MARCH 28, 2025 | TMS

Simulation and Sensing Driven Automation in Additive Manufacturing for Adaptive Materials Research

James C. Haley

Bruno Turcksin, Ashley Gannon, John Potter, Callen Kimmel, Steve Dewitt

U.S. DEPARTMENT OF ENERGY

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

ORCID

Manufacturing Demonstration Facility
(Established 2012)

$1B+ impact on U.S. manufacturing with >20:1 ROI

110,000+ sq. ft. facility

180+ staff members

40,000+ visitors, 6,000+ visiting companies

50%+ of equipment is industry owned

100+ AM systems

OAK RIDGE National Laboratory

Acknowledgments

People

Bruno Turcksin, Steve Dewitt, Alex Plotkowski, Yousub Lee, Ke An, Thomas Feldhausen, Lauren Heinrich, Ayana Ghosh, Callan Herberger, Marshall McConnell, Jesse McGaha, Ashley Gannon, Jesse Heineman, Calen Kimmell, John Potter, and Paritosh Mhatre

Facilities and Computing Resources

Oak Ridge National Laboratory | Manufacturing Demonstration Facility

Oak Ridge National Laboratory | Spallation Neutron Source

Oak Ridge National Laboratory | Leadership Computing Facility

CADES

Funding

INTERSECT — Interconnected Science Ecosystem

ECP — Exascale Computing Project

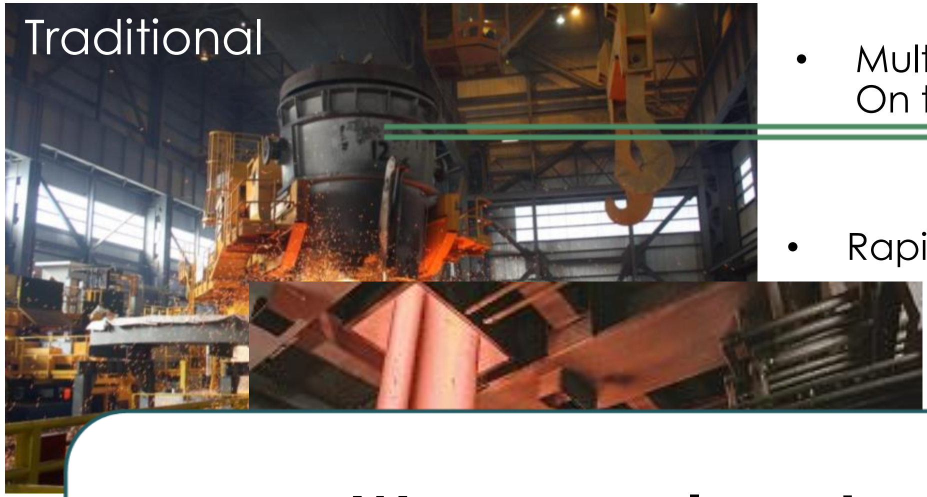
U.S. Department of Energy | Energy Efficiency & Renewable Energy — Advanced Materials & Manufacturing Technologies Office

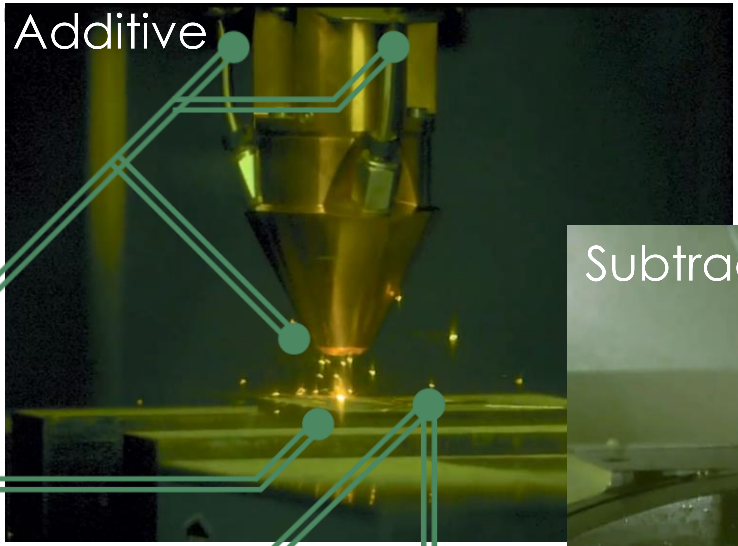
AMMT — Advanced Materials and Manufacturing Technologies

IBAS — Industrial Base Analysis and Sustainment Program

Hybrid: A ‘factory in a box’

Where is QC?





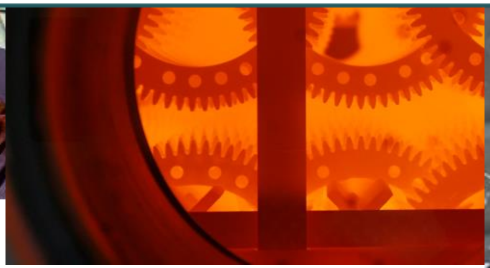
- Multiple hoppers: On the fly alloying
- Rapid solidification

We can only automate and control what we can measure.

Can we bring our sensing closer to the process to accelerate innovation?

- Solidification

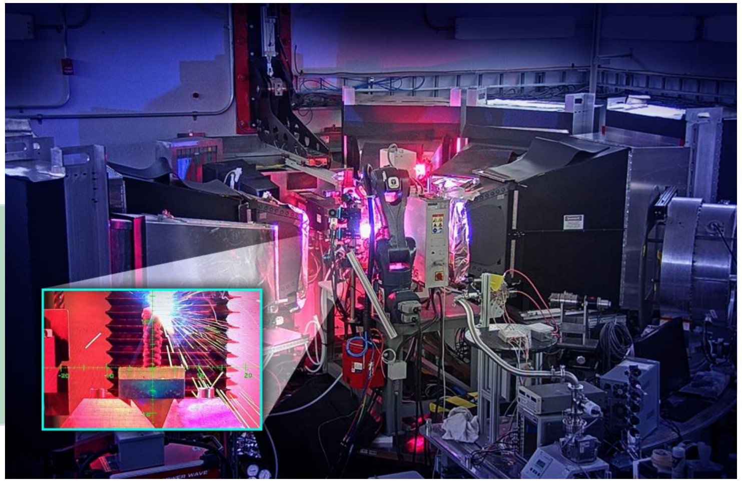
Forging
- Near net shape
- Grain refinement



Heat Treat
- Stress relief
- Microstructure tuning

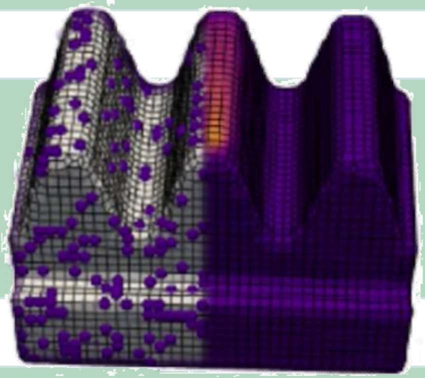
Finishing
- Surface treatments & final shape

Three tools to pursue scientific automation:



