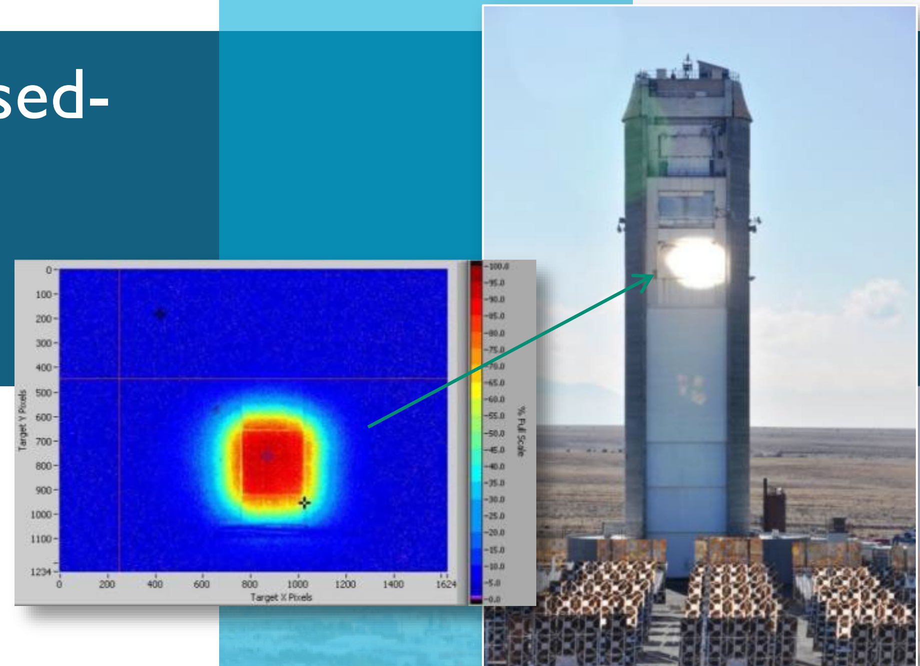
NSTTF Heliocon Wireless Closed-Loop Controls Test Bed Development

ES2023-110772



Kenneth M. Armijo, Ansel Blumenthal, Aaron Overacker, Luis Garcia-Maldonado, Dimitri Madden and Matthew Muller (NREL)

Sandia National Laboratories, Albuquerque, NM

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Agenda

Solar Roasting Challenges

- Closed loop controls test bed is in development at the Sandia National Laboratories solar tower facility as part of the U.S. DOE SETO Heliocon program
- Preliminary development of advanced feedback controls for a CSP Power Tower & field of 218 heliostats
- Progress of the highly-flexible controls and sensors which will be communicating with both wired and wireless protocols.
- Software architectures utilized to determine optimal pointing of each heliostat, accounting for unique metrology considerations

Overview

- Closed-Loop Controls
- NSTTF Heliostat Field Refurbishment
- Hardware Development
- Software Development

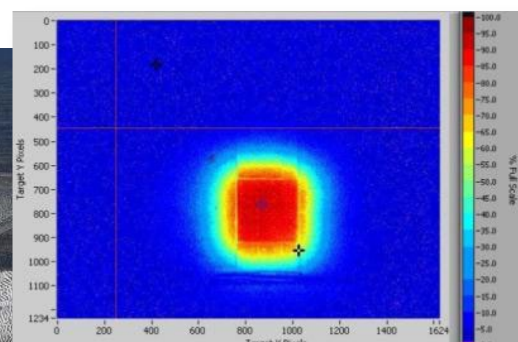
Conclusions

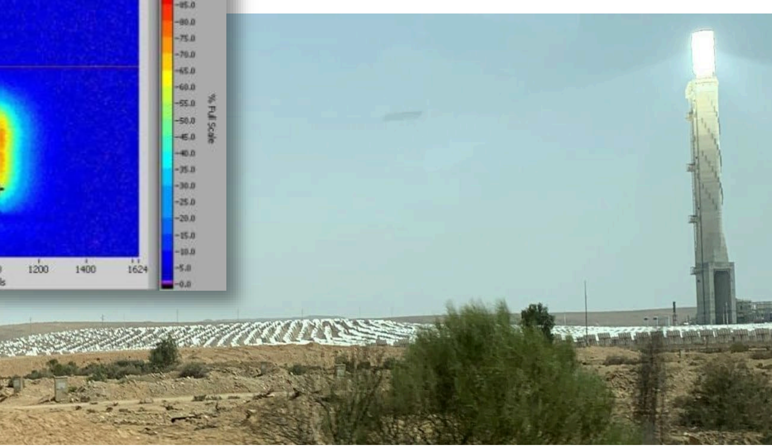
Heliostat Controls

- The operational modes:
  - Wake-up mode: Heliostat moves from a stow position to a sun-tracking position
  - Maintenance mode: Heliostat is available for manual operation and mechanical and electronic maintenance
  - Stow mode: Heliostat is in a storm-protection position
  - Tracking mode: Heliostat tracks the sun
  - Calibration mode: Heliostat error vector is able to be auto calibrated.
- Movement by two-axis motorized system, controlled by computer.
  - Computer is given latitude/longitude of heliostat's position and time/date. Using astronomical theory, controller calculates sun direction (e.g. its compass bearing and angle of elevation).
  - Given direction of receiver, computer calculates direction of required angle-bisector, & sends control signals to motors.
  - Sequence of operations is repeated frequently & with high resolution to keep the mirror properly oriented.
  - Traditionally, primary rotational axis is vertical and secondary is horizontal.
- Drives or linear actuators facilitate movement and contain seals, gaskets and hydraulic fluid.
  - Drives & Encoders/Computer include gaskets and seals to keep moisture out but has wear and humidity intrusion over time.

