SolarPACES 2022, 28th International Conference on Concentrating Solar Power and Chemical Energy Systems
Measurement Systems, Devices, and Procedures
https://doi.org/10.52825/solarpaces.v1i.618

Published: 20 Dec. 2023

A New Reflected Target Optical Assessment System

Stage 1 Development Results

Devon Kesseli[1[https://orcid.org/0000-0001-9311-3036]], Mojolaoluwa Keshiro[1[https://orcid.org/0009-0005-4276-4919]], Rebecca Mitchell[1 [https://orcid.org/0000-0002-5325-7737]], and Guangdong Zhu[1[https://orcid.org/0000-0001-9280-285X]]

[1] National Renewable Energy Laboratory, United States of America

Abstract. NREL has completed stage 1 development of an indoor optical measurement tool for fully assembled heliostats and single facets. This tool began as an indoor version of NREL's outdoor Non-Intrusive Optical (NIO) measurement technique [1]. It uses similar techniques to other available tools (deflectometry, photogrammetry, etc.), but is designed to require very little infrastructure, labor, and time to set up and collect surface slope and canting measurements, making it a valuable tool for quality assurance and laboratory measurement of heliostat optics. It accomplishes this by using computer vision, photogrammetry, and multiple images stitched together to minimize the printed target size and required setup precision. This adaptable setup is useful for taking measurements at a variety of heliostat pointing angles, and for measuring fully assembled heliostats on the assembly line. In this paper, we describe the methodology behind the measurement system, present an initial analysis of its uncertainty and sensitivity, and compare it with established optical measurement systems.

Keywords: Heliostat Optics, Measurement, Slope, Canting, Deflectometry, Photogrammetry, Computer Vision, Concentrating Solar Power

1. Introduction

Accurate mirror optics are essential to achieving a well-performing concentrating solar field and ensuring that low heliostat or parabolic trough cost-per-flux is delivered to the receiver. This is a primary driver of efficiency in Concentrating Solar Power (CSP) and Concentrating Solar Thermal (CST) plants. Ensuring precise optics during assembly is often more efficient than measuring and adjusting optics in the field.

A variety of techniques exist to measure solar concentrator optics, both in the field and in a laboratory or manufacturing warehouse setting [2]. The main classes of techniques are photogrammetry [3], [4], reflected target methods, and fringe deflectometry [5]–[8]. Photogrammetry techniques are ubiquitous and useful; however, to measure the mirror surface slope, many targets must be attached to the mirror surface. This is time-consuming and obtaining high-resolution surface slope measurements (as opposed to 3D position measurements) is nontrivial. Deflectometry methods are well-established and highly accurate. QDec, a fringe deflectometry measurement system created by the German Aerospace Centre (DLR) and CSP Services, is commercially available for optical measurement [6], [8], [9]. SOFAST is a mature fringe deflectometry tool developed by Sandia National Laboratories [5], [10]. These methods achieve high-resolution results, and when implemented properly, they set a high standard for optical measurement. However, they have several drawbacks for use as a laboratory or assembly line quality assurance tool. First, these techniques require a series of multiple target patterns to be reflected on the mirror. This means that the target must be a very large liquidcrystal display (LCD) or projector screen to accommodate the changing images. When using a single camera and a near-flat heliostat, the screen needs to be more than two times the size of the mirror. Using multiple cameras can slightly reduce the required screen size, but these systems still require large and costly infrastructure. Second, collecting optical measurements with the mirrors at different orientations—which can measure gravitational effects—is challenging, as it requires moving and remounting the screen from the wall to the ceiling. Lastly, lighting must be carefully controlled because the dark fringe tone is only as dark as the projection screen under ambient lighting.

Here, we present a new heliostat optical measurement technique, the Reflected Target Non-Intrusive Assessment (ReTNA) measurement system, that overcomes these challenges to enable fast, low-cost analysis of heliostat optics in a laboratory or manufacturing setting. In a reflected target system, printed patterns are reflected in mirrors to determine mirror shape at the reflected features. Several groups have developed this type of system for use in the laboratory and in the field. Andraka et al. used a large, truck-mounted pattern board to measure heliostats at Sandia National Laboratories [11]. Beltrán-Madrigal et al. reflected a deformed dot pattern in parabolic trough mirrors to observe mirror surface deformation [12]. The ReTNA measurement system has several unique features that make it well-suited for fast, low-cost analysis:

- Using relatively small, modular printed targets mounted on walls or ceilings makes the system scalable to a variety of mirror sizes and orientations.
- Collecting multiple images from a moving camera allows the analysis to be performed with a much smaller target.
- Leveraging recent advances in computer vision, image processing, and photogrammetry greatly reduces the time and precision required for system setup and analysis. Target and mirror positions are automatically identified with a high level of precision.