Operando Neutron Diffraction

Real-time microstructure observation in WAAM

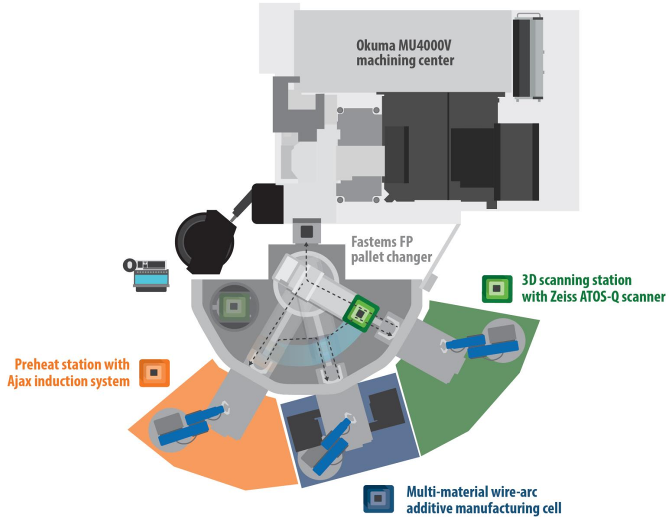


Simulation Twin

Live data synthesis for model-guided control

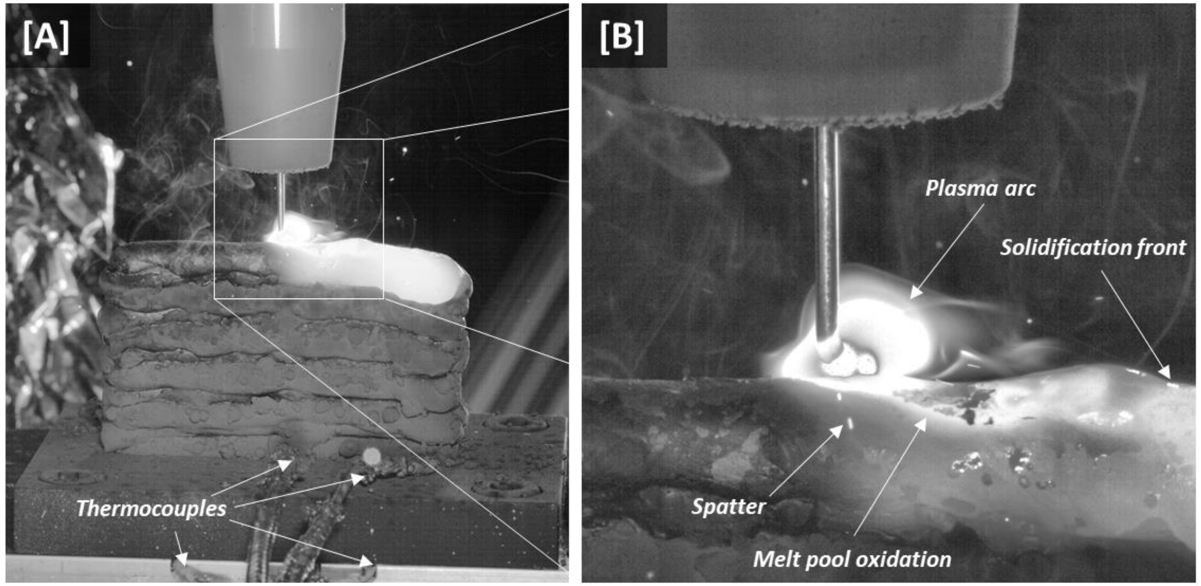
Convergent Manufacturing

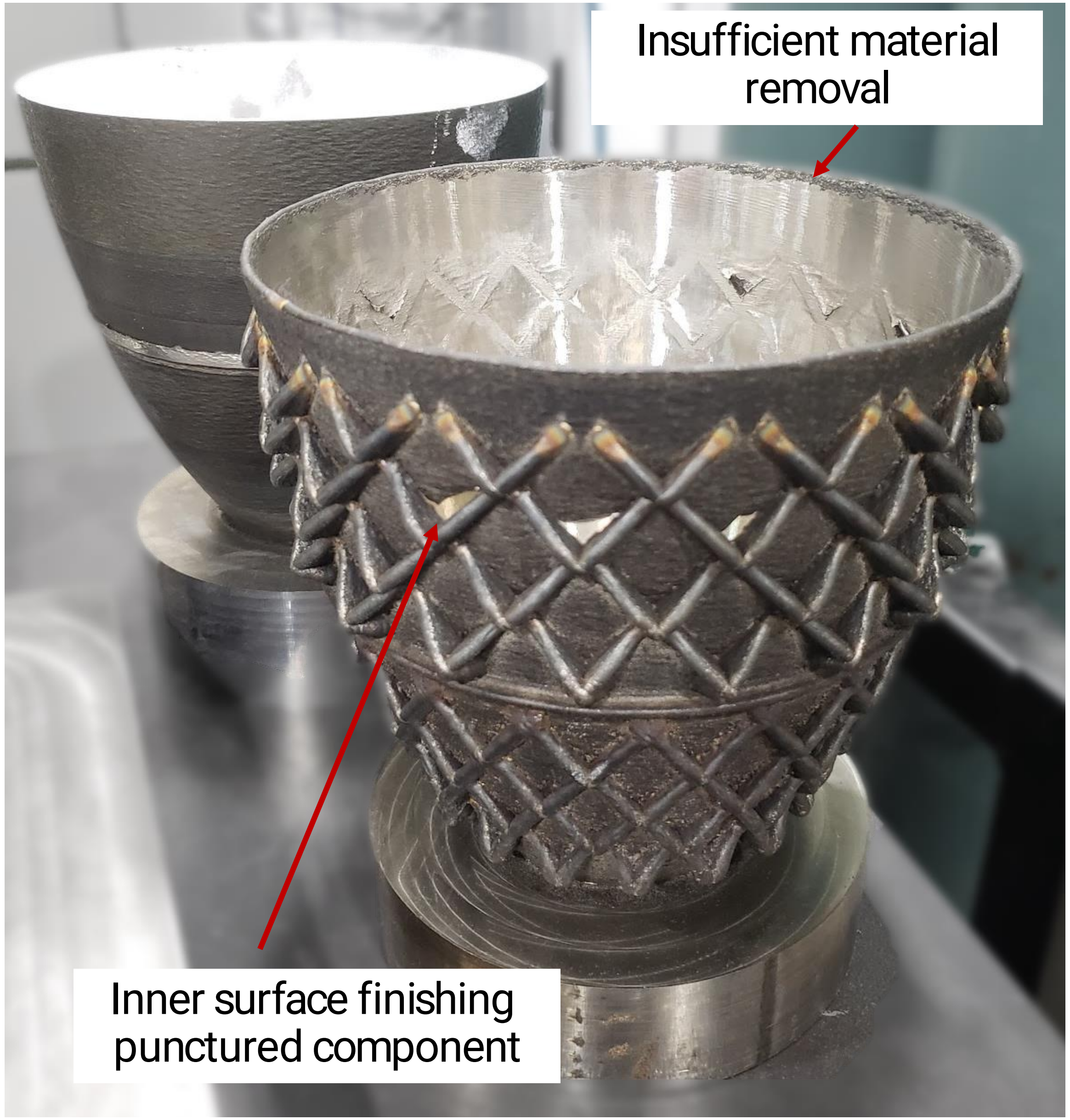
Fully automated production for high throughput process science



Distortion and Stress in DED

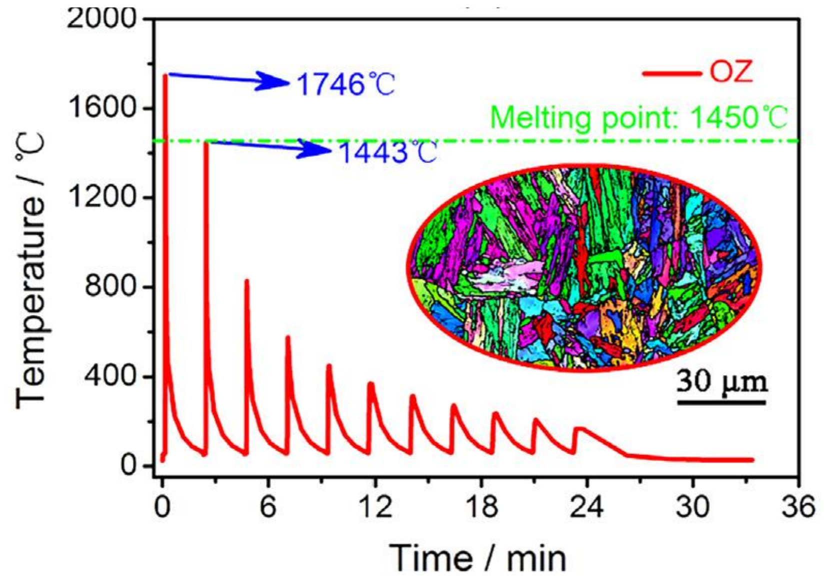
- In welding, longitudinal and transverse stresses develop
- Stresses in additive manufacturing **add up**
- The problem **scales up** with component and melt size

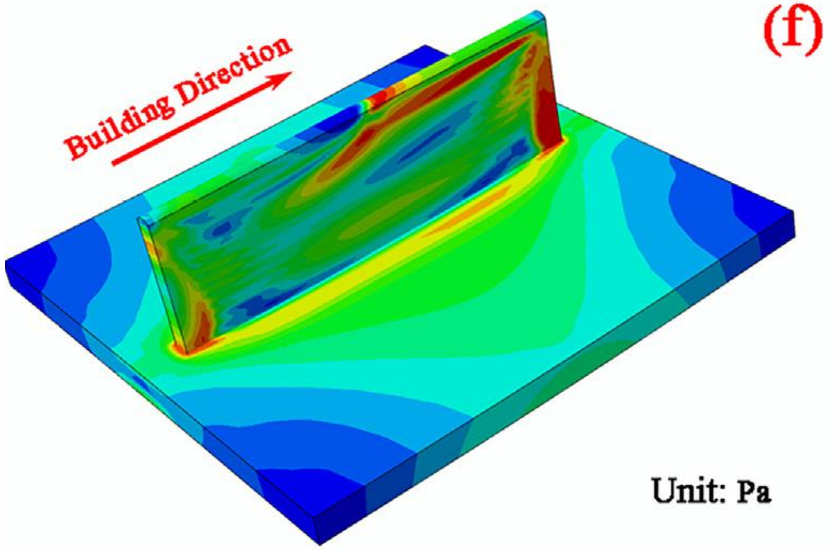




Strong interactions with microstructural evolution

- Highly worked microstructure from thermal expansion differential strain
- **Dynamic annealing** from heat buildup
  - Heat treatment isn't always an option to 'erase' complexity
  - Solid state transformation effects
- Microstructural evolution makes quantitative simulation **challenging**
  - Highly coupled and hierarchical
  - Demands **extensive calibration**

