U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

Demonstration and Automation of Reflected Target Optical Measurement for Heliostats

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NREL

NREL/PR-5700-90304

July 15-17, 2024 • ASME 2024 Energy Sustainability Conference

conceptual design • components • integration • mass production • heliostat field

State-of-the-Art Optical Measurement

Interferometry: Ultra high precision, used for telescope mirrors, difficult on larger surfaces.

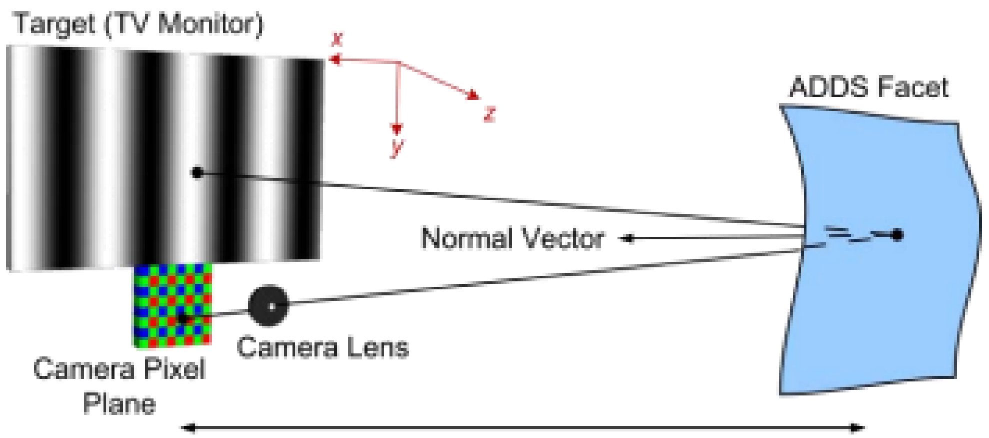
Fringe deflectometry: measurement by reflected fringe pattern. Powerful, high resolution, more complicated setup.

- SOFAST (Sandia)
- Qdec (DLR)
- Fraunhofer ISE

Structured light deflection

- VIS (ENEA).
- ReTNA (NREL)

Photogrammetry: 3D positional measurement: well established, but requires targets attached to mirror surface.



N. S. Finch and C. E. Andraka https://doi.org/10.1115/ES2011-54455

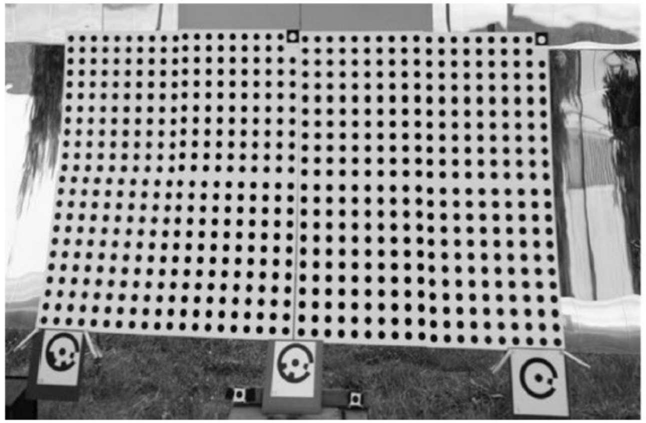
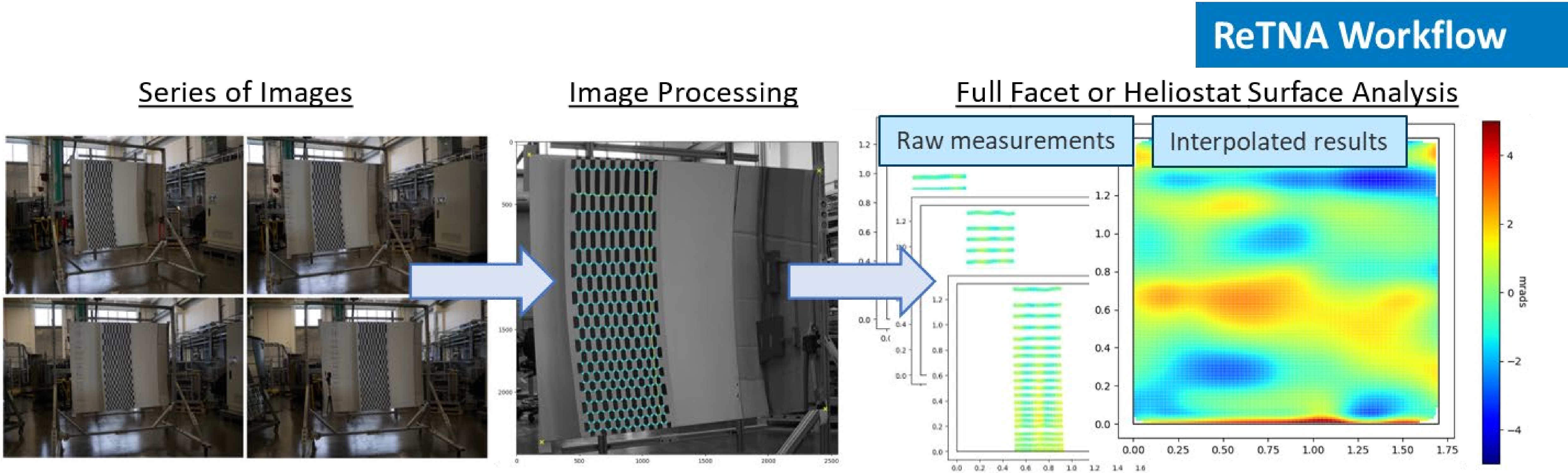


