Non-Intrusive Optics (NIO)
Technology for Characterizing Commercial Heliostat Optical Errors
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NIO Impact

An in-situ heliostat measurement tool to assess slope, canting, and tracking errors on operational heliostats in commercial fields.

- **Heliostat Consortium Roadmap** identified the following gaps in heliostat metrology
  - Opto-mechanical quality calibration after installation: there is missing metrology for opto-mechanical quality calibration after installation.
  - Opto-mechanical error in-situ monitoring tools: there are missing in-situ monitoring tools for the full spectrum of opto-mechanical error including surface slope error, mirror facet canting error, and heliostat tracking error. **The in-situ tools should be applicable to commercial-scale heliostat fields**
  - Receiver flux quality real-time assurance tools: there are missing validated receiver flux quality real-time assurance tools that can accommodate aiming strategies based on the knowledge of full field heliostat opto-mechanical performance.

- Stakeholder engagement and feedback
  - Models are used for everything – predicting performance, revenue, availability, aiming strategies
  - The models depend on the input data, you must know your heliostat in its operational condition
**NIO Methodology**

- NIO allows for the efficient optical assessment of a commercial-scale CSP solar field.
- Heliostats are scanned in seconds using Unmanned Aircraft Systems (UAS) imaging.
- The method produces detailed optical characterization data over the full mirror surface for every heliostat (slope, canting, and tracking error).
NIO Software

Point-wise deviations of the mirror surface normal vector

1: Field model
- Define heliostats and tower in space
- Assess measurability

2: Data collection
- Generate waypoints for a sector of heliostats
- Collect video data

3: Data parsing
- Define expected orientations
- Find heliostats
- Find features – heliostat corners and tower edges
- Compute a camera position

4: Optical errors
- 1D – calculate slope, canting, and tracking normal to reflected tower edge
- Apply tracking correction to refine
- 2D – solve for vector that satisfies reflection conditions for two orientations at single point
Significance of Slope Error

- Deviations at the surface of the mirror impact the direction of the incident sunlight and energy reaching the receiver
- “An increase of 2 mrad and 4 mrad on the total optical error RMS is equivalent to 1 mrad and 2 mrad on the mirror slope or canting error, respectively” [1]

If we can characterize slope error in an operational field:

- Map the flux at the receiver
- Build better power models
- Itemize solar field error budgets and isolate losses
- Optimize aiming strategies and adjust solar field controls to recoup lost power
- Monitor reflector degradation
- And if absolutely necessary, adjust and replace equipment

[1] A non-intrusive optical (NIO) approach to characterize heliostats in utility-scale power tower plants: Methodology and in-situ validation
R. Mitchell, G. Zhu 2020
NIO Software Progress

Feature detection sensitivity study

- Camera position
- Lighting
- Bounding box variability
- Crowded bounding box

Results

- Changing camera position creates error within 1 meter
- Lighting has no impact on the accuracy
- Changes in the bounding box size and position produce accuracy within 2.5 meters
- Crowding the bounding box causes the biggest effects providing accuracy within 30 meters

Optical flow video segmentation

- Shi-Tomasi feature detection combined with Lucas-Kanade optical flow
- Redetect points every N steps
- Compute relative key feature displacements for “speed” between frames
- Slow-moving features indicate camera is focused on a heliostat

Analysis by Kyle Sperber

Camera is pivoting to new heliostat

Measurement scans
NIO Software Progress

Transcription
• Translated the software from MATLAB to Python
  o Python is free
  o Python is more widely used
  o All of software is in one language
  o Allows software to be changed to object-oriented programming
• Translation is complete and currently flushing out minor bugs to the python version of the software so that it outputs the same results as the MATLAB version

Class architecture (purpose and status)
• Purpose
  o Reduces computer storage
  o Cuts computation time
  o Classes can be reused for other projects
  o Makes future development and bug fixes easier
• Status
  o Initial version is complete flushing out minor bugs to match Matlab version
  o Required computer storage cut by 20%
  o Computation time decreased by 33%
NIO: Characterizing Uncertainty

2D Optical Error Uncertainty → Variability in heliostat kinematics between 2 orientations → 1D Optical Error Uncertainty → Camera position accuracy → Resection computation variability → Heliostat deviations from design geometry → Edge detection errors → Long-distance distortion errors → Discretization errors
NIO in the CSP industry

- 75 + stakeholder interviews in the “Lean-Launch” framework
- Slope/shape error on the radar of plant owners, plant managers, heliostat designers...

**Planning**
- Heliostat selection
- Tech suppliers have internal design tolerances
- Issue “performance guarantees” for heliostat
- Not verifiable in operation

**Construction**
- Heliostats assembled on site
- Measured at construction, then installed
- May sit for months/years before plant is operational

**Commissioning**
- Multi-year test/verification of plan
- Required to meet power benchmarks
- Underperformance can result in liquidated damages for liable parties

**Normal operations**
- Power based on models
- Calibration by BCS
- Temperature swings, wind, orientation effects, gravity, and environmental factors can degrade mirror surface

conceptional design • components • integration • mass production • heliostat field
As a commissioning tool

- **Multiple-year, expensive acceptance process**
- **Often a ladder-structure, for example**
  - Year 1 – 65% design power output
  - Year 2 – 75% design power output
  - Year 3 – 90% design power output
- **Liquidated damages can impact underperforming systems**

- **NIO can validate heliostat performance**
  - As each heliostat is installed
  - As the solar field comes online

A heliostat is crane-lifted onto a pylon. Typically, no shape validation is done after this is complete.

A heliostat is measured with QDec – a system developed at CSPServices.
As a calibration tool

- The Beam Characterization System (BCS) is commonly used to characterize tracking error
  - Some BCS are limited to 1 heliostat per target face, or 4 heliostats at a time
  - Distant heliostats can be difficult to calibrate (< 1 km)
    - Weaker beam
    - Target is saturated from glowing receiver

- Use NIO to supplement existing systems and
  - Validate BCS output
  - Calibrate distant heliostats
  - Add high-resolution beam quality information to calibration

Sample NIO image taken on heliostat > 1.5 km from the tower
As an optimization tool

- **Optimized aiming strategies require strong models**
- **Strong models require well-characterized heliostats**
- **Current strategies**
  - Damping with overdesigned fields – more heliostats than needed to cover seasonal changes and optical losses
  - Models use assumed or designed errors in heliostat loss budgets
  - Heliostats are measured in a single orientation at construction

Case study found 20% increase in power by optimizing aiming strategy for post-installation optical deviation [2]

[2] Heliostat field aiming strategy optimization with post-installation calibration
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Thank You

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