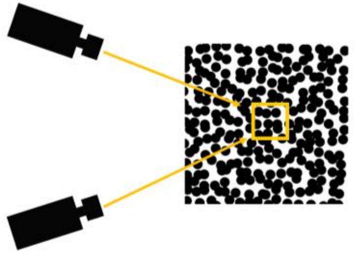


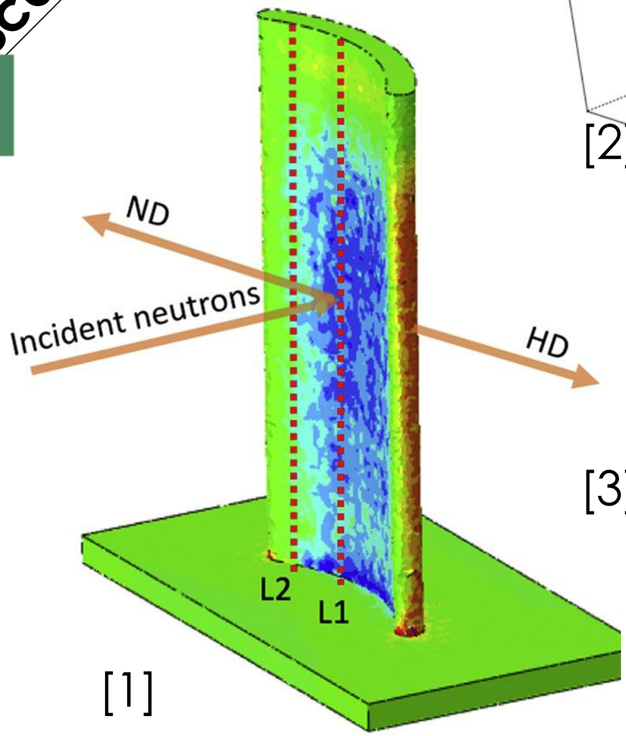


[1] J. Ge *et al.*, *Applied Thermal Engineering*, vol. 163, p. 114335, Dec. 2019, doi: 10.1016/j.applthermaleng.2019.114335.
[2] J. P. Oliveira, T. G. Santos, and R. M. Miranda, *Progress in Materials Science*, vol. 107, p. 100590, Jan. 2020, doi: 10.1016/j.pmatsci.2019.100590.

How to measure residual stress and distortion

Technique:	Dimension?	Destructive?	In-situ?	Scalable?
Neutron Diff.	Volume	Y	N	N
Synch. XRD	Small volume	N	N	N
Bench XRD	Surface	N	N	N
Contour method	Surface	Y	N	Y
Hole drilling	Point	Y	N	Y
Beam/ring/arch	Volume	Y	N	Y
Strain gauge	Line	N	N	Y
DIC	Surface	N	Y	Y





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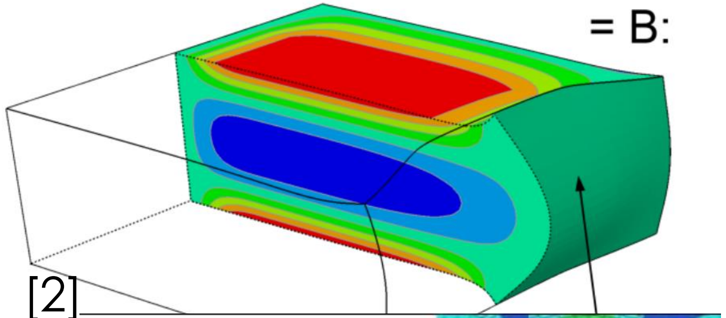

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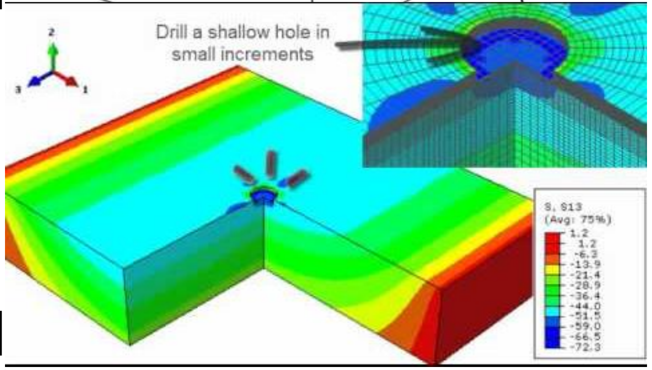


[3]

[4]

[1] K. An, L. Yuan, L. Dial, I. Spinelli, A. D. Stoica, and Y. Gao, *Materials & Design*, vol. 135, pp. 122–132, Dec. 2017

[2] The Contour Method, *Michael B. Prime and Adrian T. DeWald*, 2013, chapter 5, ISBN: 978-1-118-34237-4.

[3] VEQTER The Center Hole Drilling Technique https://www.veqter.co.uk/residual-stress-measurement/centre-hole-drilling

[4] P. Promoppatum and S.-C. Yao, *Journal of Manufacturing Processes*, vol. 49, pp. 247–259, Jan. 2020

OpeN-AM *Operando Neutron Additive Manufacturing*

Open-source control system and data collection

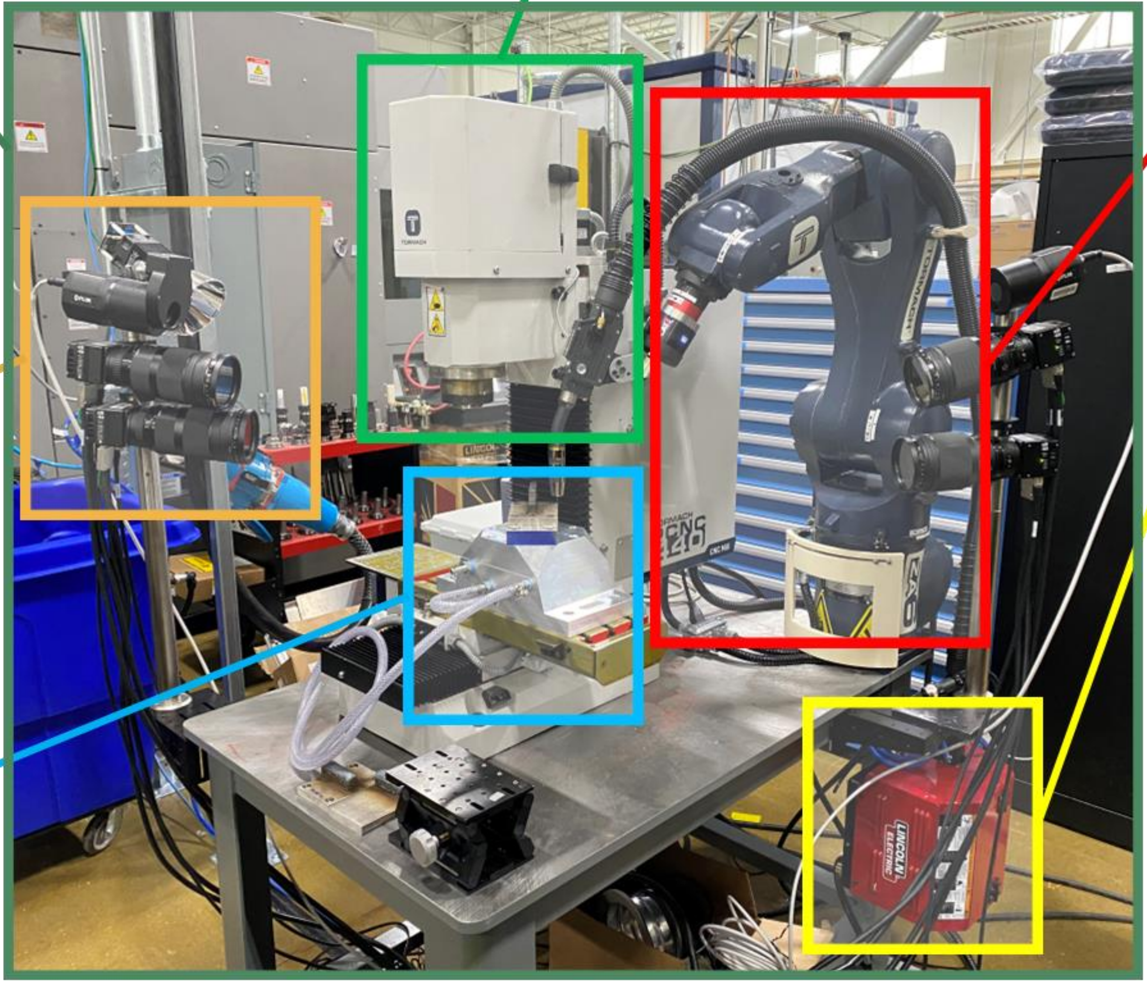
Optical and IR cameras for digital image correlation and hyperspectral thermal imaging

Active cooling with compressed air for thermal control

3-axis CNC capabilities for subtractive machining

6-axis robot for flexible deposition and scan paths

Wire-arc additive manufacturing (WAAM)