Closed-Loop Controls Overview

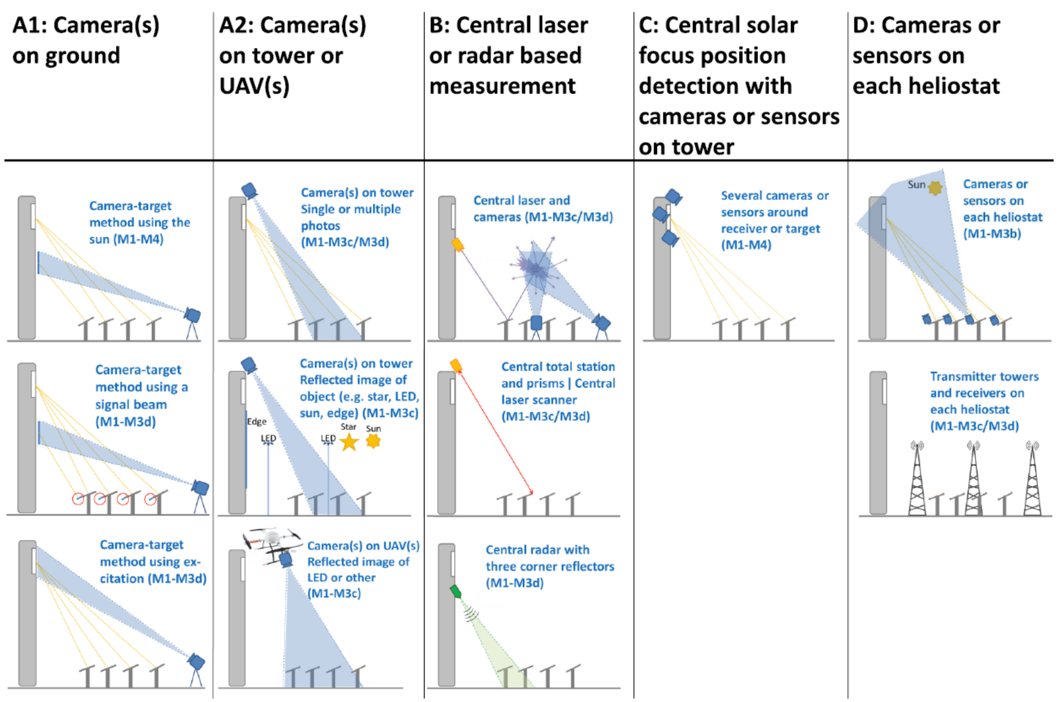
- Controls ensure each heliostat tracks angle bisector & controls flux between sun and receiver
- Closed-loop systems possess beam characterization system, provides feedback based on heliostat's receiver aiming.
- Closed-loop control enables automatic calibration as part of commissioning and fine calibration on a daily or even more frequent basis.
- Hardware to enable closed-loop heliostat control capable of feedback for plant-level control
- Software able to decide which heliostats aim at receiver to maximize flux
- Goal to decrease commissioning and O&M cost/increase plant performance.



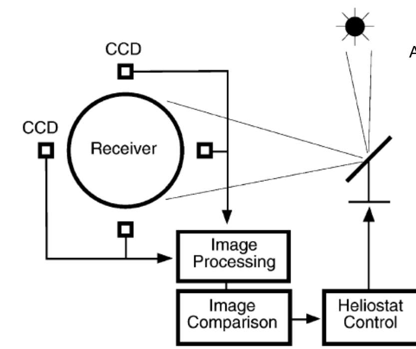


Closed-Loop Controls Design

- Varying control strategies for automation
- For every CSP system, the number of heliostats pointed at the receiver needs to be adjusted depending on the sun's position in the sky
- Closed-loop control allows operator to know exact location & diagnostics for each individual heliostat vs. entire array.

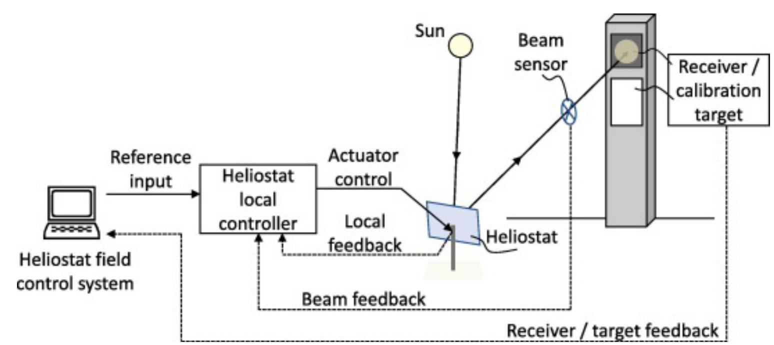


J. C. Sattler *et al.*, "Review of heliostat calibration and tracking control methods," *Sol. Energy*, vol. 207, pp. 110–132, Sep. 2020