Fig. 6. Photogrammetry measurements carried out at ENEA's PTC facility by CENER's technicians.

Reflected Target Non-intrusive Assessment (ReTNA)

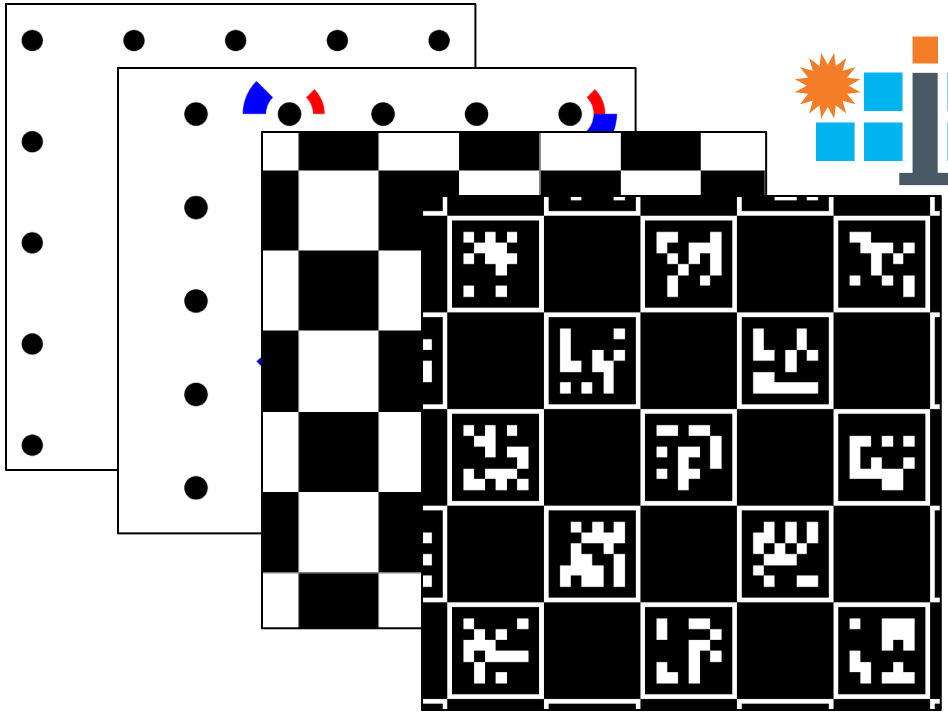
A complementary technology for the tools available today.