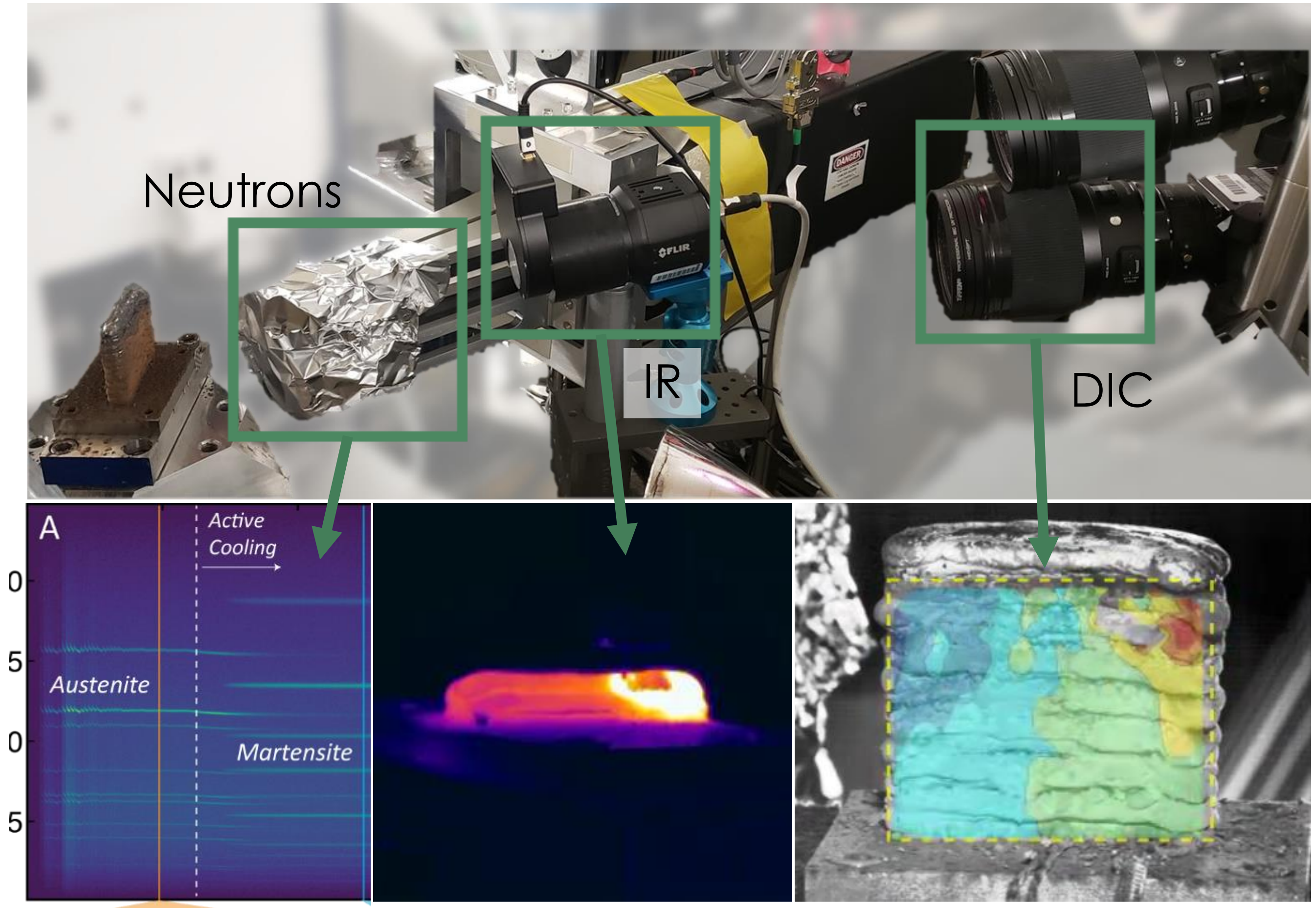


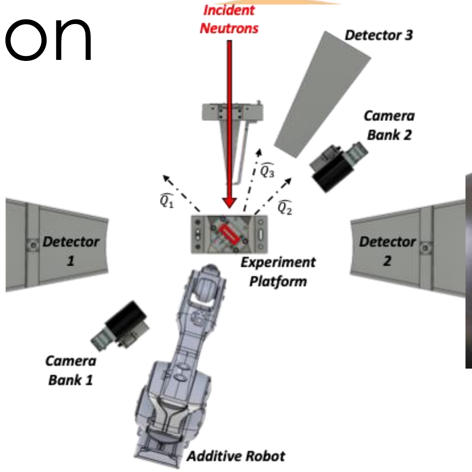
High-bandwidth edge computing node

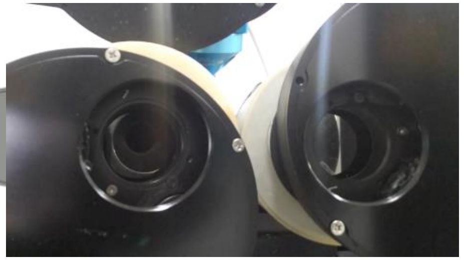
OAK RIDGE National Laboratory

OpeN-AM Sensors

- Spallation Neutron Source
- Multispectral infrared
- High-bandwidth DIC
- Low temperature transformation steels
- Phase transformations, thermal and strain evolution

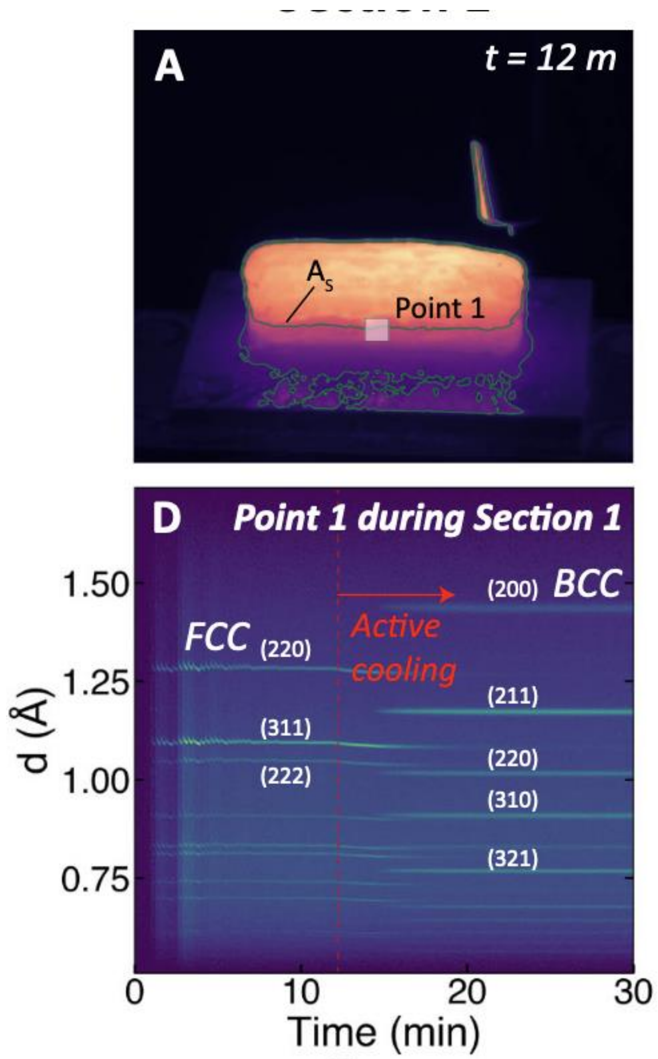




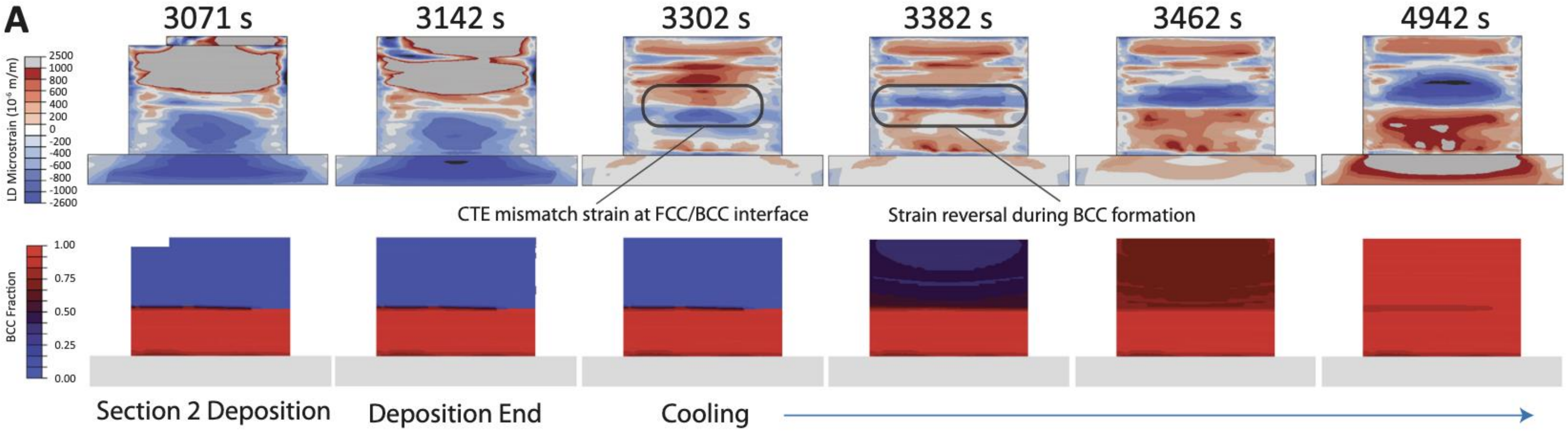


A. Plotkowski *et al.*, “Operando neutron diffraction reveals mechanisms for controlled strain evolution in 3D printing,” *Nat Commun*, vol. 14, no. 1, Art. no. 1, Aug. 2023, doi: 10.1038/s41467-023-40456-x.