Although reflected target techniques have lower resolution than fringe deflectometry methods, recent work suggests that a lower spatial resolution, on the order of one point every 2.5 cm of facet side length, is adequate to estimate the intercept factor and flux distribution profiles within 1% [13].

This method has wide-ranging applications, but it is particularly valuable for smaller-scale plants where a large, costly quality assurance installation would be impractical. It will also be useful for R&D, enabling researchers to quickly gain information on heliostat or trough optics under a variety of orientations and simulated loadings.

2. Methodology

All deflectometry systems use the same basic principles. Given the location of a camera or sensor, a target or source point in space, and the precise location of its reflection in a common reference frame, simple geometry and the law of reflection can be used to identify the surface angle of the mirror at the point of reflection. For optical metrology software, this measurement must be performed quickly, accurately, and automatically.

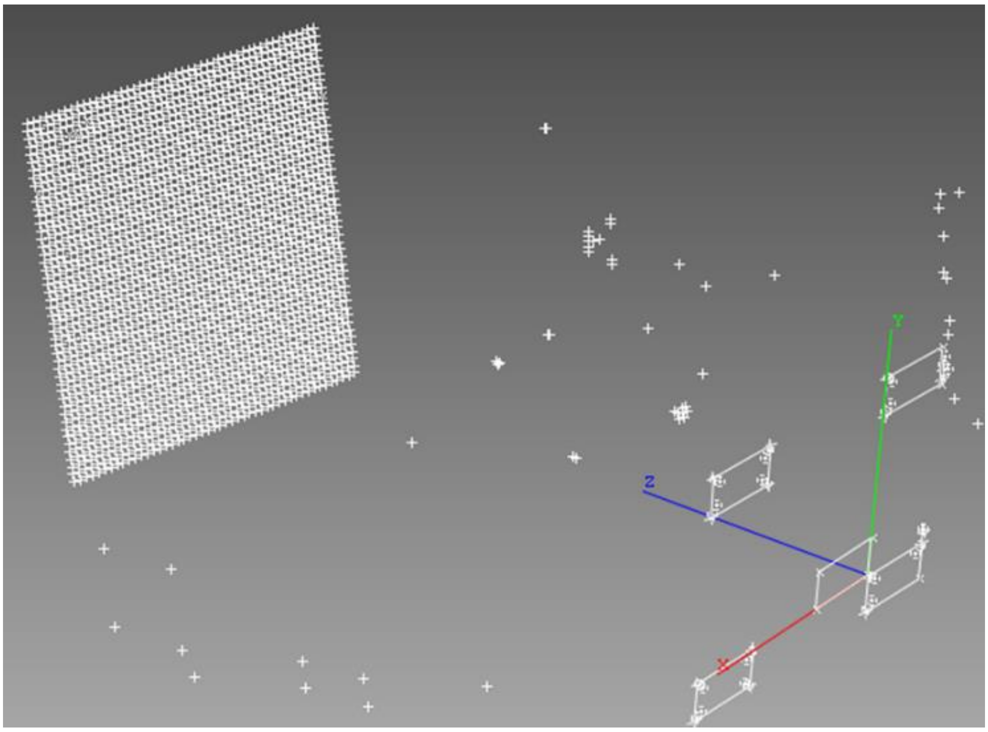

Figure 1. A photogrammetry model of the scene, with target points located in the mirror's reference frame.

The first step is to create a library of target point locations, organized by row and column, in the mirror’s reference frame. Currently, this is done using commercial photogrammetry software. In the future, this will be done by using a mirror stand or an assembly line at a known location with respect to the target; alternatively, this photogrammetry step will be incorporated directly into the ReTNA tool. For now, existing photogrammetry software meets this requirement. Once we have a model for the target, it takes only 5–15 new images to link these to a new mirror position and translate them to the new reference frame. To check the accuracy of the photogrammetry model, we examine the precision vector length of each target point, as shown in **Figure 2** (left). The library of target point positions is stored in a Pandas DataFrame for easy operation in Python, as shown in **Figure 2** (right).

	rows	cols	X	Y	Z
0	30	22	-0.5541	0.448830	6.229464
1	29	22	-0.5540	0.393556	6.218482
2	28	22	-0.5540	0.338000	6.207436
3	27	22	-0.5538	0.282600	6.196327
4	26	22	-0.5537	0.227013	6.185511