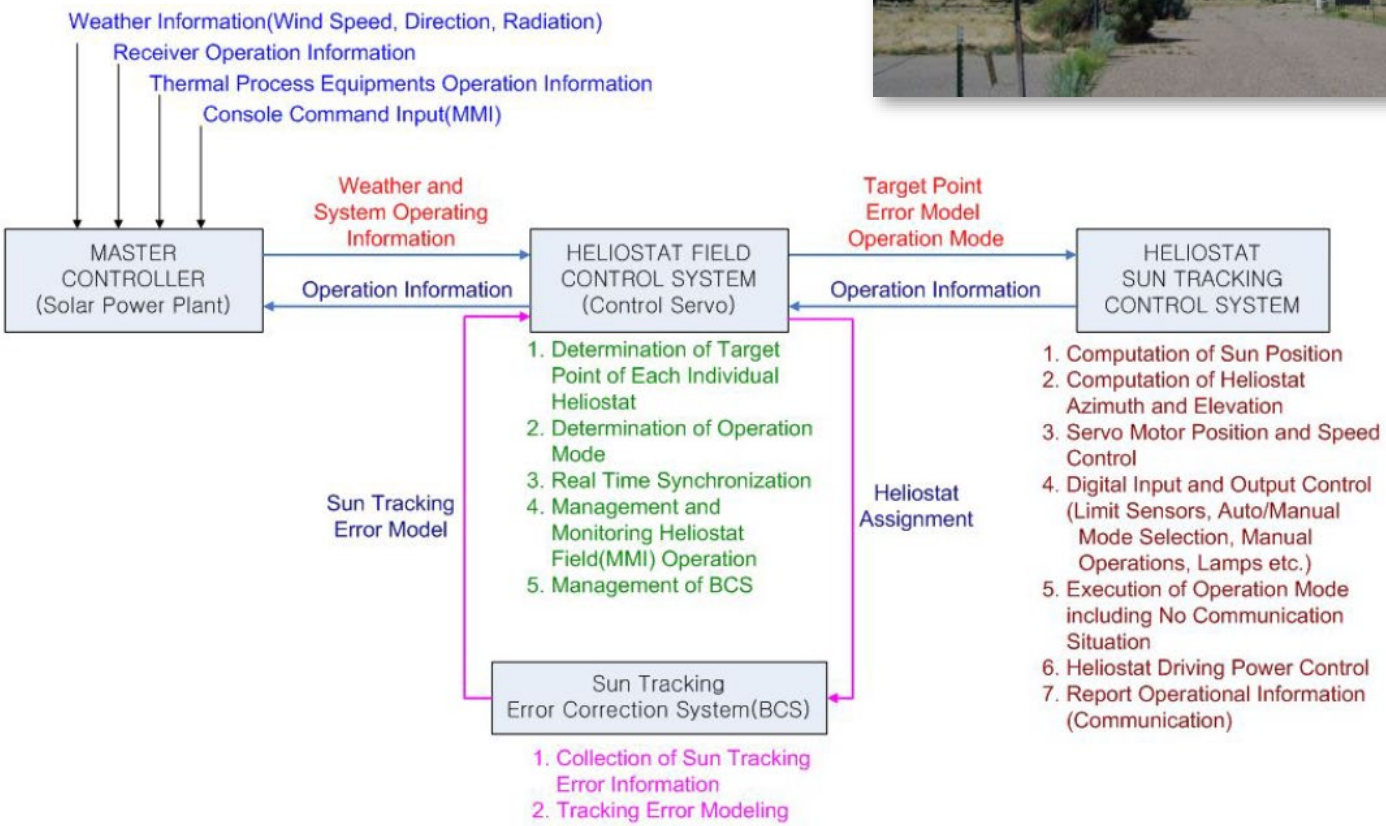
A. Kribus et al., Energy 29 (2004) 905-913

The heliostat control loop is closed by acquisition of four images around the receiver aperture, and generating a control signal by image processing.



Pearson, J. and Chen, B., An Assessment of Heliostat Control System Methods, *SERI/SP-253-2390, DE86004416*

Closed-Loop Controls Design

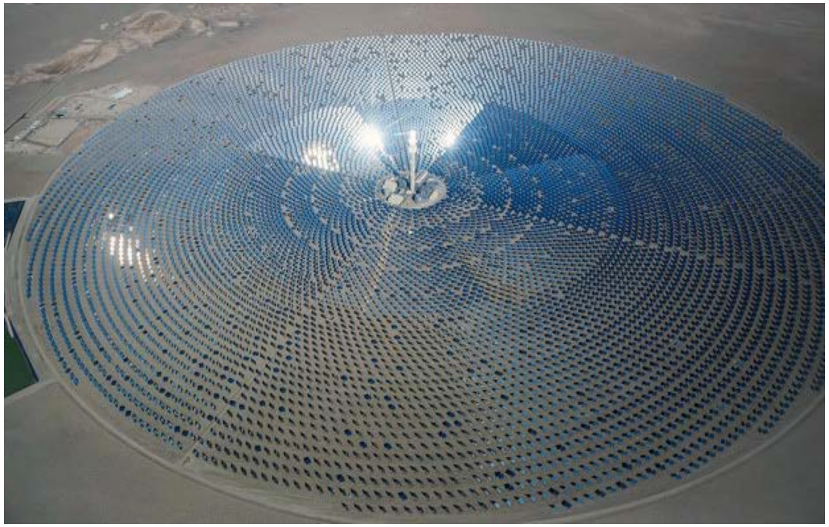


Park, Y.C., 2009. Heliostat control system. *Journal of the Korean Solar Energy Society*, *29*(1), pp.50-57.