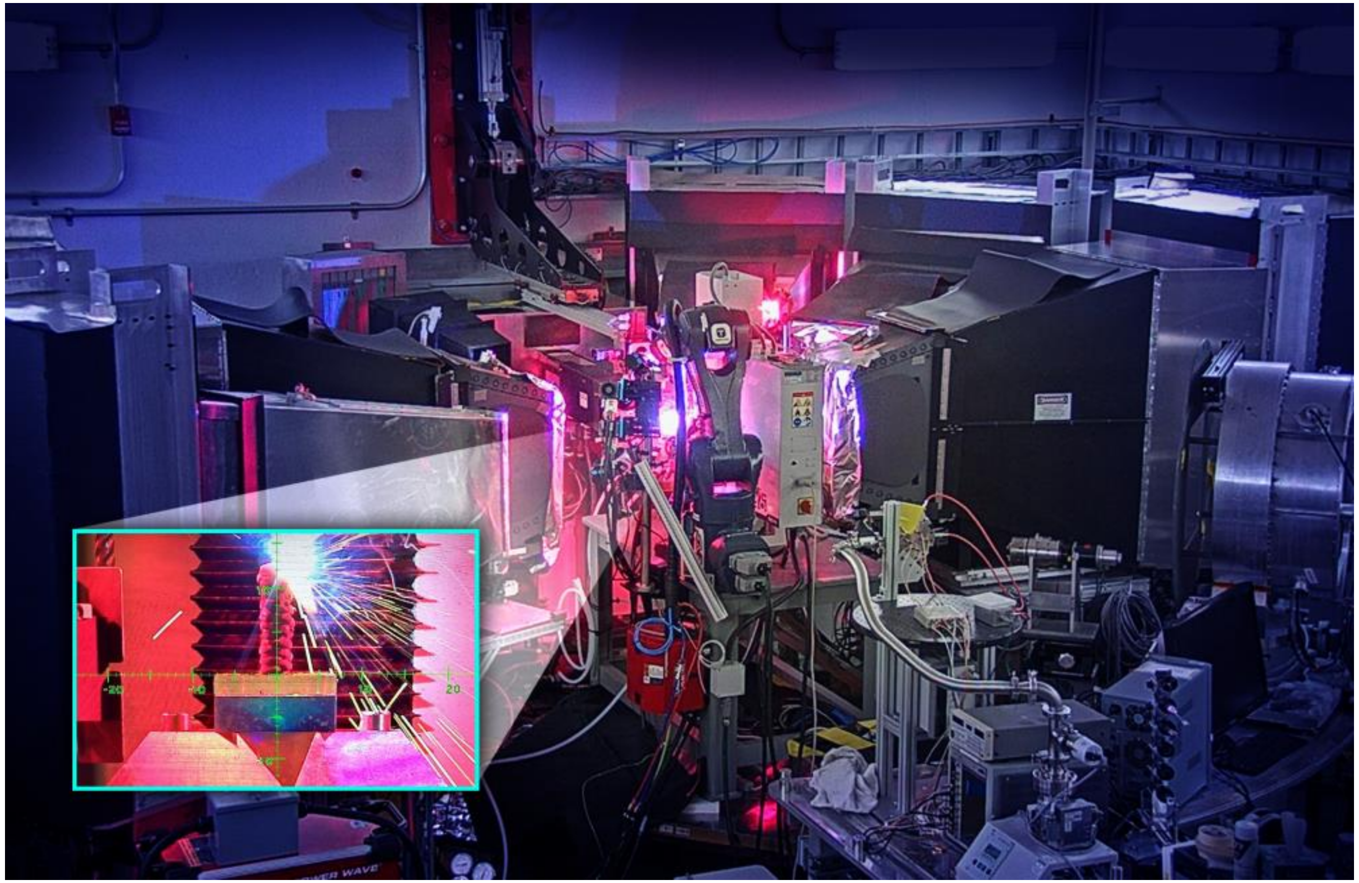
Use case – Understanding Solid State Phase Transformation



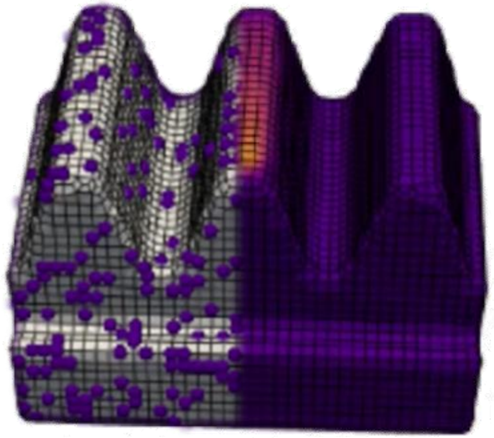
- Cyclic heating induces repeated Austenite → Martensite transitions
- This induces complex residual stress patterns
- Directly measures lattice strain, phase, and temperature over the entire build
- Relevant scale for large scale WAAM



OpeN-AM is excellent for materials processing science…
… *but can we scale it?*

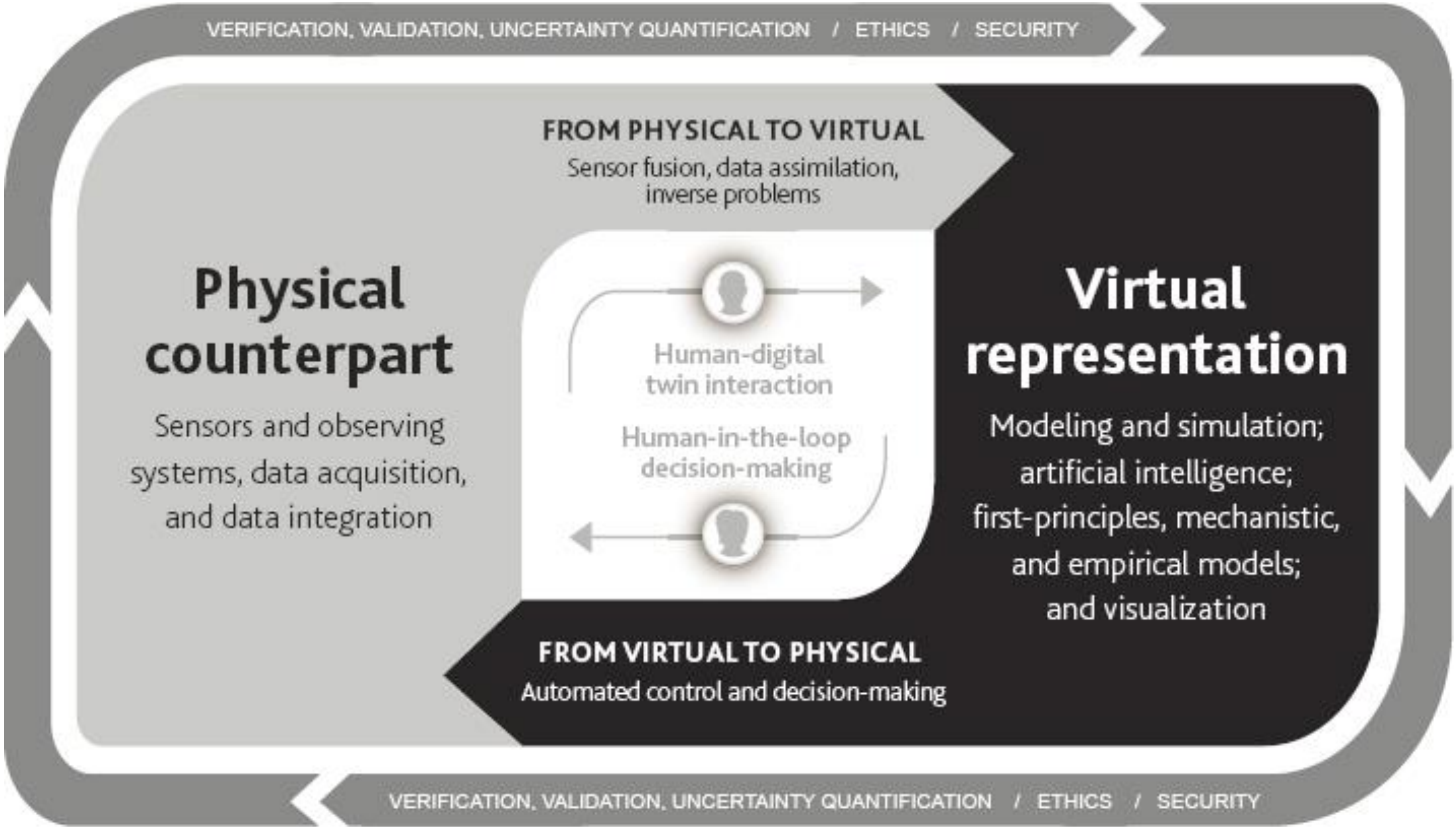


- Neutron diffraction is the gold standard for RS
- But, other methods give ***related*** information
- Can a combination of available sensing achieve similar results?



