SAND2020-2308C

1. Project Title: Development of a UAS-Driven Universal Field Assessment Correction and Enhancement Tool Adopting Non-Intrusive Optics

2. FOA / Award#: 34249, 34242

3. Principal Investigators:

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4. Other Participating Organizations: University of Colorado at Boulder, Tietronix, Inc., Gryphon Technologies

5. Project Schedule:

- Initiation Date: 10/01/18
- Dates of Intermediate Phase Completions or Go/No-Go Points: 9/30/2019, 9/30/2020
- Expected Completion Date: 09/30/21

6. Project Overview:
The heliostat collector field is the front-end of large solar power tower plants, thus any negative performance impacts on the collector field will propagate down the stream of subsystems, which can negatively impact energy projection and financial revenues. We are developing a field assessment and survey which uses multiple imaging systems designed by Sandia (UFACET) and NREL (NIO). Using a target structure (e.g., a neighboring heliostat or the power tower) it can provide accurate canting corrections on the heliostats by imaging the target in reflection through the heliostat from a small UAS, or drone. Previous efforts showed accuracies of less than 0.3 mrad for canting corrections. The project will advance the proposed concept from TRL3 to TRL6, and the solar industry will have a new set of scalable tools for improving heliostat field optical efficiency.

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 work to test and evaluate the system using real-world data obtained from large-scale CSP plants. The end 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. The research strategy includes partnering across multiple laboratories and industry partners.

8. Project Objectives:
The project aims to develop a first-of-a-kind UAS-based non-intrusive optical characterization tool to perform heliostat field assessment, correction and enhancement to improve heliostat field performance and reduce O&M costs with UAS optical payloads that collect optical data from the field and then derive optical errors (canting, slope, tracking) from observations of known geometries taken in reflection from observed heliostats.
Objective 1: Design the sensor payload that will meet the performance requirements, and specify a UAS platform that can handle the payload weight and has the required performance (in Year 1).

Objective 2: Demonstrate the integrated UAS sensor system (UFACET) can operate in monitoring mode to access heliostat canting and soiling to the specified performance requirement on the NSTTF heliostat field (in Year 2).

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Objective 3: Demonstrate UFACET can operate in field correction mode by correcting canting errors on in-situ heliostats to the specified performance requirement on the NSTTF heliostat field (in Year 2).

Objective 4: Generalize the sensor system so it works on any commercial heliostat field to the same level of performance (in Year 3).

Objective 5: Demonstrate the sensor system at a commercial heliostat field to the specified performance requirement.

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. This particular collaboration between National lab researchers and industry partners is conducting analyses in the real-world conditions for heliostat fields, which 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:

- Mr. Daniel Small – Principal Investigator, project & technical lead, report writing, optical payload design.
- Dr. David Novick - Design and develop the controls for the UAS and payload, and develop algorithms for flight paths
- Dr. Julius Yellowhair – under contract from Gryphon Tech – image processing and computer vision for optical error assessment, Inventor of the UFACET method

National Renewable Energy Lab (NREL):

- Dr. Guangdong Zhu (Senior Researcher) – CO-PI, project lead at NREL. Leading the development of the Non-Intrusive Optical (NIO) method. Writing report. Planning the NIO test plan and data analysis approach. Developing NIO test procedure.
- Dr. Rebecca Mitchell (Postdoc) – performing data analysis of collected data using NIO;
- Dr. Ryan Gooch (Postdoc) – applying machine learning to improv efficiency and accuracy of image process;
- Tucker Farrell (graduate intern) – developing drone path optimization algorithm.

TieTronix, LLC:

- Dr. Michel Izygon (Senior Researcher) – Assessing impact of optical error and optical tool to solar field performance; commercializing the optical tools into the current CSP market.

University of Colorado, Boulder (CU):

- Dr. Eric Frew (Senior Researcher) – Supporting UAS system configuration and testing.

11. **The Challenges:**

There exists three major challenges in the project:

1) Demanding measurement accuracy of 0.25 mrad for optical error measurement. 0.25 mrad is the measurement accuracy of many indoor laboratory measurement tools. With the limited resources in the field, this can be a very challenging goal to reach. In this project, by developing new image-processing techniques, we are able to demonstrate that the proposed tools (UFACET and NIO) can achieve a measurement uncertainty of lower than 0.25 mrad. A comprehensive sensitivity study was

also performed to define the system operation parameters required to achieve the target measurement accuracy.

