SAND2020-2345C

1. **Project Title:** LIDAR for Autonomous Heliostat Optical Error Assessment
2. **FOA / Award#:** 35953
3. **Principal Investigator:** Daniel Small, Sandia National Labs, 505-844-5301, desmall@sandia.gov
4. **Other Participating Organizations:** Gryphon Technologies
5. **Project Schedule:**
   - Initiation Date 10/01/19
   - Dates of Intermediate Phase Completions or Go/No-go Points: 12/31/19, 3/31/20 6/30/20 Expected Completion Date 09/30/20
6. **Project Overview:**

This project seeks to develop LIDAR techniques to autonomously assess optical errors in the heliostats, an approach that never has been attempted. Recent experiments at Sandia's NSTTF have demonstrated the ability of a commercial scanning LIDAR sensor to acquire highly accurate point cloud measurements across the surface of several NSTTF heliostat mirror arrays. This was a surprising result as the team had instrumented only the corners of the mirrors with paper fiducials (to better reflect the laser light), fully expecting the returns off the mirrored surface to be inadequate for measurement. Thousands of 3D positioned points can be collected on each facet, with range accuracy approaching +/- 2mm out-of-plane displacement, which when fitted to a plane to represent the facet, allows for determination of the relative facet canting angles. When the LIDAR sensor position is localized (GPS, landmarks, etc.), a full heliostat scan should be able to accurately determine the overall tracking angles and canting errors to 0.5 mRad. SNL has identified a candidate sensor that has the capability of being completely automated via a software API, which lends itself to integration into a small unmanned ground vehicle (UGV). The primary focus of this effort will be to develop software algorithms that automate the assessment of these optical errors, with validated testing and evaluation at NSTTF and hopefully a commercial site, such as Crescent Dunes. When combined with a UGV, the system could be programmed to run all night long (LIDAR works even better at night), autonomously assessing heliostat canting and tracking errors while the field is otherwise dormant. Integration into the command-and-control of a heliostat field control system would allow the unmanned sensing system to place a heliostat under assessment in an optimal position for scanning, then return it to its stowed position once completed. This work complements Sandia's strategic thrust in autonomy for CSP collector systems.

7. **Project Goals:**

The goal of the project is to advance these types of capabilities to a TRL6 where they could be deployed for in-situ testing. The team will endeavor to test and evaluate the system using real-world data obtained from large-scale CSP plants. The result will show a canting and tracking error correction < 0.5 mRad, resulting in better heliostat field optical efficiency. It should be robust to different field layouts and heliostat designs.

8. **Project Objectives:**
   - Objective 1: Procure an appropriate LIDAR sensor with software API amenable to autonomous measurement. Success metric: LIDAR sensor shall be able to power on, acquire target images and scan the surrounding area in 3D, under completely remote operation.
   - Objective 2: Produce software for automatic data acquisition and segmentation that takes the GPS location of the scanner, the GIS coordinates of the heliostats, current heliostat commanded azimuth and elevation angles and a CAD Model of the heliostat. This software scans the surrounding heliostats and automatically segments the data into separate datasets per heliostat, and then further decomposes it into data associated with each facet using the CAD model as a spatial filter. Success metric: software shall automatically segment 3D data taken of a heliostat into data sets bounded by individual facets.

- Objective 3: Write software that takes the data produced in objective 2 and produces the relative canting errors and tracking errors for each one that it can successfully measure.
- Objective 4: Test and validate the scanner and associated software at the NSTTF and Crescent Dunes CSP plant. Success metric: The system shall assess heliostat facet canting quality to 0.3 mRad accuracy, and heliostat tracking error to +/- 0.6 mRad.

9. **Need for Federal Funding:**
SETO funding enables the national labs to conduct informative analysis on solar energy technologies and the solar industry, using bottom-up, techno-economic cost modeling to provide important industry benchmarks. Conducting these analyses in the real-world conditions for heliostat fields de-risks the application of autonomy and unmanned systems in solar technologies. Funding for this type of applied research does not exist solely in industry; (see risk above). This leaves it to the US Government to assist with the required funding to help our team get the job done.

10. **Project Organization and Responsibilities:**
Sandia National Laboratories: Dan Small - project lead, hardware/software engineering and integration, reporting; Charles Little, Technical Lead and algorithm development

11. **The Challenges:**
We were told 1 month into the project to hold off all travel to Crescent Dunes Solar Power Plant, which is the external commercial solar power field that we were planning on collaborating with for this project. That has not changed, and we have been told to seek other collaborations and execute the work at the NSTTF. In terms of technical barriers, the work is proceeding nicely with very little that is interfering with actual progress. We believe we will have large-scale assessments being performed of the NSTTF field in the third quarter of FY20.

12. Milestone Status:

We have acquired a FARO S70 LIDAR scanner to perform this work with. We have validated that the application programmers' interface that comes with the sensor will meet the needs of the project and allow our software to remotely command data acquisition and transfer via a Wi-Fi interface.