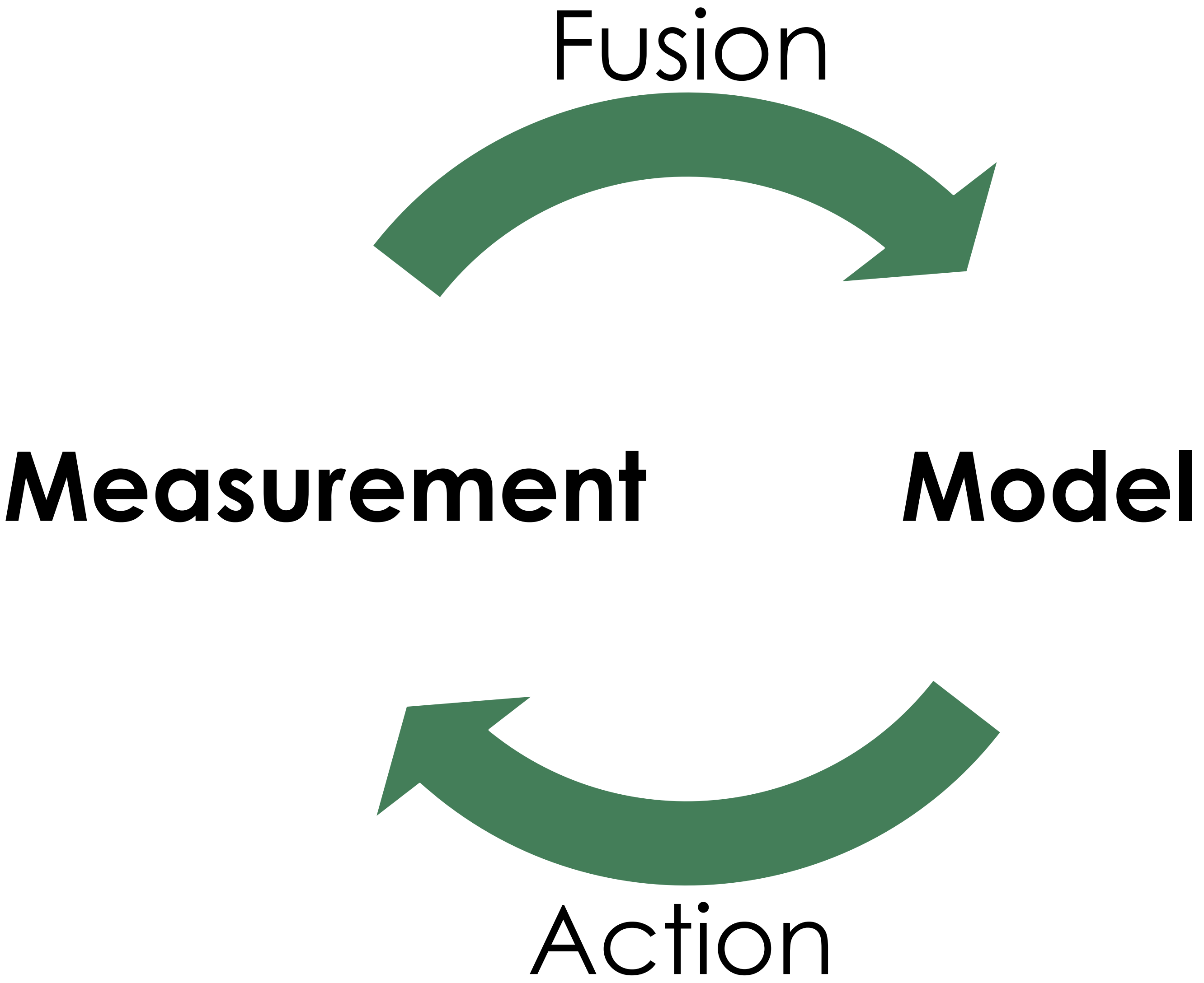
?

Let’s approach the problem by discussing ‘Digital Twins’



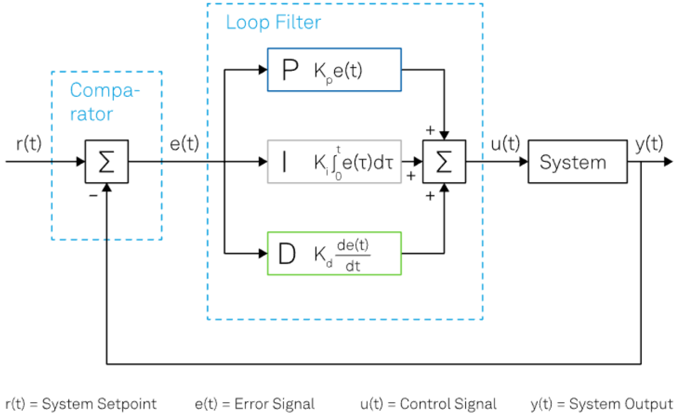
National Academies of Sciences, Engineering, and Medicine, Foundational Research Gaps and Future Directions for Digital Twins (2024)

Controlling Thermomechanical Evolution

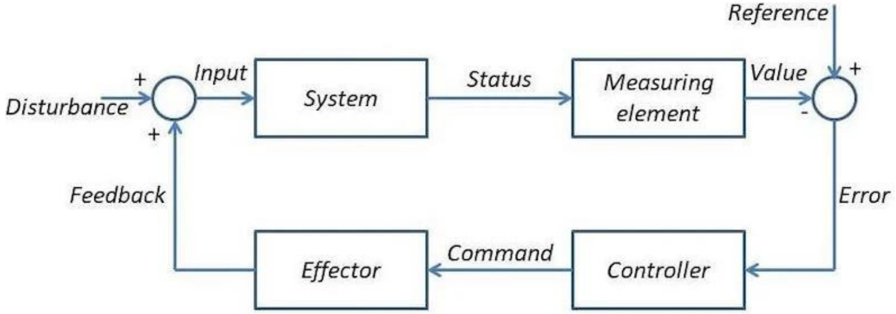


Controlling Thermophysical Evolution

Fusion



Measurement **Model**

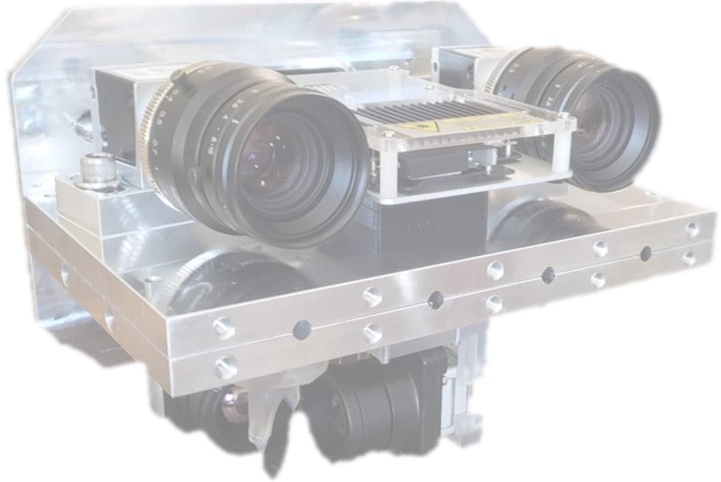


Action

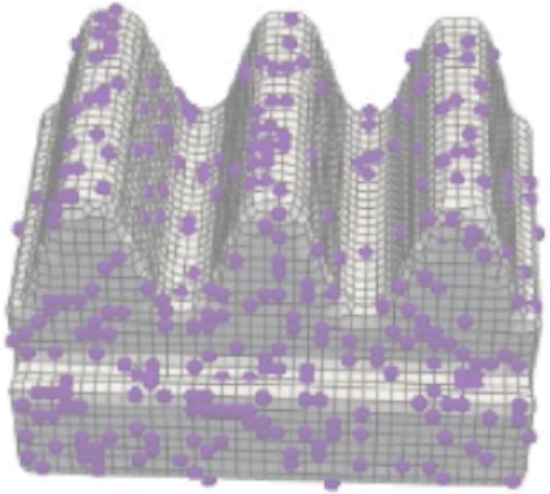
Problem: Spatially complex state & response