1. Target located in 3D with photogrammetry.
2. Series of images collected of target reflected in mirror surface
3. Deflection yields **surface slope** and **facet canting** measurements

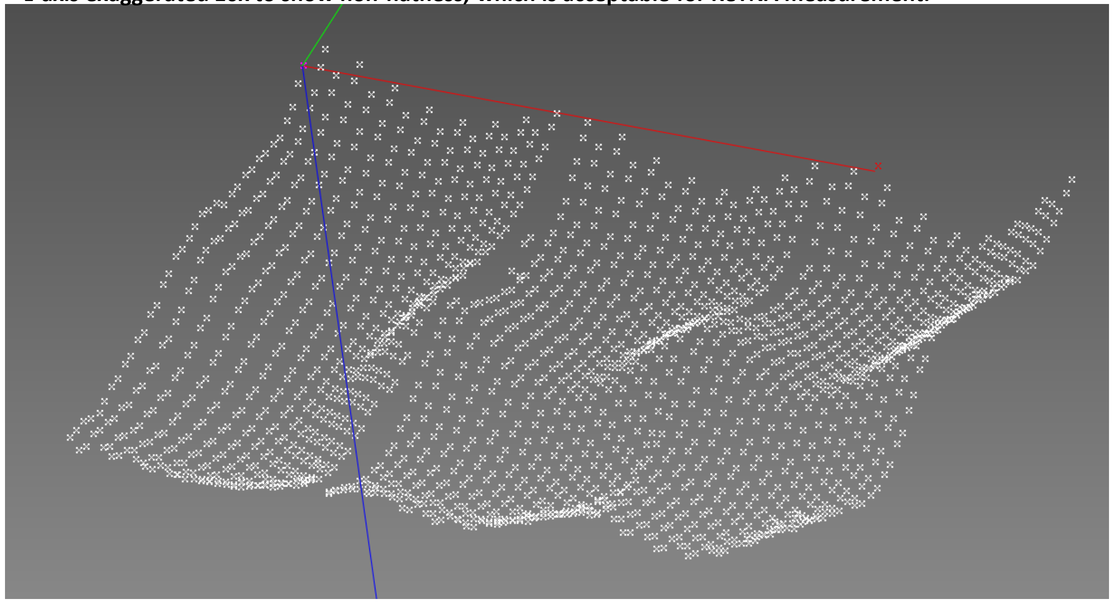


Key Differences

- 2D Printed target pattern
  - Allows for measurement in ambient lighting.
  - Allows for 2D measurement with a single image.
  - Lighter, modular, versatile targets compared to projector screens.
- Target points found in 3D space with photogrammetry
  - No flatness constraints for target, or precision required during setup.
  - Multiple images can be stitched together, to measure larger heliostats.
- Coded Targets yield fast and automatic measurement.



Above: ReTNA target evolution over time. Below: ReTNA target shape, determined with photogrammetry, z-axis exaggerated 10x to show non-flatness, which is acceptable for ReTNA measurement.



2024 Updated: Improvements and Validation

Prior to FY24, we had tested:

- A portable version of the system at ENEA in Italy
- A laboratory system, testing on a single facet sample and 2 facet canting demo.