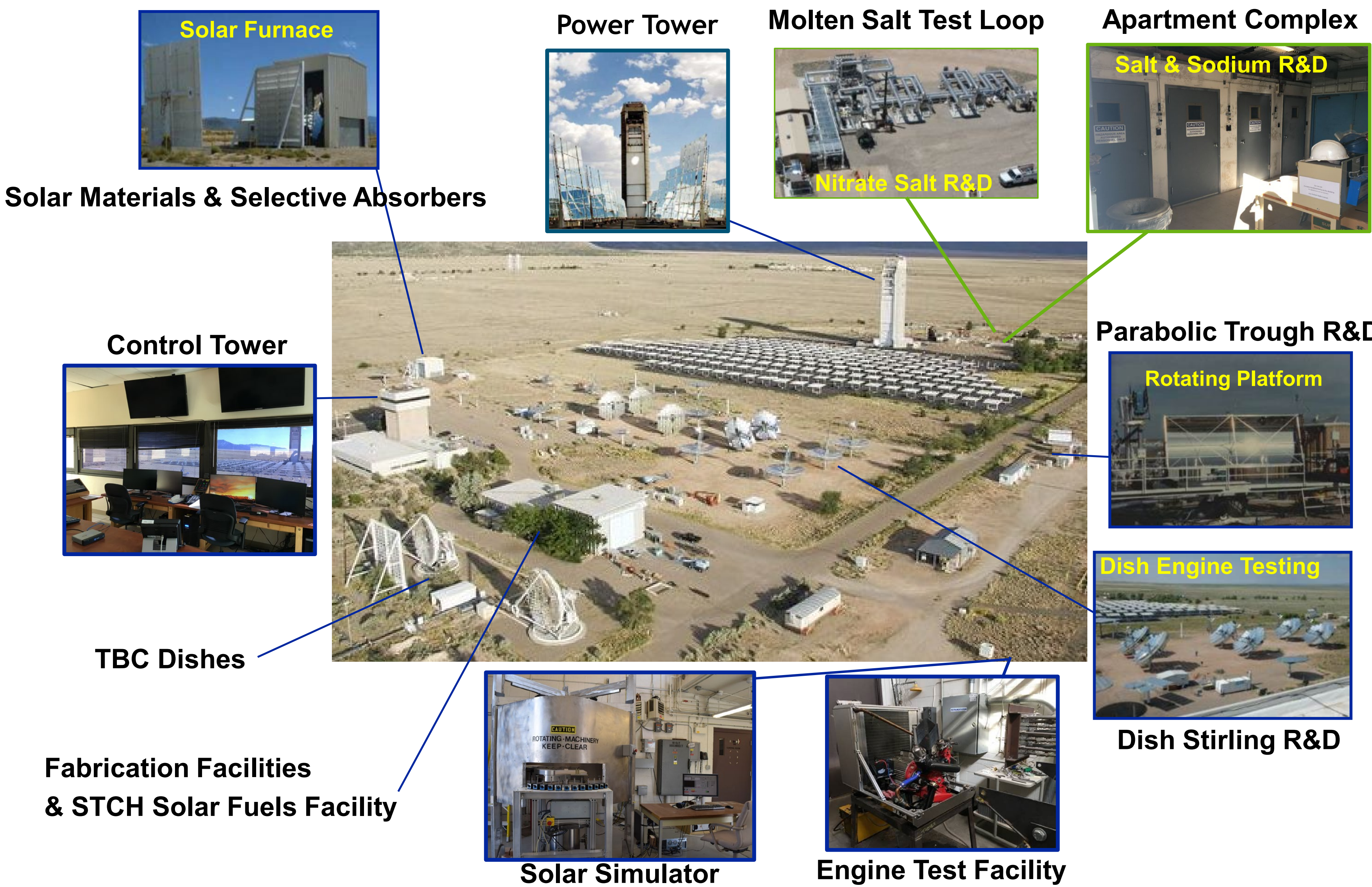
Controls Challenges

- Wireless systems approaches must be broadly introduced to capitalize on lower plant cost while wireless risks and technical issues must be avoided. Standardized requirements & testing capabilities are needed.
- Closed loop control must be more broadly applied to achieve higher flux performance and auto alignment/calibration processes.
- Robust signal communication R&D needed for resilient wireless controls. R&D needed for wireless advanced controls architectures and hardware for facilitating single node or mesh networking.
- Reliability research of current interconnection hardware with respect to signal distribution under varying controls scenarios.

- <u>**Need for a Closed-Loop Controls Test Bed**</u>



Sandia's National Solar Thermal Test Facility (active since the 70s)



NSTTF Heliostat Field Refurbishment - Hardware

- Current hardware dates to 2003 motion technology
  - The heliostats are driven by 2 axis motors (Azimuth and Elevation)
  - A 16-BIT SSI encoder is used to obtain positioning for each heliostat
  - An open loop GPS timer tracks sun position
  - Each heliostat is controlled by National Instruments (NI) Real Time Controller (CRIO), which is outdated and no longer supported by NI
- New hardware upgrades include a new NI Real Time Controller that is supported by NI for the next 10 years (CRIO 9053)
  - The current Motor Drive Modules (NI 9505) will be used to perform the motion of each axis
- New SCRAM DAQ system for rapid emergency operations
- New GPS time system to track sun position
- New data management system of Heliostat System Status
  - Current system saves local files to a local hard drive
  - New system will be a network attached storage device (NAS) that saves 24/7 Heliostat System Status
- New Communication infrastructure
  - Old communication infrastructure was "Power over Ethernet" limited to 2 Mbps
  - Fiber Optic line will be installed to allow speeds up to 10 Gbps
  - Wireless Communication integration with speeds of 3 Mbps installed alongside hardwire connection

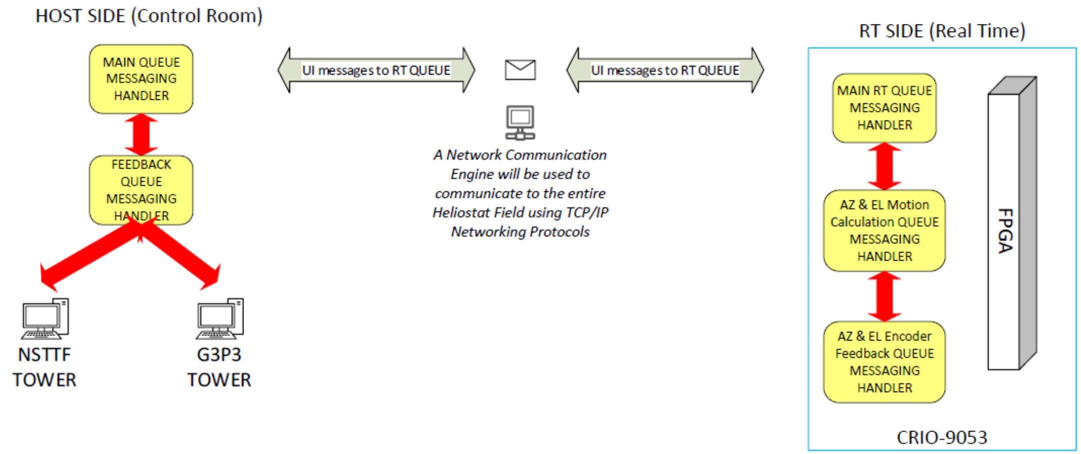
NSTTF Heliostat Field Refurbishment - Software

- Flexible solar field distributed control system (DCS) manages the flux distribution of energy across test articles and solar receivers using real-time heliostat-aiming and closed-loop feedback algorithms for solar field.
- Feedback control is facilitated with a variety of sensors, located: 1. On the heliostat, 2. On the tower or 3. At an ancillary field tower station
- System developed to incorporate environmental information to provide real-time feedback into advanced algorithms for solar field management.
- Current Deployed software dates to LabVIEW 8.6 released in 2008
    - Outdated Windows 7 Operating System
    - Open Loop Control procedure
- New Control software will be developed in LabVIEW 2020
    - Each Heliostat Real Time Controller will have the CRIO OS 2020
- The control software will contain a new architecture to allow integration of Closed Loop Control procedures
- New Network communication protocols to allow faster data transfer for high reaction operations

