Intern Projects in Heliostat Technologies at NREL, SNL, and DOE

The HelioCon Intern Team
Host: Dr. Rebecca Mitchell

August 1, 2022
Seminar Guidelines

• The seminar will be recorded and shared afterwards
• Please stay on mute with cameras off during the presentations
• Feel free to put questions in the chat during the presentations; make sure to indicate who your question is for
• During the Q/A, you may unmute and turn your camera on to ask your questions
Intern Projects at the National Renewable Energy Laboratory (NREL)

Raven Barnes, NREL  
Mentor: Dr. Alex Zolan

Mackenzie Dennis, NREL  
Mentor: Dr. Rebecca Mitchell

Kyle Heinzman, NREL  
Mentor: Tucker Farrell

Maggie Kautz, NREL  
Mentors: Dr. Guangdong Zhu, Dr. Rebecca Mitchell

Mojolaoluwa Keshiro, NREL  
Mentor: Devon Kesseli

Dylan Mayes, NREL  
Mentor: Tucker Farrell

Katelyn Spadavecchia, NREL  
Mentors: Mackenzie Dennis and Devon Kesseli

Gabriel Shuster, NREL  
Mentor: Dr. Rebecca Mitchell

Daniel Tsvankin, NREL  
Mentor: Dr. Matt Muller
Heliostat performance testing and validation

Mackenzie Dennis
Beam Characterization System (BCS) Overview

Kyle Heinzman
BCS Hardware & Data Collection

Katelyn Spadavecchia
BCS Software Development

Daniel Tsvankin
BCS support and heliostat standard qualification and validation

conceptual design • components • integration • mass production • heliostat field
Beam Characterization Systems:
Automated image processing to detect and correct for heliostat pointing error

Setup and process:
• A heliostat in the field is diverted from the receiver onto target
• Camera takes photo of beam on target
• Image processing algorithm finds:
  • Beam shape and flux map
  • Beam placement on target
  • Pointing/tracking error of heliostat

**Objective:**
- To design and develop the necessary hardware to train a BCS image processing algorithm.

**Experimental Modeling:**
SolTrace used to model experimental setup & determine maximum target size.

- **Assumptions:**
  - Perfectly flat mirror
  - Estimated optical properties of mirror

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**SolTrace ray modeling**

**Corresponding flux map**
HelioCon: BCS Hardware/Data Collection

Kyle Heinzman, Mackenzie Dennis, Daniel Tsvankin

**Heliostat Frame**  
**Target Frame**

**Design Constraints:**
- Mirror to Target Size
  - Mirror Size = 21” by 31”
  - Target Size = 4ft by 3.2ft
- Forces due to Wind Loading
- Target Material & Coating

*Beam image collected at the Outdoor Testing Facility (OTF)*
HelioCon: BCS Hardware/Data Collection
Kyle Heinzman, Mackenzie Dennis, Daniel Tsvankin

Experimental Testing:
• Repeatability
• Compatibility of Images with Algorithm
  • Camera Specs / Settings
  • Camera Position / Orientation

<table>
<thead>
<tr>
<th>Data Measurements for Repeatability</th>
<th>Camera Settings Manipulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distances</td>
<td>Aperture</td>
</tr>
<tr>
<td>Compass Orientation (Aimpoints)</td>
<td>Shutter Speed</td>
</tr>
<tr>
<td>Inclination angles</td>
<td>ISO sensitivity</td>
</tr>
</tbody>
</table>

Future of Project:
➢ Upscale model for OTF roof testing using an automated heliostat with solar tracking.
➢ Rectangular target design used with BCS image processing software can characterize site specific CSP Power Towers plants.
 imports Images (Crescent Dunes)
2. Create Binary Image using filters
3. Apply Hough Transformation
4. Extract Hough Lines
5. Segment and intersect lines
6. Test each image
HelioCon: BCS Software Development
Katelyn Spadavecchia, Devon Kesseli, Mackenzie Dennis
HelioCon: BCS Software Development

Katelyn Spadavecchia, Mackenzie Dennis

- Images were taken at OTF with varying target aspect ratios and camera ISO settings
- Larger target ratios are better for detecting edges
- No clear ISO preference

Future of Project

With accurate target edges, features of the beam such as centroid and diameter can be identified more meaningfully.
HelioCon: Standards Development

