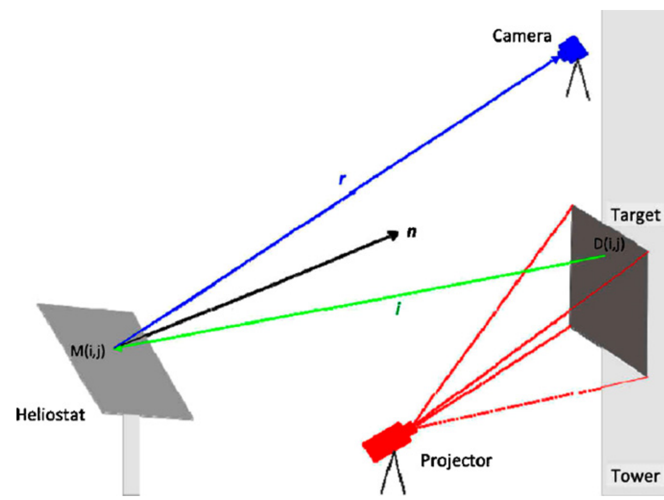

Fig. 11. Measurement set-up used for heliostat measurements in the field [26].

can be determined. According to the author this method can characterize facets quickly enough for 100% inspection on a production line.

In order to outperform the currently used photogrammetry, a new method named "Coloured Pattern Deflectometry (CPD)" was exploited by Scott et al. in 2010 [24]. This method differs from other deflectometry systems that a coloured pattern is used instead of phase shifting techniques. The initial idea to use colour in the patterns came from colour-coded target dish measurement system [25]. By using the coloured pattern, we can print a sheet of paper instead of the LCD monitor, and it reduces the price and complexity of the system. The basic setup of the CPD method is shown in Fig. 10.

A camera views the reflection images of a patterned object. The slope errors at each point are calculated by the difference of the measured surface normal from the fitted surface normal. This system is proved to be economical, speedy and simple. And inspiring news is that the programme of the CPD method will be released as open source code.

Recently, the German Aerospace Center (DLR) has developed an optical measurement system based on the principle of deflectometry, and it can measure the heliostats in the field [26]. The set-up is shown in Fig. 11.

It uses a projector to project series of regular vertical and horizontal stripe patterns on a white target surface at the tower at night. A digital camera located on top of the tower takes images of the heliostats. In order to evaluate the images and calculate the deviations in local surface slope a computer is used. And a ray tracing software based on this system has been developed by Belhomme et al. [27]. At present, a resolution of about 1 million points per heliostat with a measurement uncertainty of less than 0.2 mrad is reached. The measurement time for one heliostat is about 1 min, so the measurement can be completed during one night. Thus this method offers significant gain in speed and handling. But we must guarantee that the reflection of the stripe patterns on the target can be seen in the whole heliostat. Additionally, other solar concentrators such as dishes, troughs or individual facets may also be able to use this described measurement.

3. Summary and outlook

The mainly three types for surface measurement methods of solar concentrators were discussed above. These methods were proposed in the past three decades, and all of them have their own advantages and disadvantages. The Video Scanning Hartmann Optical Test (VSHOT) is a procedure directly measure surface slopes and it is suitable to characterize the optics of dishes and parabolic troughs where it is sufficiently accurate. However, their set-up is time consuming, and it may take a long time to scan large surfaces with high resolution. Additionally, the VSHOT might be difficult to adapt to heliostat measurements, because the large distances means there need an extremely high pointing precision of the laser. What is more, the solar concentrators have to be vertical in the VSHOT measurement, but the collectors' position face more or less horizontally in the field. It is also a restriction of this method.

Photogrammetry is a method based on photographic processes and widely used for the 3-dimensional measurement of objects. It allows the measurement independent of its orientation, so it can be used to test almost any type of the solar concentrators. However, in this method the measured surface has to be equipped with a large number of target points which are used as individual surface measurement points, but the application and evaluation of the large numbers of targets is a time-consuming task, therefore it is not appropriate for the higher resolution measurement of large numbers of mirrors. Another shortage is that the slopes of the reflective surface are calculated from coordinates of points in space, so any inevitable measurement deviations can lead to significant errors in the local slope calculation. Two evolutionary methods improved the situation, one is the so-called "absorber reflection method" which uses the reflection images of the absorber tube and the other is called "Solar Concentrator Characterization At Night" (SCCAN) which use the reflection of a star in the mirror at night. But the former method is just suitable for parabolic trough system, and the latter one depends on clear-sky conditions at night, and when high spatial resolution is desired, it is also a time consuming task.

The Deflectometry or fringe reflection technique is a measurement principle which has been coming up in the last decade. It is suitable for measuring large surfaces with high resolution, particularly for measuring heliostats of a central tower system with a typical focal length of 100 m or larger. And compared to other existing measurement methods, the biggest advantage is that it can cut down the measurement time greatly. Additionally, the phase shift algorithm which used in Phase Measuring Deflectometry (PMD) method can optimize the mathematical process. And the use of coloured pattern can simplify the system and reduces the cost. However, the images processing procedure seems not that easy, and the calibration problem is a trouble we will encounter in the practical measurement.

Solar concentrators are the key components of the concentrating solar power system, and to find an accurate, inexpensive and fast tool to measure their surface shape and optical quality is our permanent goal. The methods discussed above seems not fulfill the entire requirement perfectly. Due to the short measurement time and suitable for measuring large surfaces, the deflectometry method maybe is the most promising techniques in the future. But there is a lot work to have to do with the calibration techniques, algorithms optimizing and many other images processing problems.

Acknowledgements

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