POWERED BY LabVIEW

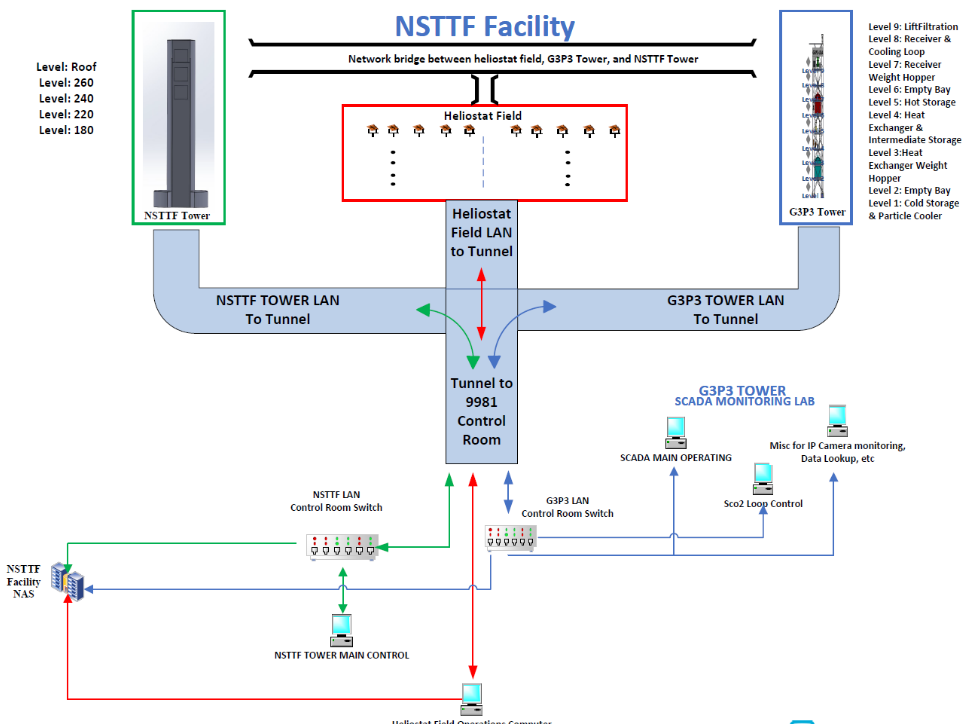
Communications Development

NSTTF NEW HELIOSTAT CONTROL ARCHITECTURE



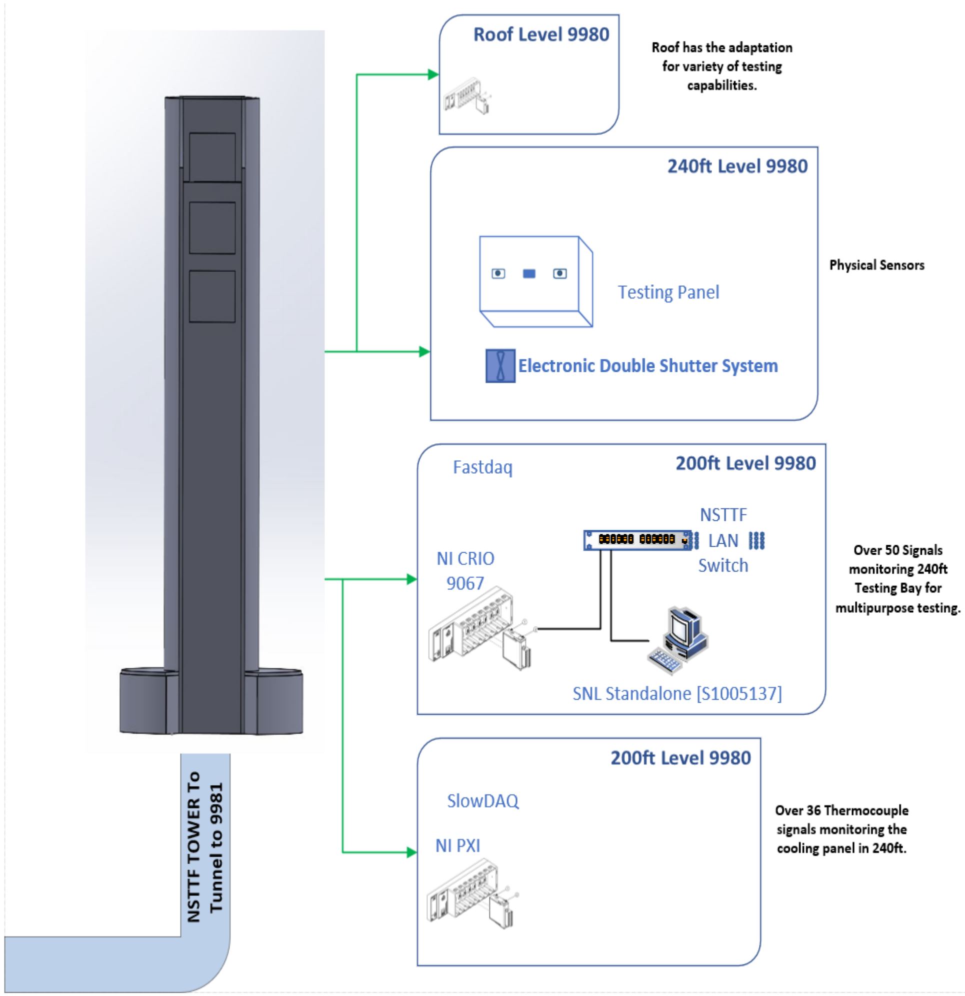
Each CRIO uses FPGA processing for high speed I/O analysis for both Az and El motors and Encoders.