Daniel Tsvankin

Component testing

Hemispherical reflectance (reflector)
Specular reflectance (reflector)
Abrasion resistance (all)
Ingress resistance (all)
MTBF and lifespan (all)
Backlash and hysteresis (drives)

Heliostat testing

Beam error after HALT
Pointing accuracy after HALT
System reliability
System serviceability

Field performance testing

Flux control and capacity
Field safety and operability
Soiling
Site acceptance

conceptual design • components • integration • mass production • heliostat field
HelioCon: Standards Development

Daniel Tsvankin

- Mechanical longevity tests adapted from IEC 62817
- Beam quality tests adapted from SP
  - Simulation
  - Physical test
- Tracking error tests adapted from SP and IEC
- Publicly-available software for processing test images

- SolarPACES Guideline
- IEC 62817
- IEC 62108

Gap identification
IEC language translation
Procedure modification
Test verification
Tool development

IEC 62842-4-X

Heliostat performance parameters from SolarPACES Guideline for heliostat performance testing
HelioCon: Standards Validation

Daniel Tsvankin, Kyle Heinzman, Mackenzie Dennis

- Static (on ground) and dynamic (tracker-mounted) mirror setups
- Feedback loop between running tests, updating standards language, and developing accompanying tools
HelioCon: Standard Tools

Daniel Tsvankin, Katelyn Spadavecchia

- Goal: publicly-available software for processing beam-on-target methodologies
  - Collection of feedback from partner institutions
  - Image-based approximation of SolarPACES beam quality and tracking accuracy values

Sample program output. Dot is beam centroid. Each color represents 10% of the overall flux. Removing the gray region yields the 90% flux region, which is used for further analysis under SolarPACES Guidelines and the draft IEC standard.
Heliostat optical characterization and modeling

Dylan Mayes
Non-Intrusive Optical (NIO) tool Automation

Gabriel Shuster
NIO slope error sensitivity analysis

Mojolaoluwa Keshiro
Lab NIO development

Maggie Kautz
Optimizing heliostat shape through ray trace modeling

conceptual design • components • integration • mass production • heliostat field
Heliostats & the Non-Intrusive Optica Method (NIO)

Mojolaoluwa Keshiro

A Heliostat

The law of reflection

Conceptual design • Components • Integration • Mass production • Heliostat field
HelioCon: NIO Algorithm Overview

Mojolaoluwa Keshiro, Dylan Mayes, Gabriel Shuster

UAS image data collection for the NIO method (Mitchell and Zhu, 2020)

Optical error types measured by the NIO method (Mitchell and Zhu, 2020)
HelioCon: NIO Algorithm Overview

Dylan Mayes, Gabriel Shuster

- Processes image datasets collected from field acquisition stage using UAS
- Outputs image dataset as input to MATLAB post-processing error analysis

- Original algorithm development and testing
- Serves as the backbone for NIO approach theory and calculations
  - Slope error uncertainty
  - Canting error, heliostat tracking error
HelioCon: NIO Algorithm Overview

Dylan Mayes, Gabriel Shuster

Edge detection plot for the tower reflection (top side in this case)

\[
\theta_c \text{ (mrad) After Correction}
\]

Canting error plot per facet generated from optical error calculations
• Remove user inputs

• Develop functionality, loops, and calculations

• Decrease labor time to run and process code

• Create GUI to assist the user

• Remove user interaction with blocks of code
HelioCon: NIO Automation

Dylan Mayes

- Automatic feature detection
  - Corners, tower edges, and ID of heliostat

- Compilation and merging of original and automated NIO algorithms using GitHub

- Automation removes hours of labor needed to run the algorithm
NIO Slope Error Sensitivity Analysis

Gabriel Shuster

NIO method uses drone captured images of heliostats to calculate slope error

• Reflected tower edge shows warping of mirror surface
  • One reflection line -> one dimension of information

Two reflection lines needed to fully characterize mirror surface

• Error in calculation will be too great if difference between heliostat position is too small
• Used simulated reflection lines to find useful range of positions
NIO Slope Error Sensitivity Analysis

Gabriel Shuster

Reflected lines are mostly vertical -> more information is known in the x-dimension
- Smaller error values in x-dimension
- Larger error values in y-dimension