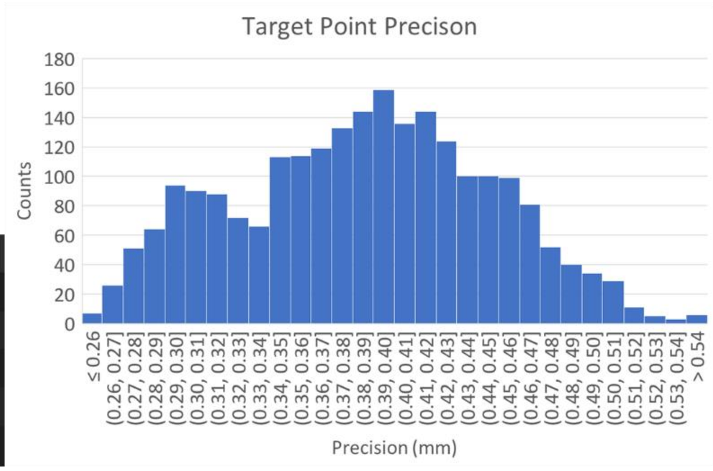

Figure 2. Photogrammetry is used to generate a library of target point locations (left). The precision of each target point is plotted (right).

Initial tests of the ReTNA system used projected targets, which can easily be changed to test different target styles and densities. **Figure 3** shows example images on a curved parabolic trough panel and a small, multifaceted heliostat. Printed targets, which will be used in the next version of ReTNA, were also tested successfully.

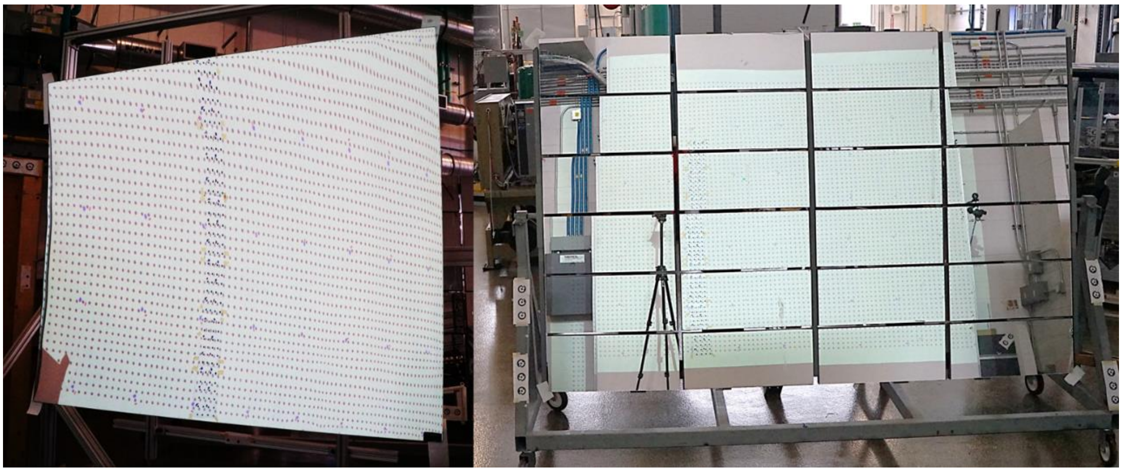

Figure 3. Example images used in the ReTNA analysis for a parabolic trough facet (left) and a multifaceted heliostat (right). Smaller, printed targets were also tested.

In an analysis image, like the ones in **Figure 3**, several features must be identified to generate the ReTNA measurements. These features are indicated in **Figure 4**. Nonreflected features like the corners of the mirror are used to create a common reference frame for the system. These points, which are at known relative positions with respect to one another (the length and width of the mirror panel), are used to directly solve for the position of the camera. Directly solving for the camera position allows ReTNA to use multiple images with a moving camera, without requiring the camera location to be known with high accuracy. Right now, these corner points are identified manually, but finding mirror corners using computer vision has been demonstrated by the ReTNA team and other researchers [14]–[16], and is a likely next step for the software.