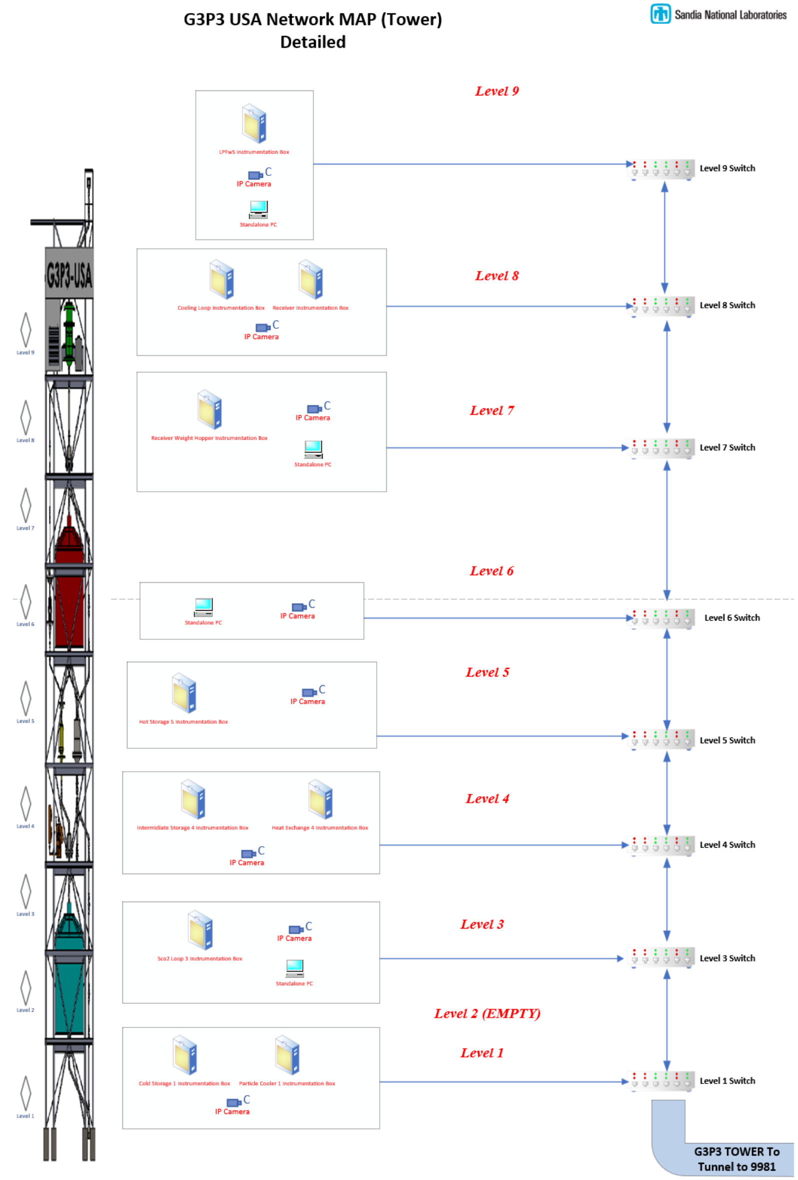
218 RT Targets Deployed



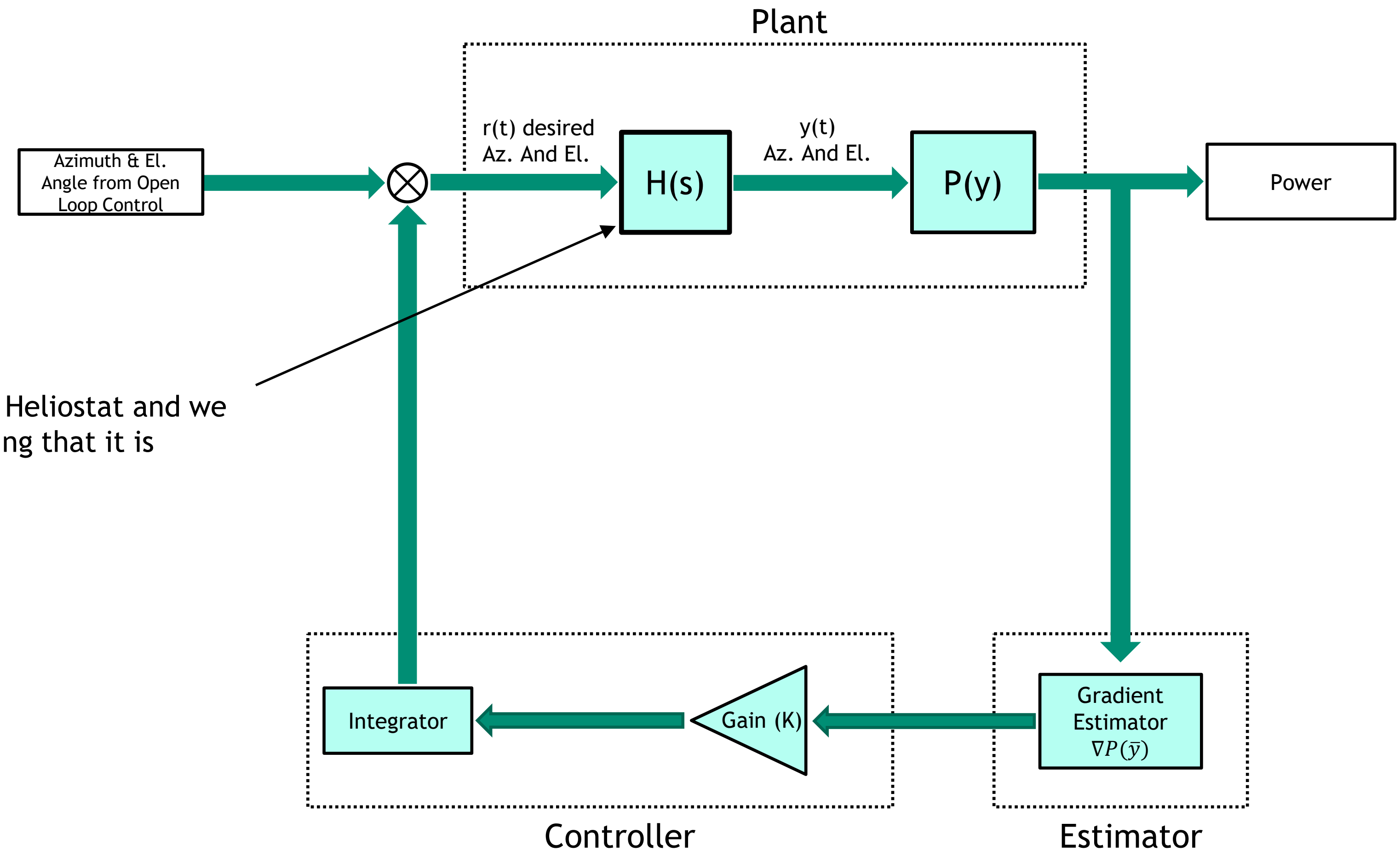
Tower Feedback Controls

Current NSTTF Tower



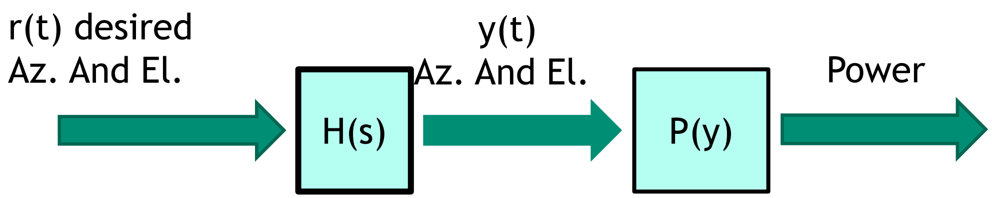


Closed Loop Controls Initial Architecture



H(s) is our Heliostat and we are assuming that it is servoed

Plant



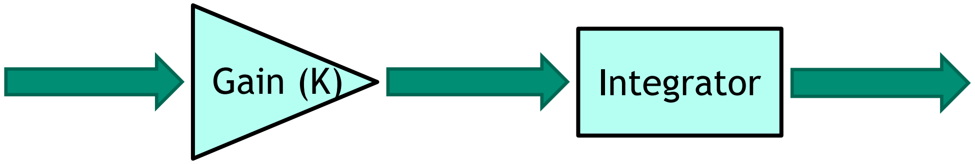
- H(s) is the transfer function of our Heliostat
  - This is a Dynamic System
  - Input: Desired Azimuth and Elevation angle
  - Output: Actual Azimuth and Elevation angle
- P(y) is our reward function which is our power and is nonlinear
  - Algebraic function which is non-dynamic
  - Input: Actual Azimuth and Elevation angle
  - Output: Power
- We integrate open loop algorithm to get desired azimuth and elevation which acts as a feedforward controller
- Goal is to maximize our power on the tower

$$P(t) \rightarrow P^* = \max P(y^*)$$

- An associated optimal Azimuth and Elevation that give P^*

$$y(t) \rightarrow y^* = (az^*, el^*)$$

Controller



- Extremum Seeking Control is an optimization algorithm
  - Finds direction needed to improve the reward function ($\nabla P(y)$)
  - Moves the heliostat in the necessary direction

$$Goal: r^{+} = r^{*}$$

  - Using the steepest ascent optimization algorithm below

$$r^{+} = r + K\nabla P$$