As difference between azimuth angle increases the error in Y becomes smaller
- The minimum difference between azimuth angles is 19 degrees
- Elevation angle has little effect on slope error
• Moving to python
• More Image tests
• Sensitivity Studies

More parameters depend on these too
Sensitivity Analysis

Pick a parameter

Plot

Slope error difference

Perturb n times

slope error for each step

Major Results

Maximum Uncertainty Values to reduce errors to 0.25 mrad maximum

<table>
<thead>
<tr>
<th>Perturbed Parameter</th>
<th>Allowable Uncertainty</th>
<th>Usual Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heliostat corner</td>
<td>0.005m</td>
<td>0.003</td>
</tr>
<tr>
<td>Camera position</td>
<td>0.006m</td>
<td>0.15 *using initial method</td>
</tr>
<tr>
<td>Target points position</td>
<td>0.006</td>
<td>0.00039</td>
</tr>
<tr>
<td>Reflected points</td>
<td>3.2 pixels</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>
Fixed Shape Optimization of Heliostat Mirror
Maggie Kautz

- **Power tower plant**: a field of mirrors, heliostats, concentrate sunlight onto a central tower that has water or sand running through it as the medium for driving a heat engine.

- Efficiency needs to be increased.

- The goal of this project is to determine the optimal fixed shape of a heliostat mirror that will yield the highest intercept factor on the power tower throughout a given day and ultimately throughout a year.

\[
IF = \frac{\text{Power intercepted by target}}{\text{Power incident on heliostat}}
\]
HelioCon: RTE Database Development

Mackenzie Dennis

- Central database: currently in Zotero
  - Over 1000 resources
  - Searching, sorting, topic areas
    - Easy citations
  - Tutorial
  - HelioCon website: Resources content (Gabe)

- Other resources
  - Intro videos
  - Useful images
  - Online resources
HelioCon: RTE Materials

• Literature review and paper
  • “An Overview of Heliostats and Concentrating Solar Power Tower Plants”
    • March 2022
• Basics and overview of advanced topics
• Condensed resources for each topic
Gabriel Shuster

• Created structure for the Resource section of the HelioCon Website
  • Place for people to learn about CSP and heliostats
  • More knowledgeable workforce
  • Lower costs associated with training staff
• Publicly available resources
  • Overview paper
  • Available Software: DelSol, SolTrace, SAM, NIO, etc.
  • Zotero library
• Diversity, Equity and Inclusion
  • Comprehensive plan in RTE section
  • Incorporate in every aspect of HelioCon
• Industry standards and O&M
  • List of current standards
  • Best practices of current CSP plants
Resource Database Information Compilation

Gabriel Shuster & Raven Barnes

- Database of general information on CSP tower plants
  - Developed with SolarPaces and literature review
  - Zoterro Resources

- Compilation of general/best practices related to the O&M of CSP tower plants
  - Best Practices report by NREL
  - Roadmap report by HelioCon
  - Interviews with industry professionals in CSP tower plants

No Correlation

High Concentration in Low Range
Survey of Industry Professionals

Survey developed using O&M database
- Staffing
- Washing
- Calibration
- Vegetation Control
- Equipment Malfunction
- Soiling
- Extreme Weather
- Wind Speeds

Survey is currently being broadened to include questions by other HelioCon task groups of the roadmap report
HelioCon Social Media CSP Education

Objectives

Educate younger audience

Short videos (TikTok, IG)

Knowledge, information, and news
Intern Projects at Sandia National Laboratories (SNL)

Felicia Brimigion, SNL
Mentor: Dr. Randy Brost

Natalie Gayoso, SNL
Mentor: Dr. Ken Armijo

Dimitri Madden, SNL
Mentor: Dr. Ken Armijo
SOFAST Interactive CAD Tool

Felicia Brimigion
Sandia National Laboratories

SOFAST is a Sandia tool for precise CSP mirror measurements.

We have created a SOLIDWORKS interactive SOFAST tool to aid in the visualization of the SOFAST testing setup and environment.

This tool allows the user to not only visualize their setup in their space, but to also assess what equipment and their sizes can or cannot be used in their desired space.

Ex: screen size, type of projector and lenses, camera lens, and their positions necessary to execute the test accurately
Ex: what mirror sizes are possible

The tool allows the user to adjust the model to visualize the correct positioning required of projector, mirror, and camera in order to work effectively in their space/environment.