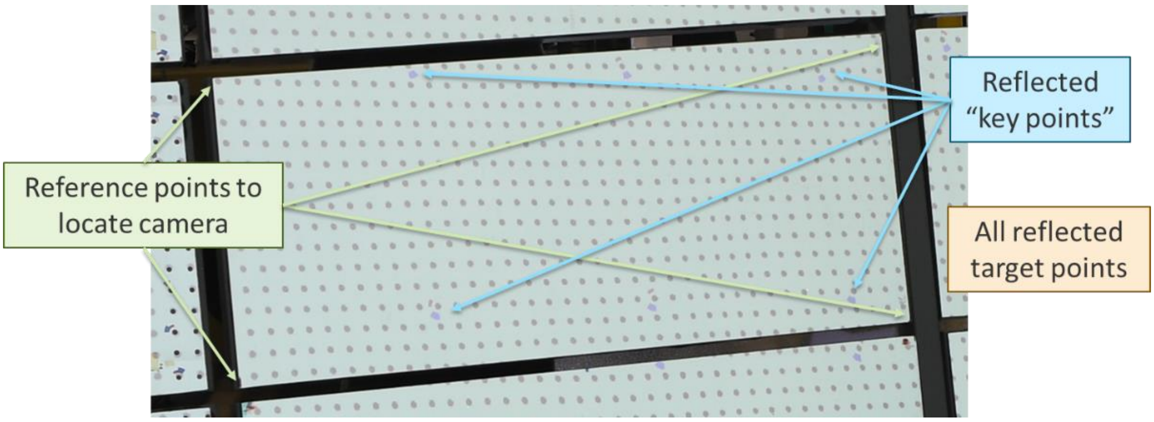

Figure 4. An expanded image of targets reflected in a mirror facet. Mirror corners, reflected target points, and reflected coded key points are identified for analysis.

All reflected target points are identified automatically using contouring and Hough Circle methods. The final pre-processing challenge is to map the reflected points to their corresponding points on the target. To do this automatically, key points are added to the target. These points are surrounded by unique code markings. Once four of these key points are identified in the reflection, ReTNA generates a transformation matrix, projecting reflected points onto the target. Each reflected point is transformed into the target's reference frame, and then a k-d tree is used to identify the closest point on the target. This method has been demonstrated to be fast (<1 second to associate over 500 points) and 100% effective for all tests on heliostat mirrors. Finding target points for distorted point positions can be challenging. This issue can be mitigated by adjusting the distances between the mirror and the target, however, it could present a challenge for mirrors with greater curvature. Testing this projection technique on parabolic trough mirrors is a priority for the next year.

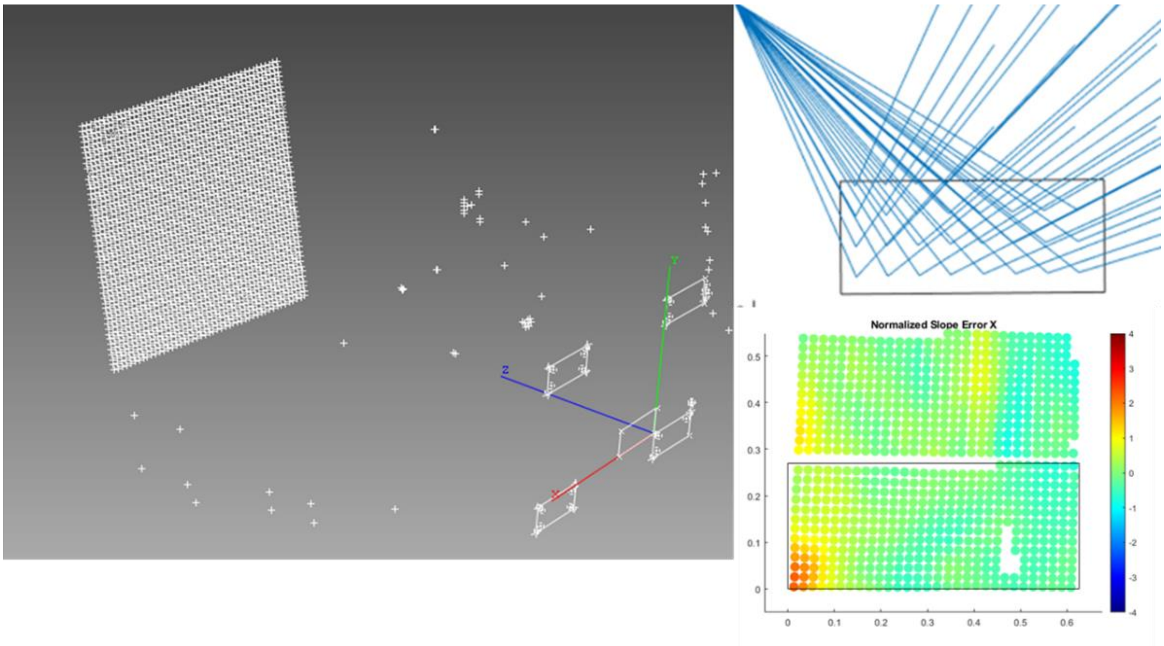

Figure 5. Photogrammetry is used to create a 3D scene (left). Once the camera point is solved, the mirror's surface slope can be measured (top right) to yield ReTNA results (bottom right).

Once the camera position has been calculated and the reflection points have been identified and referenced to their respective target points, the reflection points are projected from the x-y plane (defined by the corners of the mirror) onto the actual expected mirror surface. For a curved trough mirror, this means simply extending a ray from the camera location through the reflection location on the x-y plane and finding the intersection point with the ideal mirror surface. Surface slope can then be calculated in the x and y directions and subtracted from the ideal surface shape to get the optical surface error at each reflected target point.