$$r^{+} = r^{*} \; when \; \nabla P = 0$$

- Goal of the controller is to track the ever improving reference

$$y(t) \rightarrow r(t) \rightarrow r^{*} and \; P(t) \rightarrow P^{*}$$

Estimator

- Trying to Maximize P(y)
- Measure: Power versus Position

$$P_i = P(y_i)$$

  - Using the real-time dataset below to provide feedback

$$\{P_i, y_i\}_{i=1}^{N}$$

- Goal: $Estimate\ \nabla P(\bar{y})$

$$P_i = P(\bar{y}) + \nabla P(\bar{y})^T (y_i - \bar{y}) = \theta^T \Phi_i$$

$$\Phi_i = \begin{bmatrix} 1 \\ y_i - \bar{y} \end{bmatrix}$$

$$\theta = \begin{bmatrix} P(\bar{y}) \\ \nabla P(\bar{y}) \end{bmatrix}$$

Estimator

- Approach: Least-Squares Estimator

$$E = \frac{1}{2}\left(P_i - \begin{bmatrix} P(\bar{y}) \\ \nabla P(\bar{y}) \end{bmatrix}^T \begin{bmatrix} 1 \\ y_i - \bar{y} \end{bmatrix}\right)^2$$

$$E = \frac{1}{2}(P_i - \theta^T \Phi)^2$$

- To minimize estimator cost we take derivative with goal to find when derivative equals 0:

$$\frac{dE}{d\theta} = \Phi P_i - \Phi \Phi^T \theta$$

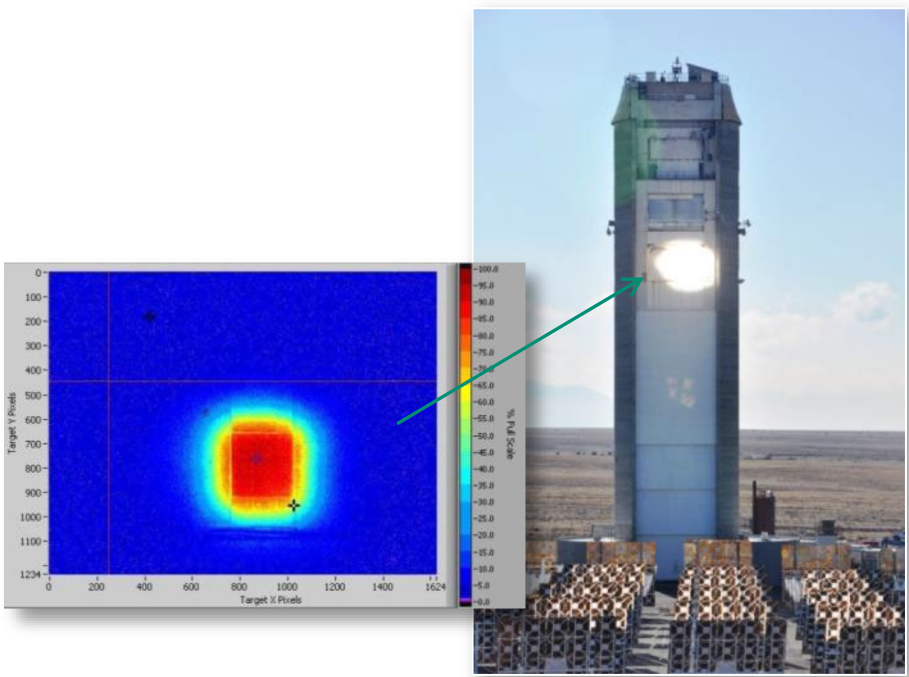
- Challenge with this is that we must have data such that:

$$\Phi \Phi^T = \begin{bmatrix} a & b \\ b & c \end{bmatrix}^{-1}$$

- Take condition number where higher the condition number the better the data is. We would like Quality of data over Quantity of data.