The model is built to automatically update the mirror’s reflection accurately according to Snell’s law when adjusting either the mirror’s or camera’s angles and positions.

This allows the user to solve for three distinct cases:
1. known mirror, unknown environment
2. known environment, known mirror, unknown mirror placement
3. general purpose instrument optimal design (see figs 3 and 4)

The interactive SOFAST tool has been used to design 8 test setups to date.
Objective: Compare and contrast methodologies and data sources for modeling heliostat fields. Use results to develop preferred methods, improve data sources, and attempt to answer fundamental questions about CSP heliostat field design and performance.

What is Techno-Economic Analysis (TEA)?

Identifies economic feasibility and sustainability of a new technology by analyzing costs, benefits, and uncertainties in scaling up a system.
Why do we do TEA?
Sandia National Laboratories: Natalie Gayoso

• Maximize the impact of your research by identifying important cost/benefit drivers

• Establish a common language between industry and researchers

• Differentiate yourself by demonstrating the knowledge and desire to commercialize

• A customer or reviewer asks for a "TEA"
# Initial Literature Review Results

**Sandia National Laboratories: Natalie Gayoso**

<table>
<thead>
<tr>
<th></th>
<th>Mirror Module</th>
<th>Support Structure</th>
<th>Drive</th>
<th>Drive electrical</th>
<th>Controls</th>
<th>Pedestal</th>
<th>Total Direct Cost</th>
<th>Overhead/Profit (20%)</th>
<th>Total Fabricated Price</th>
<th>Field wiring</th>
<th>Foundation</th>
<th>Field alignment</th>
<th>Rotation Assembly</th>
<th>Site labor</th>
<th>Transportation</th>
<th>Total Installed Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM [1]</td>
<td>150 m² ($/m²)</td>
<td>148 m² ($/m²)</td>
<td>48.5 m² Commercial [2] ($/m²)</td>
<td>27 m² Advanced [2] ($/m²)</td>
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<td>42.99</td>
<td>23.06</td>
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<td>16.39</td>
<td>2.29</td>
<td>2.29</td>
<td>142.90</td>
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<tr>
<td>Commercial [2]</td>
<td>1.87</td>
<td>1.84</td>
<td>1.94</td>
<td>1.78</td>
<td></td>
<td></td>
<td>82.24</td>
<td>18.15</td>
<td>82.24</td>
<td>5.15</td>
<td>1.51</td>
<td>12.19</td>
<td>7.10</td>
<td>1.76</td>
<td></td>
<td>127.27</td>
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<tr>
<td>Advanced [2]</td>
<td>16.73</td>
<td>16.96</td>
<td>6.79</td>
<td>8.11</td>
<td></td>
<td></td>
<td>64.21</td>
<td>8.11</td>
<td>64.21</td>
<td>9.01</td>
<td>5.15</td>
<td>7.08</td>
<td>7.79</td>
<td></td>
<td></td>
<td>95.92</td>
</tr>
</tbody>
</table>

## Key Takeaways:
- There is potential to reduce cost by downsizing the heliostat aperture area.
- There are a number of drivers favoring smaller heliostats that can be identified using TEA and can guide design direction throughout the entire development cycle of CSP.

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**Table 1. Heliostat cost breakdown of four heliostat scenarios: Stretch Membrane (SM), Advanced Thermal System (ATS), Stelio Commercial, and SunRing Advanced heliostats, respectively**

**References:**
**Important Challenges**

**Sandia National Laboratories: Natalie Gayoso**

**Analyze cost parameters further, such as:**
- Levelized Cost of Energy
- Levelized Cost of Heat
- Levelized Cost of Optics
- Levelized Cost of Coatings

**Explore open-source TEA tools to model CSP tower plants**
- System Advisory Model (SAM)
- SolarPILOT
- SolTrace
- SolarTherm

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**Objective:** Develop heliostat field, tower, and receiver model for industrial process heat application
NSTTF of Sandia National Laboratories is the only CSP test facility of its kind

- The NSTTF has been at the forefront of CSP for 40+ years
- Combined with our collective experience, we performed an extensive review of historical, existing, and cutting edge heliostat technology
- We have identified standards, heliostat components, and control systems that could all be improved to reduce heliostat cost and improve efficiency
Intern Projects at the Department of Energy’s (DOE) Solar Energy Technologies Office (SETO)