2) Configuring a UAS system with sophisticated requirements. For proper operation of both UFACET and NIO tool, a detailed system configuration has been derived regarding to camera focal length, positioning accuracy, etc. In addition, a series of field tests have carried out to test different UAS models.
3) Identifying an industrial partner for demonstration field tests at a commercial-scale heliostat field. There are limited options to perform a field test at a commercial-scale solar field in US. Right now, we are in discussion with both domestic and foreign developers to secure a solar field for testing.

12. Milestone Status:

We have successfully completed all milestones defined in the first year. In particular, the end of year no/no-go milestone is to "Show measurement uncertainties of slope and canting errors using hand-held camera to less than 0.25 mrad." Regarding to this milestone, a detailed data analysis was completed to derive slope error, canting error and pointing error of the heliostat under tests. Over 10 sets of measurement data were analyzed and suggested a measurement uncertainty of 0.22 mrad for the NIO method. UFACET has demonstrated horizontal and vertical RMS variation of < 0.3 mrad in one data set and < 0.2 mrad in a second. Therefore, the measurement uncertainty is < 0.3 mrad during hover of the UAS. The results suggest 1) viability of both in-situ optical tools and 2) high measurement accuracy of the proposed technologies. A more detailed milestone status can be seen in the table below.

Milestone Number	Milestone Title	Description	Metric(s)
1.1.1	Complete Subtask 1.1	Using hand-held cameras, collect reflection images for near-field and far-field targets for at least 3 heliostats (with different slant ranges) at NSTTF for optical error characterization. This task will allow for image data collection in parallel to the UAS development to begin development of processing algorithms (Sandia/NREL)	Sucessful static image collection at NSTTF
1.1.2	Complete Subtasks 1.2 and 1.3	- Develop algorithms to calculate canting error by using near-field targets from the images collected - Develop algorithms to calculate surface slope errors and canting errors by using far-field	Develop functional algorithms to calculate optical
1.1.3	Measurement uncertainty on slope error and canting error	To assess the capability of the developed algorithm, multiple sets of relfection images will be post-processed for the optical slope errors. By performing the anlaysis of multiple sets of reflections images on the same heliostat, the measurement uncertainties can then be readily calculated. Calculation of measurement uncertainties can be an effective tool to debug and improve the developed optical characterization algorithm and a meaningful metric to demontrate the capability of the developed algorithm.	Measured slope error and canting error uncertainty
1.1.4	Deliver a functional program for use on static images	Deliver an optical error measurement program (assuming a hand-held camera and a stationary heliostat) to the industry.	Deliver program in the form of
1.2.1	Complete Subtask 2.2	UAS hardware selection, procurement, integration, and flight testing	Completion of UAS
1.2.2	UAS positional accuracy	Show that the hovering position control accuracy of the UAS system can achieve 15 cm in lateral direction and 30 cm in vertical direction at the operating wind speed of 10 mph or less with a 95% confidence level on repeated measurements.	UAS positional accuracy

13. Scalability / Replicability / Impact:

The project aims to advance the proposed technology into the field demonstration – TRL 6. Upon the completion of the project, the proposed technology will reach a point that it can be directly licensed to commercial entities. A complete commercial licensing package will be ready for each optical technology, including hardware specifications and software operation manual.

Replicability will be demonstrated with proper assistance from national lab researchers. Scalability will be accomplished by taking advantage of the economies of scale made available by parallelizing the approach with swarms of small UAS measuring large fields simultaneously.

Without a reliable O&M technology to efficiently characterize the heliostat field, it is possible that energy collection may be 20% less than expected, suggesting that the heliostat field was not performing up to expectations. Past analysis shows that the heliostat tracking errors could degrade by more than 2 mrad in the field. The proposed optical survey/correction system will have two major impacts on the heliostat field—reduced O&M costs and increased field performance—both of which lead to reduced levelized cost of electricity (LCOE). In addition, a properly monitored and well-maintained field will prevent unintentional occurrences of hot spots resulting from problematic heliostats, which could lead to a plant shutdown and the loss of millions of dollars in revenue. Assuming a conservative nominal 1.0-mrad degraded heliostat field and considering the reduced O&M costs, the proposed optical survey/correction toolset would result in a total LCOE reduction of 1.03¢/kWh.