3. Initial results

ReTNA has successfully generated surface slope measurements on multiple facets of a heliostat simultaneously (**Figure 6**) and on a parabolic trough mirror (**Figure 7**). To display these results, we plot a circle at the measurement location on the mirror surface and colour it according to the slope error value (in milliradians). Separate plots are generated for slope error in the x and y directions. When examining slope error, each facet is normalized, shifting the distribution of error measurements to be centred around zero.

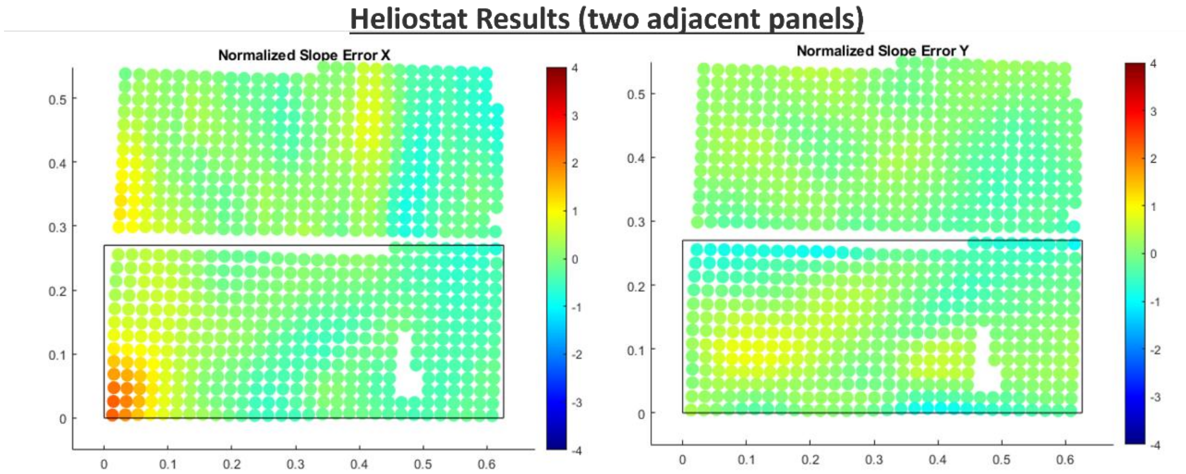

Figure 6. ReTNA results on adjacent heliostat facets in the x-direction (left) and y-direction (right).

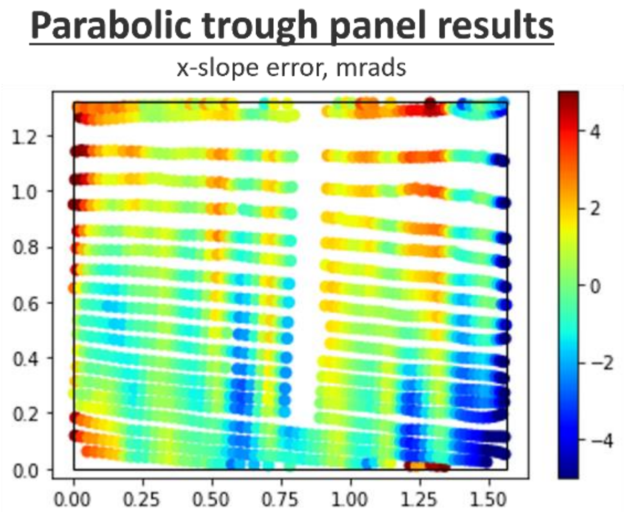

Figure 7. ReTNA results for slope error in the x-direction on a parabolic trough mirror.

We compared ReTNA measurements to measurements collected with NREL's SOFAST installation. This comparison is shown in **Figure 8**. On the left of this figure, ReTNA results (circles) and SOFAST results (background) are plotted on the same color scale, showing strong qualitative agreement. The ReTNA measurements can be directly subtracted from the SOFAST slope measurements in the x and y directions, generating the difference distribution shown on the right of **Figure 8**. The differences here are likely due to both inaccuracy in ReTNA's camera position calculation and an issue with NREL's SOFAST setup. The SOFAST measurements were not centered around zero, which implies some facet canting. It is unclear what this would mean for a single mirror. More analysis is necessary to resolve these small discrepancies.