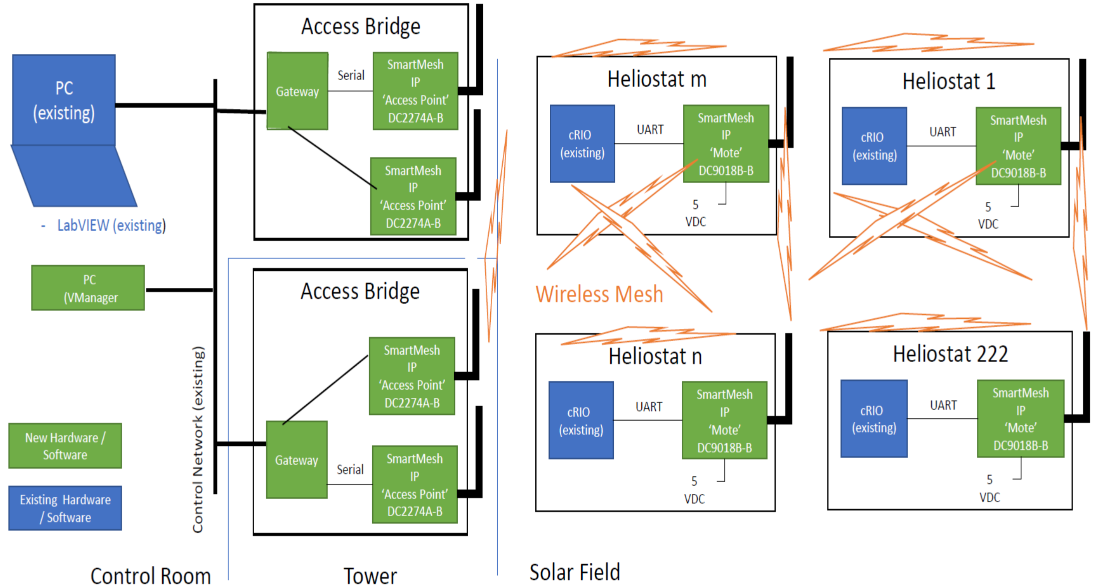
Closed-Loop Controls Dev.

- Analysis being performed against BCS and IR Cameras
- Flux and Thermal Gradients to provide fine resolution controls
- Course assessment based on inherent open-loop algorithm controls
- On-Going data collection as training data for improving accuracy
- Heliocon metrology task collaboration for final controls analysis

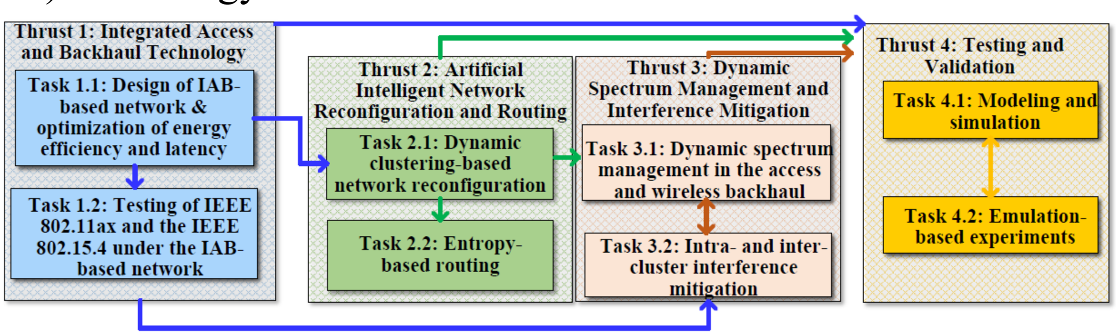


Heliocon RFP Controls Projects

- Solar Dynamics Mesh Network
  - Demonstrate reliable solar field wireless control system to replace wired networks.
  - Wireless Radio Frequency (RF) demonstration system.



- UNM Mesh Network Protocol
  - HELIOCOMM resilient wireless communication protocol system based on Integrated Access & Backhual (IAB) technology.



Conclusions & Future Work

- NSTTF Heliostat Field Controls/Comms Refurbishment to support G3P3.
- DOE Heliocon Closed-Loop Controls Test Bed Architecture Development.
- Closed-Loop Controls algorithm development based on initial hybrid Least Squares Law & Open Loop initialization.
- Heliocon RFP projects to support Wireless Mesh Network Communication hardware and software protocol development
- Future work required to obtain training controls data for improving pointing and controls.
- Looking for users of the Closed-Loop Controls and Wireless Heliostat Field test bed.

Acknowledgements

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kmarmij@sandia.gov

Thank you.

Field Hardware Timeline

- cRIO 9053 Hardware Update: June 2022 – Aug 2022
  - 218 cRIO 9053 delivered to NSTTF and passed quality check: June 2022 – July 2022
  - Operating System Update: June 2022 – July 2022
- Field-programmable gate array (FPGA) Interface for cRIO 9053: July 2022 – Oct 2022
  - Synchronous Serial Interface (SSI) Encoder: July 2022 – Aug 2022
  - Test Interface: Aug 2022 – Sept 2022
  - Simulation & Validation (Installation onto 9053 Test module): Sept 2022 – Oct 2022
- Heliostat Field cRIO Deployment: Jan 2024 – Mar 2024
- SCRAM, GPS, & NAS Deployment: April 2024
- Wireless Communication Installation: Jun 2024 – Aug 2024

Control Software Timeline

- RT Interface: Sept 2023 – Jan 2024
  - Communication with FPGA: Sept 2023 – Oct 2023
  - Develop calculations and Connections: Sept 2023- Dec 2023
  - Simulation Testing: Oct 2023 – Jan 2024
  - Validation: Dec 2023 – Jan 2024

- Closed Loop Controls: June 2023 – July 2024
  - Single Heliostat Algorithm: June 2023 – Nov 2024
  - Small Cluster Heliostat Algorithm: Sept 2023 – Mar 2024
  - Large Cluster Heliostat Algorithm: Feb 2024 – July 2024

- Closed Loop Interface: Jan 2024 – Mar 2024
  - Sensors for DNI, wind, weather, camera: Jan 2024 – Feb 2024