Controlling Thermophysical Evolution

SCOPS



Adamantine



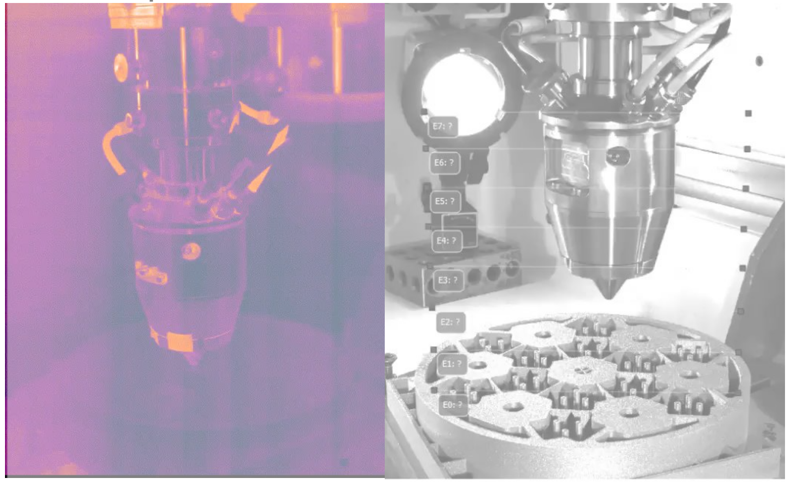
Fusion

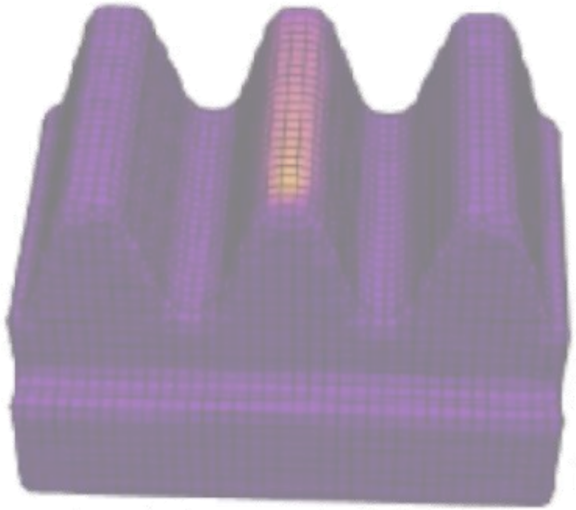
Measurement

Model

Temperature

Strain

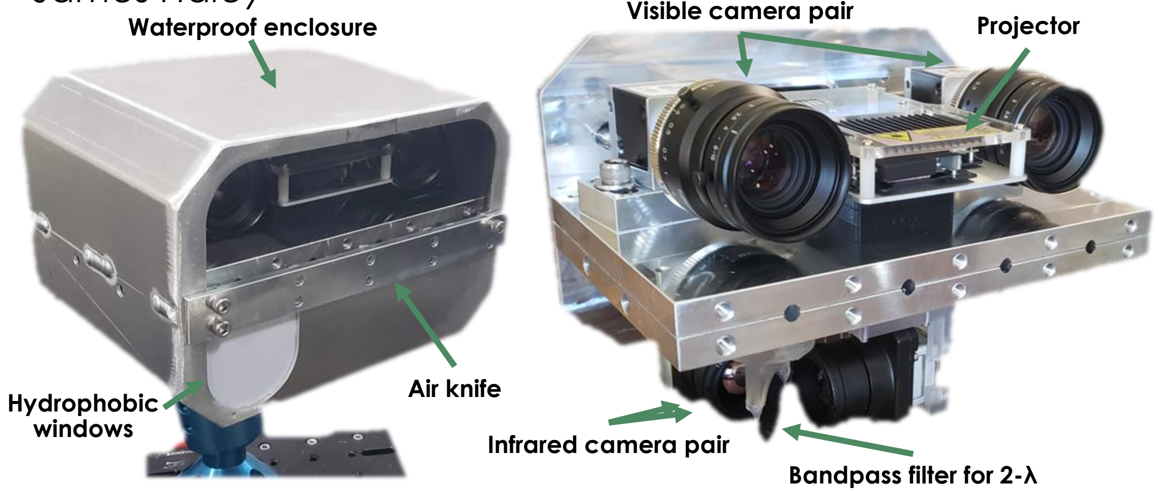




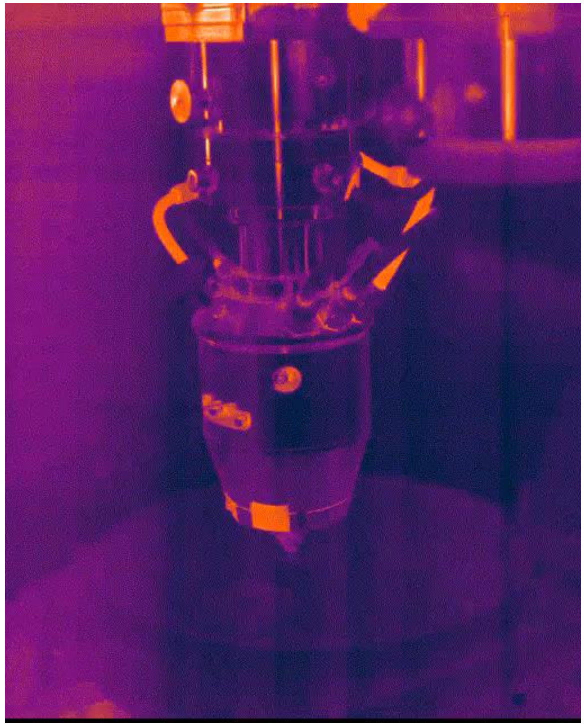
Action

SCOPS: 'Stereo Correlated Optical and Pyrometric System'

James Haley

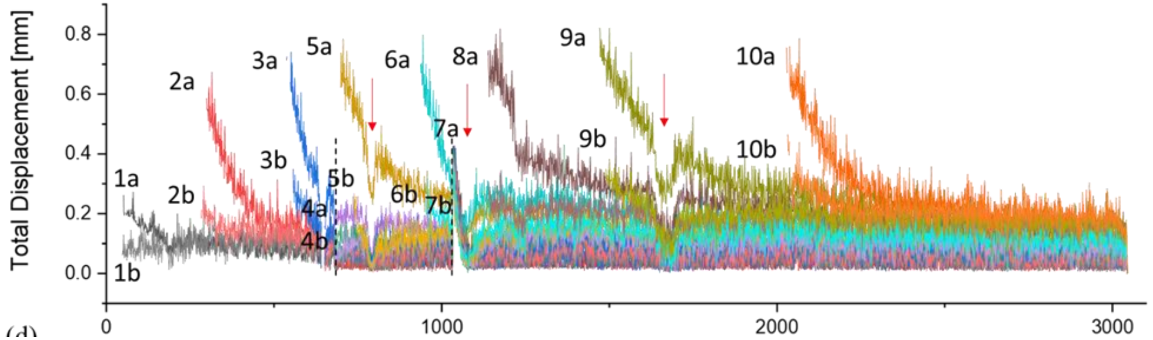


In-situ 3D **strain**



Infrared **temperature**

- Directed Energy Deposition welding induces distortion. *Control requires measurement.*
  - DIC tracks surface roughness features in 3D, IR tracks temperature over time
  - *Thermoplastic* history observed
- Imaging enhances simulation.
  - Validation, or *assimilation* into live
- Works for all DED classes



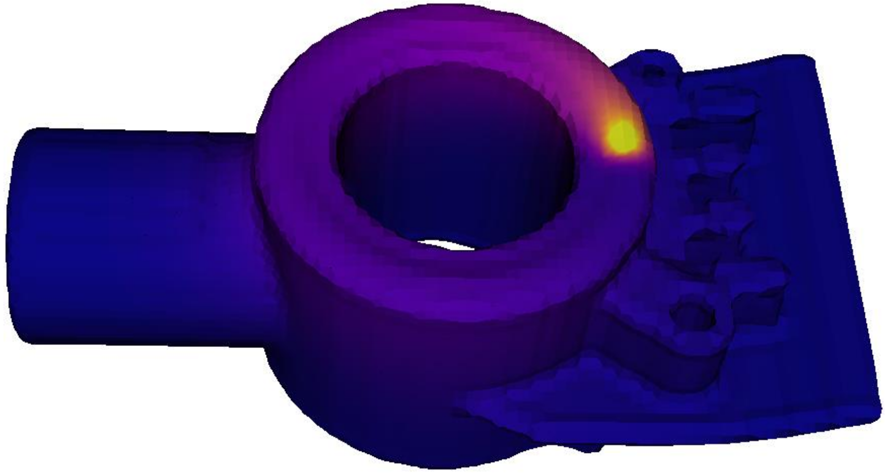
Control reactions rely on **fast simulation…**