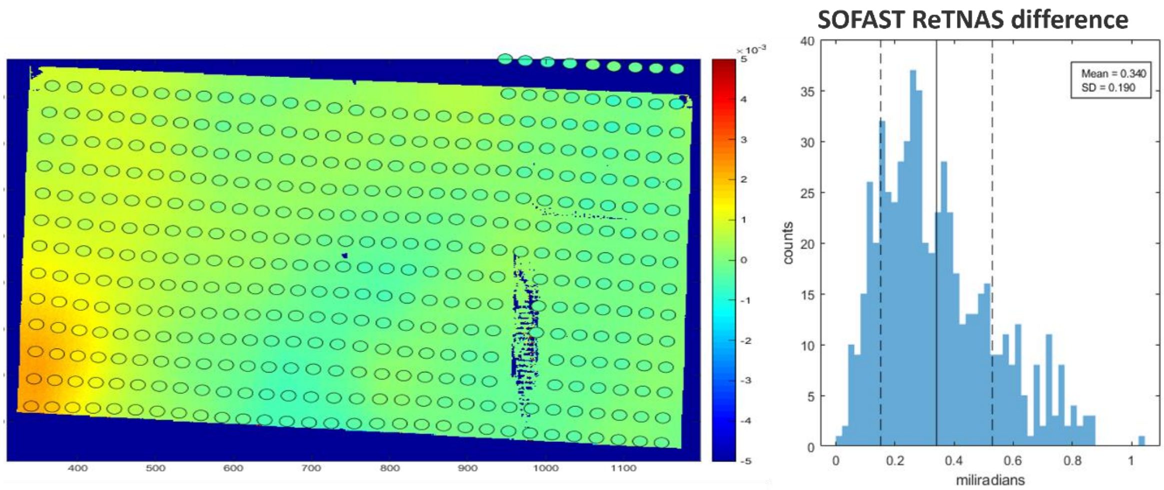

Figure 8. Left: ReTNA slope errors in the x direction (circles) are plotted directly on top of the same measurements from SOFAST (background). ReTNA and SOFAST results are plotted on the same color scale, showing good agreement. Right: ReTNA point values are subtracted from the SOFAST measurements to produce a difference distribution.

As shown in Figure 9, non-normalized ReTNA measurements can also be used to measure the relative canting of mirror facets. The average measured value on each facet can be compared, giving relative canting in the x and y directions. We compared two ReTNA measurements with slope measurements from a high-precision digital level. Both ReTNA measurements were well within the digital level's uncertainty of ±0.05 degrees, or 0.87 milliradians. However, more data must be collected to establish ReTNA's uncertainty.

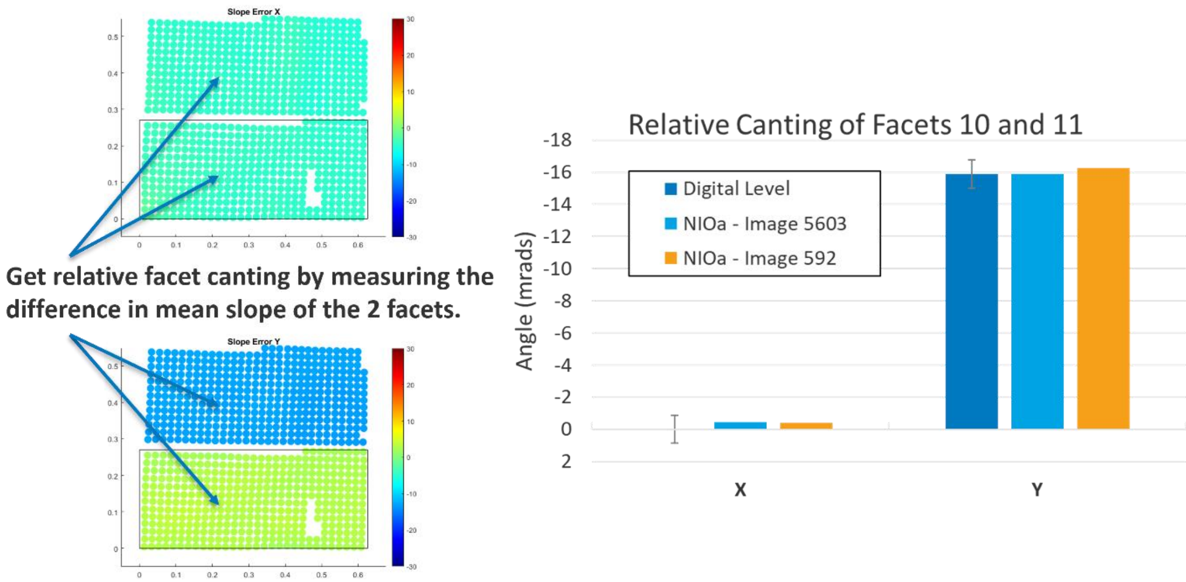

Figure 9. Left: The relative canting of adjacent facets is measured by comparing average measured slopes. Right: Two ReTNA results are compared to a high-precision digital level measurement.