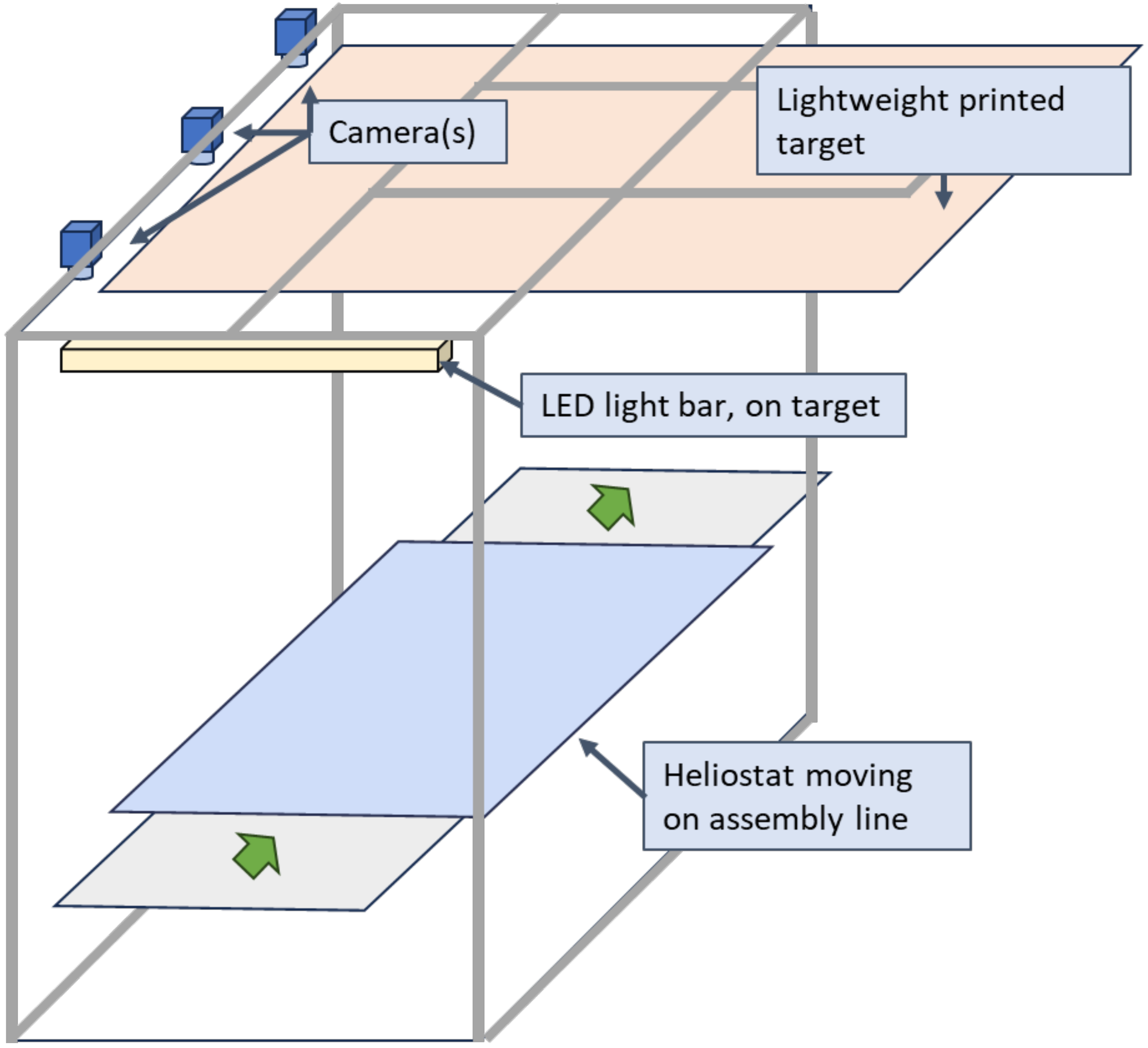
So far in FY 24:

- 2 Demonstration campaigns at a commercial heliostat developer:
    - Campaign 1: proof of concept with portable system, validation vs their existing tools. (October 2023)
    - Campaign 2: Custom assembly line QC layout. Over full 300 heliostat measurements. (March 2024)
- Test campaign with portable system at Sandia (December 2023).
    - Measuring trough facets for international round robin.
    - Comparison with SOFAST and important limitations of ReTNA identified.
- Test campaign a NREL's Solar Furnace heliostat (April 2024).
- Test campaign at a second commercial heliostat developer (June 2024).