We have milestones written with Crescent Dunes as a place that we will take data but have no authorization to visit that site. Our current plan is to assume that we will not be given access to the site, and to double the level of effort at the NSTTF by taking more data and doing larger scale analyses. This could also be addressed with a no-cost extension if it becomes apparent that the current restriction is going to be lifted later.

Other milestones include:

1) automatically take a scan and retrieve scan data to a computer

2) segment the data down to individual heliostats

3) automatically segment each individual heliostat into 25 separate facets which can then be analyzed for canting errors

These are progressing on schedule.

13. **Scalability / Replicability / Impact:**

Direct measurement of heliostat facets using an active LIDAR sensor has the potential to be integrated onto minimally manned or unmanned vehicles whose job it is to present the sensor to each heliostat. Unlike other optical methods, this could be performed at night, allowing for optimal angular placement of the heliostat for mensuration. In terms of scalability, we are currently using a somewhat expensive lidar sensor, but the cost of these is coming down significantly with the economies of scale of the autonomous-car industry bringing the prices on long-range high accuracy sensors down significantly. It is our hope to be able to assess more inexpensive sensors over the course of this project. In terms of replicability, we will make the software available to commercial vendors that wish to try it out and can make the data sets that we collect available as well. The impact that this could have in existing plants is tremendous, as autonomous systems could continuously be assessing the heliostat field for the most badly canted heliostats, allowing for a more targeted recalibration of the field. This will lead to significant reductions in O&M costs.

14. **Project Results:**

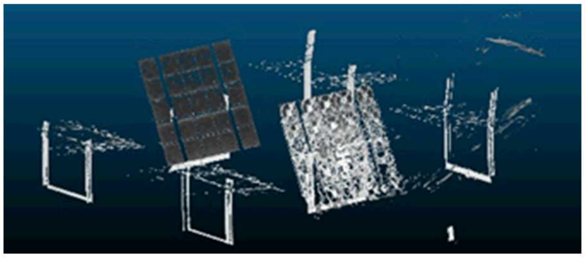
The steps to getting to fully autonomous operation hinge on segmenting the data from the larger data set into individual facets. Currently we have the capability to perform the following steps automatically:

1) Remotely specify and execute the 3D scan
2) Remotely copy the scan data off the sensor head via Wi-Fi
3) Use a statistical method to remove the ground floor of the data
4) Use clustered components to isolate the heliostats.
5) Use physical model data of the heliostat design to isolate individual facets
6) Use a planar fit on individual facet data to determine its normal
7) Compare facet normals to determine canting errors between facets.

Figure 1 shows an aerial photo of the NSTTF field of heliostats. Figure 2 shows a 3D scanned point cloud of the field, with the scanner placed in the middle of the field. The data here consists entirely of 3D points, often referred to as a point cloud. This scan has the potential of 176 million points (the sky returns no points). Figure 3 shows the point cloud with the floor data removed. Figure 4 shows a front side and back side point cloud of isolated heliostats.

Figure 1. NSTTF heliostat field image

Figure 2. 3D scan point cloud



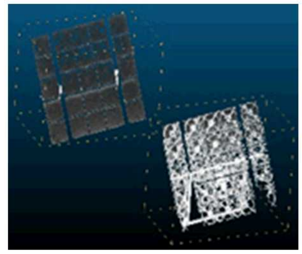
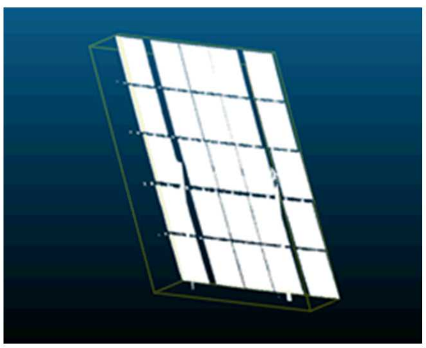
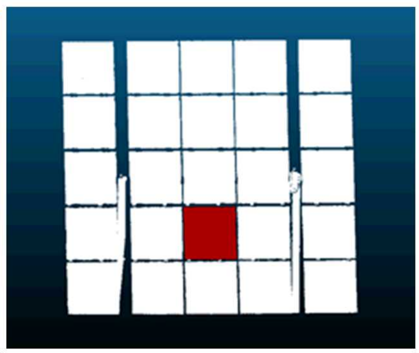


Figure 3. Point cloud with floor removed

Figure 4. Isolated heliostats

Isolating individual facets is done by using the physical model of the target heliostat as a template to find each facet. In figure 5, we show a minimum oriented bounding box around the heliostat. The dimensional data of the facet locations are used to segment each facet as show in figure 6 for one facet, and figure 7 for all facets.