Nicole Piatko, DOE
Mentor: Andru Prescod
Heliostat Drives and Opportunities for Cost Reduction: Objectives

Nicole Piatko

- Define the characteristics necessary for a heliostat drive
- Review the state of the art for heliostat drives
- Describe the obstacles in drive development
- Explore cost reduction opportunities for drives
Drive Requirements

Nicole Piatko

- High reduction ratio
- No back driving, self locking
- Static and dynamic torque
- Low backlash of less than 0.5 mrad
- High pointing accuracy
- Lifetime of 30 years with low maintenance

The State of the Art

- Azimuth-elevation
  - Worm gear for azimuth
  - Linear actuator for elevation
- Linear drive system
  - Two linear actuators

ASTRI Heliostat Cost Down Scoping Study – Final Report (ASTRI 2014)
Double Enveloping Worm Gear | Worm Drive Gear | Cone Drive
Linear Actuators 101 - How does an Actuator work | FIRGELLI (firgelliauto.com)

Worm Gear Technology Helps CSP Plant Stay Locked on Target (powermag.com 2019)
Heliostat field cost reduction by “slope drive” optimization (Arbes 2016)
The obstacles

Nicole Piatko

- High cost of material, parts, and manufacturing
- Lack of standard methods or specifications for testing

Opportunities for cost reduction

- Heliostat developers choosing linear drive systems
- Decreasing the cost of manufacturing by creating a supporting heliostat industry
- Funding research into drive testing and drive development

Recommendation

- Research and development into a specific heliostat mirror area size range to create focus on standardization and development of heliostats in industry
Thank You Mentors!

Dr. Ken Armijo, SNL
Dr. Randy Brost, SNL
Mackenzie Dennis, NREL
Tucker Farrell, NREL
Devon Kesseli, NREL

Dr. Rebecca Mitchell, NREL
Dr. Matt Muller, NREL
Andru Prescod, DOE
Dr. Gaungdong Zhu, NREL
Dr. Alex Zolan, NREL
Future Opportunities with HelioCon for Students

• Science Undergraduate Laboratory Internships (SULI) at NREL and SNL
  • How to apply: https://science.osti.gov/wdts/suli/How-to-Apply
  • Applications for Spring due **Oct 5**, applications for summer due **Jan 10**

• Internships at NREL
  • [https://www.nrel.gov/careers/internships.html](https://www.nrel.gov/careers/internships.html)

• Fellowships at SNL

• Internships at DOE
  • SETO: [https://www.energy.gov/eere/solar/fellowships-and-research-opportunities](https://www.energy.gov/eere/solar/fellowships-and-research-opportunities)
  • EERE: [https://www.energy.gov/eere/education/internships-fellowships-graduate-and-postdoctoral-opportunities](https://www.energy.gov/eere/education/internships-fellowships-graduate-and-postdoctoral-opportunities)
More From HelioCon

- Past seminar presentations now available on the NREL YouTube learning channel: https://www.youtube.com/playlist?list=PLmIn8Hncs7bGAK-hlf4qxuAbHUHK-xgZK
- Slides and flyers available here: https://drive.google.com/drive/folders/1162LN82ImgurpCODnJDLKsERCWo-698R
- Subscribe to the seminar series or get in touch: heliostat.consortium@nrel.gov

Next Seminar August 11th!

HelioCon Seminar Series: Advanced Manufacturing for Heliostats - What We Can Learn from Automotive Joining Technologies, Materials, and Automation
Speakers: Wagon Wills, Gonzalez Group | Dr. Randy Brost, SNL
When: 3-4 pm MDT Thursday August 11th
Zoom: https://nrel.zoomgov.com/j/1608929076?pwd=RStHcURySCtpRnVyYkgrKzBOTS81UT09
More From HelioCon

- Past seminar presentations now available on the NREL YouTube learning channel: https://www.youtube.com/playlist?list=PLmln8Hncs7bGAK-hlf4qyuAbHUHK-xgZK
- Slides and flyers available here: https://drive.google.com/drive/folders/1162LN82lmgurpCODnJDLKsERCWo-698R
- Subscribe to the seminar series or get in touch: heliostat.consortium@nrel.gov