Significant learnings and improvements with each test campaign

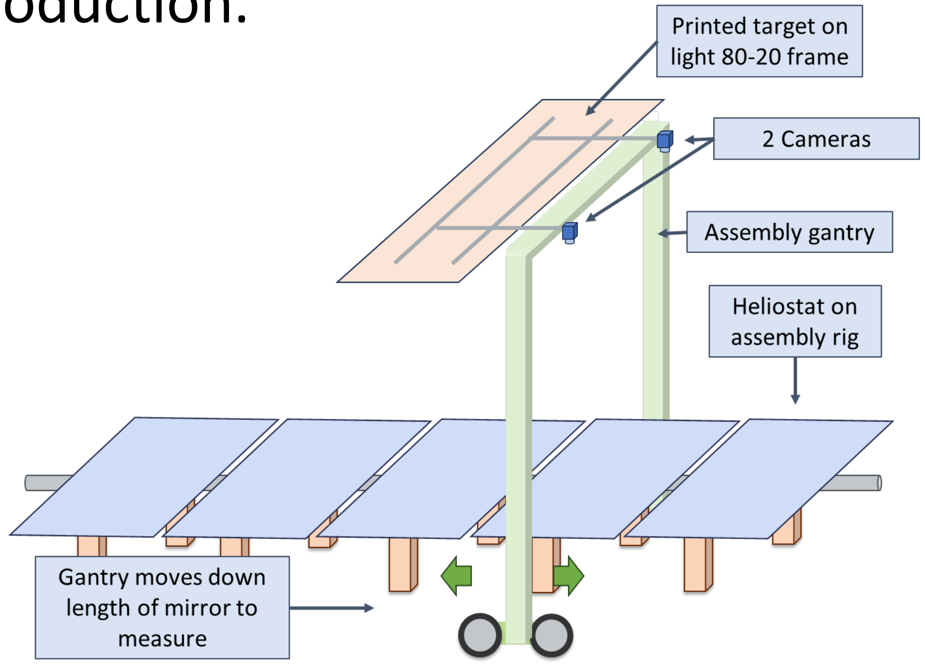
Layout Changes: Assembly Line

- Layout changed for integration into a commercial assembly line.
  - No moving parts (except heliostat).
  - Ambient lighting
  - Analysis from a single image
  - Currently >700 measurements per m^2. Can likely reach >2000 with single image.
  - Heliostat does not need to be removed from assembly line.

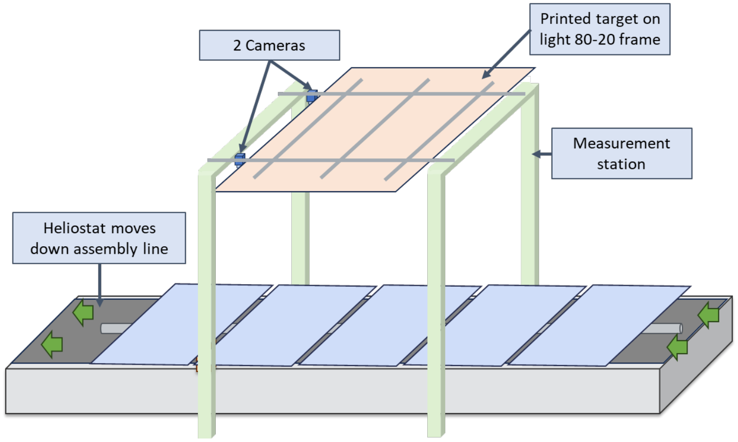


Layout Changes: Development

- Heliostat developer version for measurement during assembly.
  - Camera(s) and target mounted on rolling gantry crane.
  - Allows for scan of heliostat without removing it from the assembly rig.
  - Can be adapted back to assembly line version for mass production.



Adaptable back to assembly line version



Measurement Validation

Extensive measurement system validation campaign undertaken in March 2024 at commercial heliostat assembly line:

- 300+ full heliostat measurements.
- 10+ full system calibrations
- 2 Target heights
- 3 different camera positions/full system takedown and reassembly.
- 3 different camera lenses.
- Different lighting conditions.

These led to some crucial improvements, most notably:

- Camera calibration procedure improvement. At larger imaging distances, changing camera focusing distance led to slight changes in calibration parameters.
- Understanding of lighting.

Measurement Validation Results

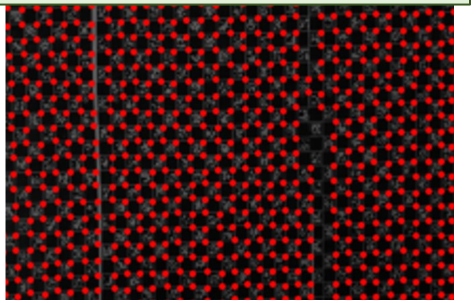
- Standard deviation of repeated measurement on each mirror with all variables (camera/target height change, camera position change, lighting change, ISO change, system recalibration) is 0.127 mrads.
- +/- 0.255 with 95% certainty.
- From our tests, we can see what changes the results most significantly. Surprisingly, this was camera lens, leading us to the conclusion on the previous slide. Improving our calibration procedure will likely reduce this uncertainty.
- Likely larger uncertainty when using a smaller target, stitched together images.