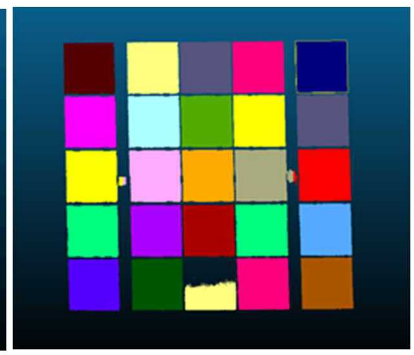


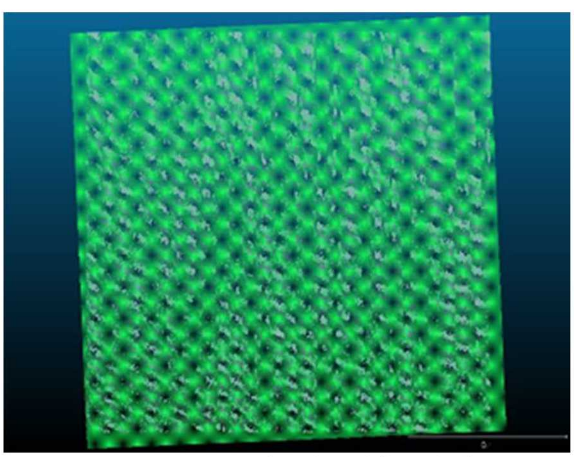
Figure 5. bounding box of heliostat.

Figure 6. One segmented facet.

Figure 7. All facets segmented

Facet Plane Fitting

The goal is to calculate the canting or pointing angle of each facet. Figure 8 shows a point cloud of a single facet along with a fitted plane; figure 9 shows the same data from an edge view. The normal to the plane will be considered the pointing angle. The statistics of the fit to the plane were calculated for this data. The RMS error for the point distance to the estimated plane of the facet is 0.00246 mm.



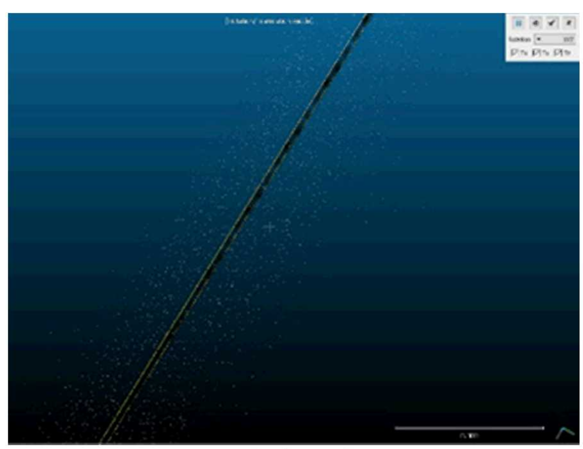


Figure 8. Facet point cloud and fitted plane.

Figure 5. Facet points and plane from edge view

Normal Angle Comparisons – Canting Error

The canting errors can be expressed as the relative difference between the central facet normal and its neighbors. This was done for this target heliostat. Each facet normal was calculated using the planar fit. The center facet, given the 5 by 5 facet configuration of the target heliostat, was used as the reference normal. Each facet normal was compared to the center facet. The angular difference is expressed in terms of two components; the difference in the horizontal or X direction, and the same for the vertical or Z direction (with Z being the vector coming out of the heliostat). The following table shows these values, with each facet data showing the x and y angular difference to the center facet. They are arranged as the appear looking at the heliostat from the front. The data is in degrees.

Table 1. Angular difference in X and Y for 25 faceted Heliostat

1.142	-1.040	0.408	-0.912	-0.122	-0.951	-0.561	-1.056	-1.220	-1.079
1.174	-0.463	0.460	-0.483	-0.046	-0.432	-0.486	-0.413	-1.166	-0.460
1.174	-0.001	0.380	0.005	0.000	0.000	-0.578	-0.005	-1.209	-0.011
1.216	0.581	0.522	0.610	-0.042	0.486	-0.441	0.536	-1.246	0.626
1.157	1.078	0.518	1.094	-0.004	1.169	-0.554	1.076	-1.267	1.134

15. **Budget Tables:**

Spending Summary by Budget Category							
	Approved Budget				Actual Expenses		
Budget Categories	BP 1	BP 2	BP 3	Total	This Quarter	Cumulative	%
a. Personnel	107,790			107,790	21,971	21,971	20%
b. Fringe Benefits							
c. Travel	42,649			42,649	242	242	1%
d. Equipment							
e. Supplies	43,520			43,520			
f. Contractual							
g. Construction							
h. Other	37,000			37,000	34,183	34,183	92%
i. Total Direct Charges	230,959			230,959	56,396	56,396	24%
j. Indirect Charges	145,041			145,041	26,973	26,973	19%
k. Total Charges	376,000			376,000	83,369	83,369	22%
DOE Share	376,000			376,000	83,369	83,369	22%
Cost Share							
Cost Share Percentage							

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