14. **Project Results:**
The NIO and UFACET approaches have been developed to perform efficient measurements of optical errors on heliostats in a solar power-tower plant. It is demonstrated that the proposed approaches can measure mirror surface slope error, mirror facet canting error, and heliostat pointing error based on images taken in-situ at a large-scale test heliostat field. In particular, the NIO approach developed an innovative scheme to correct relative position of the tower and to derive the pointing error. By using multiple datasets, it is shown that the measurement uncertainty of optical errors using NIO is less than 0.22 mrad in the x dimension (with plans to validate the method in the vertical dimension). An additional sensitivity study on the impact of various design parameters to measurement uncertainties was also carried out and will be presented in a separate publication. The NIO approach has demonstrated in-situ measurement of mirror canting and slope error using the tower. The UFACET approach has demonstrated in-situ measurement of mirror canting angles using the neighboring heliostats in reflection. Both approaches are applicable to a utility-scale heliostat field.

With the increasing deployment of solar power-tower plants around the world, these tools (incorporating the state-of-the-art UAS technology) will provide a unique approach to monitor and improve the optical performance of a heliostat field.

Two journal articles have been submitted: 1) R. Mitchell, LG. Zhu*, "An Innovative Non-Intrusive Optical Method to Perform in-situ Measure Optical Characterization of Heliostats in Utility-Scale Power Tower Plants", *under preparation*, 2019. 2) R. Mitchell, G. Zhu*, "Sensitivity Study on a Non-Intrusive Optical (NIO) Method to Measure Optical Errors of Heliostats in Utility-Scale Power Tower Plants", *under preparation*, 2019.

Multiple record of inventions have been submitted and formal patent applications are under development: G. Zhu*, R. Mitchell, "Novel solar collector tracking error detection", US Provisional Application No. 62/906,880, NREL PROV/19-134A, 2019. D. Small, J. Yellowhair, C. Little, " LIDAR for In-situ Heliostat Optical Error Assessment", Sandia Technical Advance SD #15183 in preparation for Provisional Patent.

15. **Budget Tables:**

Sandia National Labs (Cumulative With NREL as contractual):

Spending Summary by Budget Category							
	Approved Budget				Actual Expenses		
Budget Categories	BP 1	BP 2	BP 3	Total	This Quarter	Cumulative	%
a. Personnel	227,289	343,839	193,099	764,227	55,328.02	254,182.40	33%
b. Fringe Benefits							
c. Travel	6,350	18,219	20,500	45,069	2,141.76	10,232.87	23%
d. Equipment							
e. Supplies	43,100	23,369		66,469	5,828.19	42,702.02	64%
f. Contractual	566,457	883,112	600,431	2,050,000	154,244.13	676,142.37	33%
g. Construction							
h. Other	54,292	80,245	43,845	178,382	54,659.80	98,358.20	55%
i. Total Direct Charges	897,488	1,348,784	857,875	3,104,147	272,201.89	1,081,617.86	35%
j. Indirect Charges	315,631	434,869	245,353	995,853	68,691.97	339,915.63	34%
k. Total Charges	1,213,119	1,783,653	1,103,228	4,100,000	340,893.86	1,421,533.49	35%
DOE Share	1,213,119	1,783,653	1,103,228	4,100,000	340,893.86	1,421,533.49	35%
Cost Share							
Cost Share Percentage							

NREL:

Spending Summary by Budget Category							
MOD1	**Approved Budget per SF-424A**				**Actual Expenses**		
Budget Categories per SF-424a	**BP 1**	**BP 2**	**BP 3**	**Total**	**This Quarter**	**Cumulative**	**%**
a. Personnel	$416,505	$697,158	$450,491	$1,564,154	$111,441	$510,671	33%
b. Fringe Benefits				$0		$0	
c. Travel	$12,240	$18,019	$12,228	$42,487	$3,790	$23,326	55%
d. Equipment				$0		$0	
e. Supplies	$15,384	$15,384	$15,384	$46,152	$1,323	$18,201	39%
f. Contractual	$104,808	$126,068	$104,808	$335,684	$26,194	$65,598	20%
g. Construction				$0		$0	
h. Other	$1,942	$2,227	$1,008	$5,177	$5,692	$5,692	110%
i. Total Direct Charges	**$550,879**	**$858,856**	**$583,919**	**$1,993,654**	**$148,441**	**$623,489**	**31%**
j. Indirect Charges	$15,578	$24,256	$16,512	$56,346	$1,288	$4,885	9%
k. Total Charges	**$566,457**	**$883,112**	**$600,431**	**$2,050,000**	**$149,729**	**$628,374**	**31%**
DOE Share				$0			
Cost Share				$0			
Cost Share Percentage	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	