Lighting and Exposure

Exposure Testing: how dark can the images look?

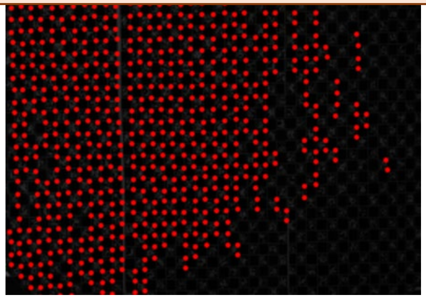
Acceptable

Full target recognition



Too dark

Partial target recognition

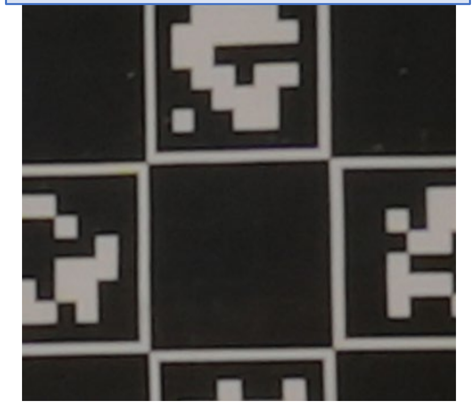


Lighting changes during testing will not affect measurement results

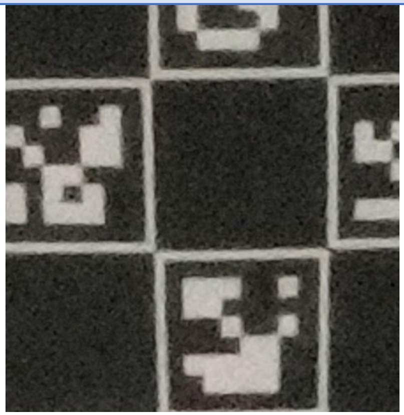
Shutter speed and ISO: Noise and blur.

- Does a high ISO cause noise in results?
  - Yes, but only at extreme ISO values (>2000)
- Does a low shutter speed cause blur in results?
  - Depends on movement of system, but we results show this will not be a concern on expected setups.