Finally, some consistency issues remain with the ReTNA system. **Figure 10** shows an extreme example of this. In images from two different ReTNA measurements, the same surface error structures are visible, but the magnitudes differ greatly. A sensitivity study has indicated that this is likely due to uncertainty in the camera position calculation. In the next year, we hope to resolve this by locating the camera more accurately with additional automatically identified reference points.

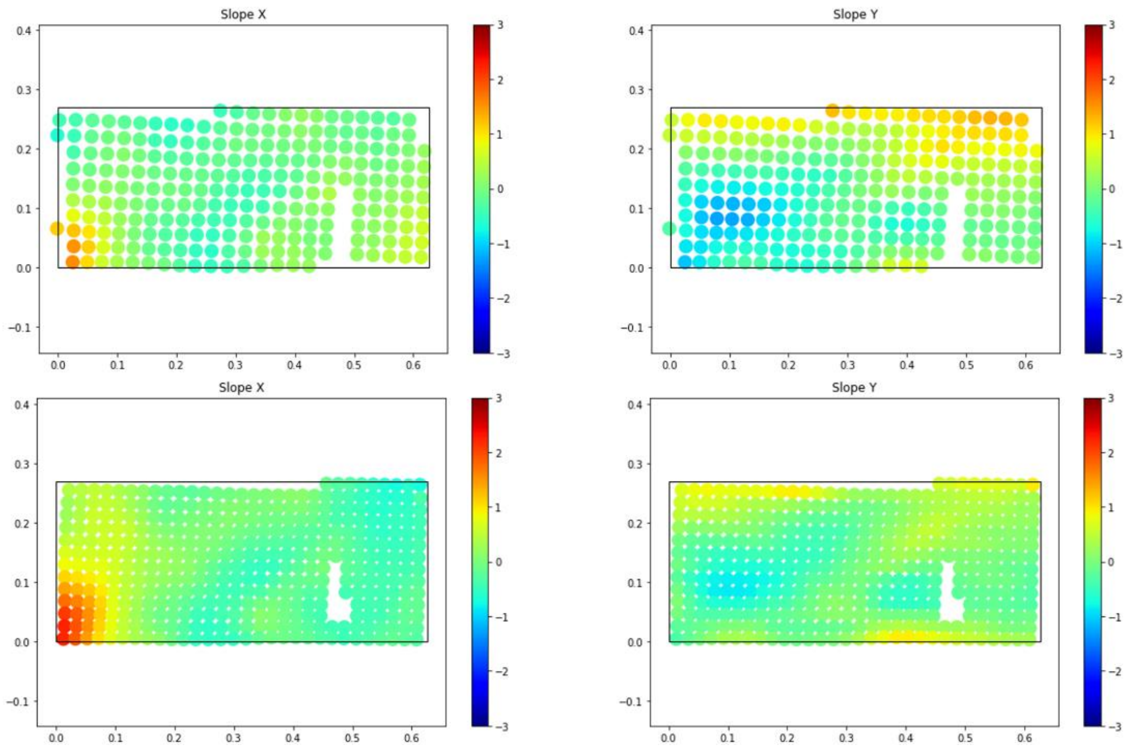

Figure 10. An extreme example of error in the ReTNA system. In two different data sets (top and bottom), the same surface error structures are visible, but magnitudes differ significantly.

4. Conclusions and next steps

This paper describes initial work to design and test the ReTNA measurement system. Although the initial results are promising, further work is required to establish this metrology system. We have identified the following next steps:

- Conduct more rigorous quantitative analysis and/or measurement system uncertainty.
- Further automate the system using computer vision.
- Refine the camera position calculation with additional automatically identified reference points.
- Build a fully automated prototype system with an automatic camera track to scan mirrors.

The ReTNA system is a powerful tool for heliostat and parabolic trough research and design (R&D) and assembly line quality assurance and control. During R&D, it can quickly and accurately measure a range of heliostat geometries at any orientation, with very little setup cost and time. During manufacturing, ReTNA can be directly incorporated into the assembly line process without large, costly projector screens or photogrammetry targets attached to the mirror surface. ReTNA works by leveraging recent developments in open-source computer vision and image processing technology and has been demonstrated to accurately measure mirror surface slope and relative facet canting.

Data availability statement

At this stage, all measurements were performed on NREL's laboratory test mirrors. These data are available from the authors on request.

Author contributions

Devon Kesseli: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing - Original Draft, Investigation. **Mojolaoluwa Keshiro:** Software, Validation, Formal analysis, Investigation, Writing - Review & Editing. **Rebecca Mitchell:** Methodology, Software. **Guangdong Zhu:** Conceptualization, Methodology, Funding acquisition.

Competing interests

The authors declare no competing interests.