Low ISO, slow shutter



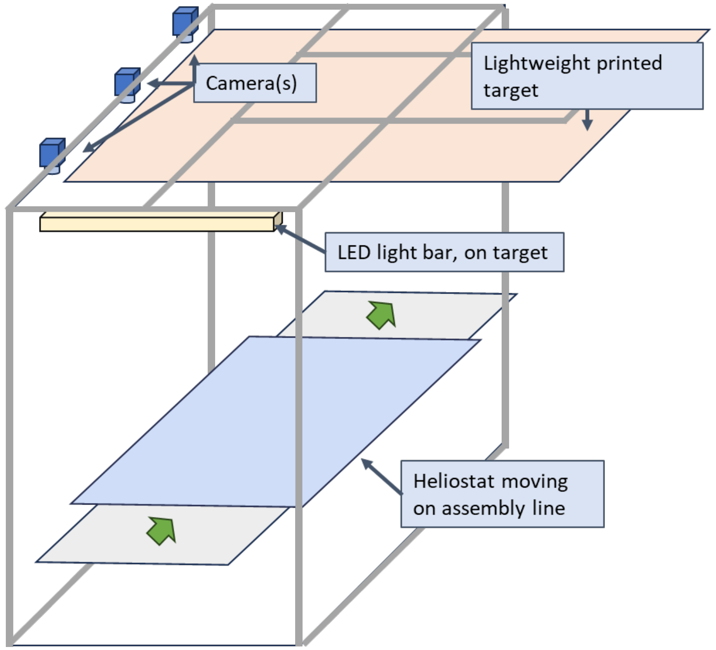
High ISO, fast shutter



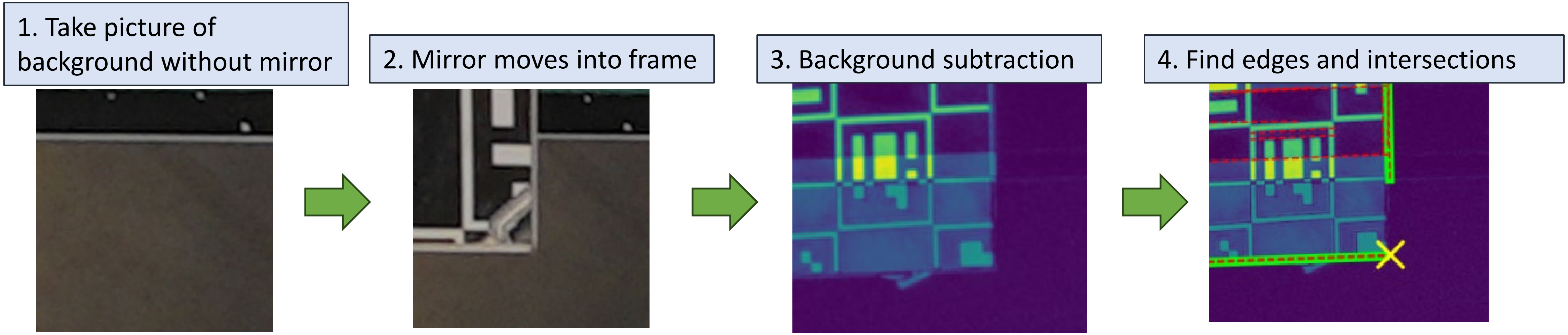
Software Automation Improvements

Two new methods to automate measurement analysis:

1. Computer vision capture of heliostat on assembly line via background subtraction.
   - This method can effectively automate the QC layout, where the heliostat moves under a stationary camera and target.
2. Define an external reference frame with computer identifiable targets.



Method 1



HelioCon Milestones

Milestone #	Milestone Title	Description	Metric	Success Value
1.5.2	Development of NIO-a for heliostat quality assessment in the warehouse.	NREL will expand the NIO technology into a short-distance version (NIO) suitable for heliostat optical error assessment in a warehouse. A procedure will be designed for near-target warehouse optical characterization and calibration of heliostats including a painted target to be reflected in a mounted heliostat and mobile camera scanning device. NIO algorithms will be extended to perform near-target measurement of slope, focusing, and canting errors using inputted image data from the camera scan and heliostat design geometry. One prototypes of the measurement apparatus will be built in an NREL's dedicated test lab.	Measurement uncertainty of slope error measurement	0.5 mrad, 95% confidence level
2.5.2	Refinement, validation, and streamlining of indoor optical quality assessment tool (NIO-a), and Helio-OPAL lab development.	NREL will expand and validate the warehouse optical metrology tool (NIO-a) developed in FY22. A new test apparatus will be built in NREL's new Heliostat Opto-mechanical Performance Assessment Laboratory (Helio-OPAL), and NIO-a measurements will be compared with other surface metrology systems. The tool's ability to collect and assess slope and canting measurement within a target uncertainty will be demonstrated. The data collection and analysis procedures will be streamlined for fast commercial data collection using computer vision and photogrammetry methods. Instructions for data collection and analysis will be captured in a formal operations manual. Collect data in Helio-OPAL lab space.	1) Measurement uncertainty of slope error measurement. 2) Improved software setup and operation time. 3) NIO-a documentation. 4) Completion of prototype system installation at Helio-OPAL facility and test campaign.	1) 0.25 mrads, 95% confidence level. 2) <8 hours for new system setup and calibration, <20 minutes for measurement and analysis. 3) Instruction manual document. 4) Yes.
3.5.2	Helio-OPAL facility and metrology tool development	Development of draft test process and protocol with a template test report. Continue to perform industry outreach to determine most valuable measurement capabilities and results.	1) Speed and performance improvements for NIO-a installation, lowering data collection and analysis time for a positioned optical surface. 2) Draft protocol and perform optical assessment test in Helio-OPAL. 3) Industry outreach and assessment of other useful Helio-OPAL capabilities. 4) Complete validation study at Heliogen or Sandia to verify ReTNA accuracy.	1) 1 minute 2) Protocol document and template test report. 3) Memo on additional capabilities and development costs. 4) 0.25 mrads *pointwise* error (not rms).

Questions?

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