Acknowledgement

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding was provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

References

1. R. A. Mitchell and G. Zhu, “A non-intrusive optical (NIO) approach to characterize heliostats in utility-scale power tower plants: Sensitivity study,” Solar Energy, vol. 207, pp. 450–457, Sep. 2020, doi: 10.1016/j.solener.2020.06.093.
2. C. A. Arancibia-Bulnes, M. I. Peña-Cruz, A. Mutuberría, R. Díaz-Uribe, and M. Sánchez-González, “A survey of methods for the evaluation of reflective solar concentrator optics,” Renewable and Sustainable Energy Reviews, vol. 69, pp. 673–684, Mar. 2017, doi: 10.1016/j.rser.2016.11.048.
3. Pottler, Klaus, Lupfert, Eckhard, Johnston, Glen H. G., and Shortis, Mark R., “Photogrammetry: A Powerful Tool for Geometric Analysis of Solar Concentrators and Their Components,” J. Sol. Energy Eng., vol. 127, Feb. 2005.
4. J. Fernández-Reche and L. Valenzuela, “Geometrical Assessment of Solar Concentrators using Close-range Photogrammetry,” Energy Procedia, vol. 30, pp. 84–90, 2012, doi: 10.1016/j.egypro.2012.11.011.
5. C. Andraka, “SOFAST: Sandia Optical Fringe Analysis Slope Tool for Mirror Characterization,” p. 10, Dec. 2018.
6. S. Ulmer, B. Brix, H. Koch, and A. Kämpgen, “QDec-M-Line: A Geometric Quality Control System to Assess Fully Assembled Parabolic Trough Modules in Series Production,” p. 8, 2020.
7. C. E. Andraka, S. Sadlon, B. Myer, K. Trapeznikov, and C. Liebner, “Rapid Reflective Facet Characterization Using Fringe Reflection Techniques,” Journal of Solar Energy Engineering, vol. 136, no. 1, p. 011002, Feb. 2014, doi: 10.1115/1.4024250.
8. T. März, C. Prahl, S. Ulmer, S. Wilbert, and C. Weber, “Validation of Two Optical Measurement Methods for the Qualification of the Shape Accuracy of Mirror Panels for Concentrating Solar Systems,” Journal of Solar Energy Engineering, vol. 133, no. 3, p. 031022, Aug. 2011, doi: 10.1115/1.4004240.

9. S. Schedler et al., “From research to industry: Development of a high-resolution measurement system for mirrored heliostats in series production,” presented at the SOLARPACES 2018: International Conference on Concentrating Solar Power and Chemical Energy Systems, Casablanca, Morocco, 2019, p. 030051. doi: 10.1063/1.5117563.

10. N. S. Finch and C. E. Andraka, “Uncertainty Analysis and Characterization of the SOFAST Mirror Facet Characterization System,” J. Sol. Energy Eng., vol. 136, no. 1, p. 011003, Jul. 2013, doi: 10.1115/1.4024251.

11. C. Andraka et al., “Sandia capabilities for the measurement, characterization, and analysis of heliostats for CSP.,” SAND2013-5492, 1090214, Jul. 2013. doi: 10.2172/1090214.

12. J. Beltrán-Madrigal and R. Díaz-Uribe, “Progress in the design of chromatic null screens to test cylindrical parabolic concentrators,” in 22nd Congress of the International Commission for Optics: Light for the Development of the World, R. Rodríguez-Vera, R. Díaz-Uribe, R. Rodríguez-Vera, R. Díaz-Uribe, R. Rodríguez-Vera, and R. Díaz-Uribe, Eds., SPIE, 2011, p. 80111R. doi: 10.1117/12.903315.

13. C. Iriarte-Cornejo, C. A. Arancibia-Bulnes, J. F. Hinojosa, and M. I. Peña-Cruz, “Effect of spatial resolution of heliostat surface characterization on its concentrated heat flux distribution,” Solar Energy, vol. 174, pp. 312–320, Nov. 2018, doi: 10.1016/j.solener.2018.09.020.

14. D. Kesseli, V. Chidurala, R. Gooch, and G. Zhu, “A Combined Computer Vision and Deep Learning Approach for Rapid Drone-Based Optical Characterization of Parabolic Troughs,” Journal of Solar Energy Engineering, vol. 145, no. 2, Aug. 2022, doi: 10.1115/1.4055172.

15. R. Morales-Sánchez, A. Lozano-Cancelas, A. Sánchez-González, and J. C. Castillo, “Detecting the Reflection of Heliostat Facets through Computer Vision,” p. 8.

16. M. Röger, C. Prahl, and S. Ulmer, “Heliostat Shape and Orientation by Edge Detection,” Journal of Solar Energy Engineering, vol. 132, no. 2, p. 021002, May 2010, doi: 10.1115/1.4001400.