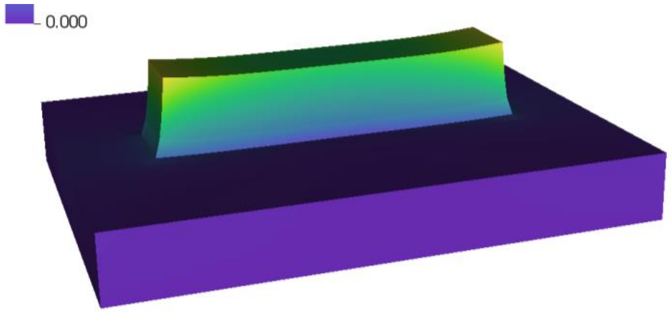
adamantine

Built to scale from **laptops to GPU supercomputers**

10x faster than real-time for thermal simulations

Adamantine *and its key dependencies* developed at ORNL, **we can modify and integrate at-will**



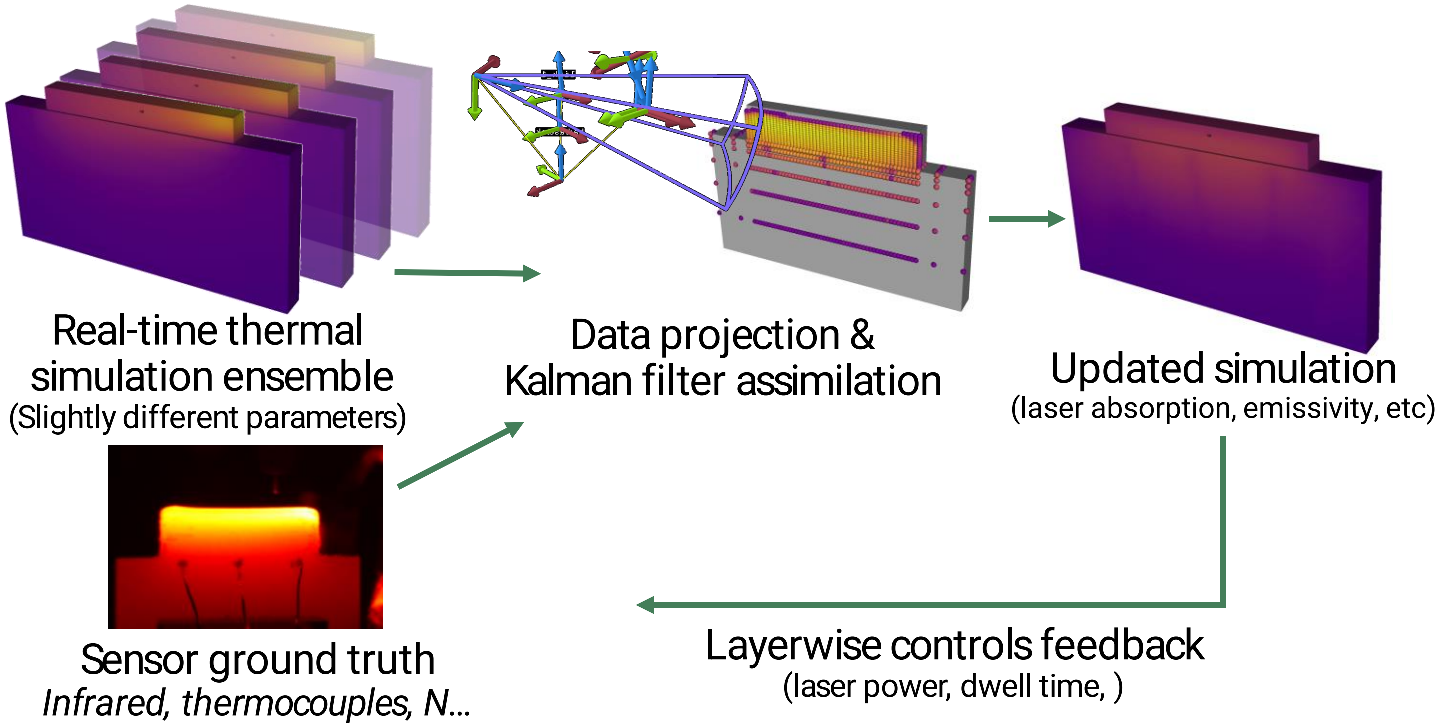


https://github.com/adamantine-sim/adamantine

B. Turcksin, S. DeWitt, Journal of Open Source Software, 9 (102), 2024.

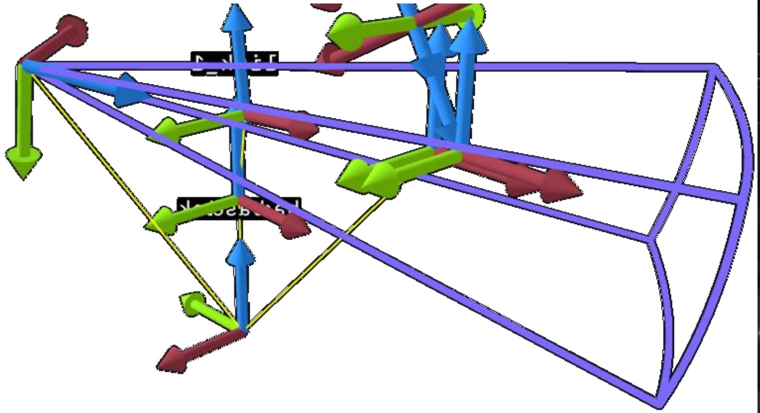
The “Shadow Simulation” approach to distortion in DED

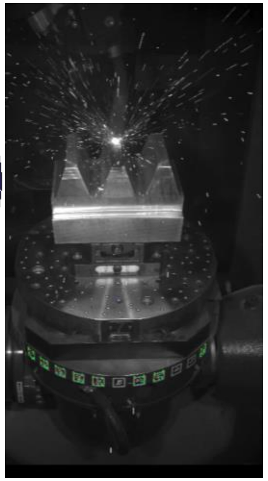
- A **print-time FEA model**
- Information is ‘cast’ into the shadow from ground truth sensors
- Simulation assumptions **are iteratively tuned** to match reality on the fly
- Provides a **better snapshot** of temperature state for process controls

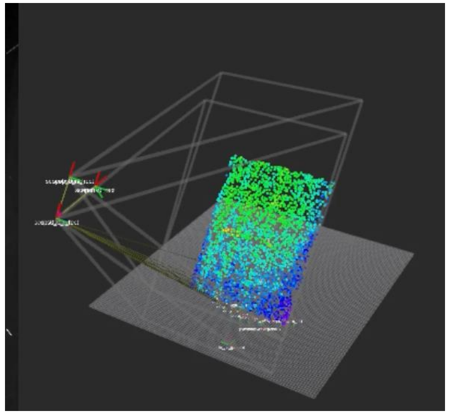


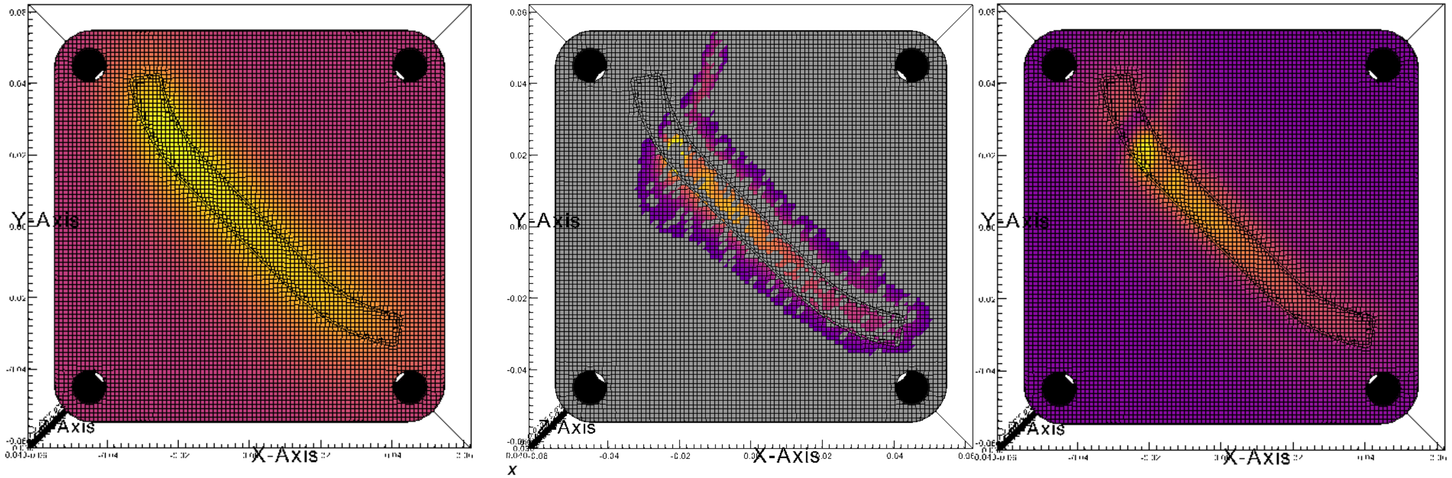
Sensor data mapping

- Robust spatial calibration
  - Simultaneous intrinsics & extrinsic parameters
  - Visible and infrared
  - 0.02MP to 64MP cams
- Build frame localization
  - Fiducial markers
  - ICP fit mesh to pointcloud
- Ray trace to sim. Mesh
  - Nearest neighbor node
  - Export as CSV



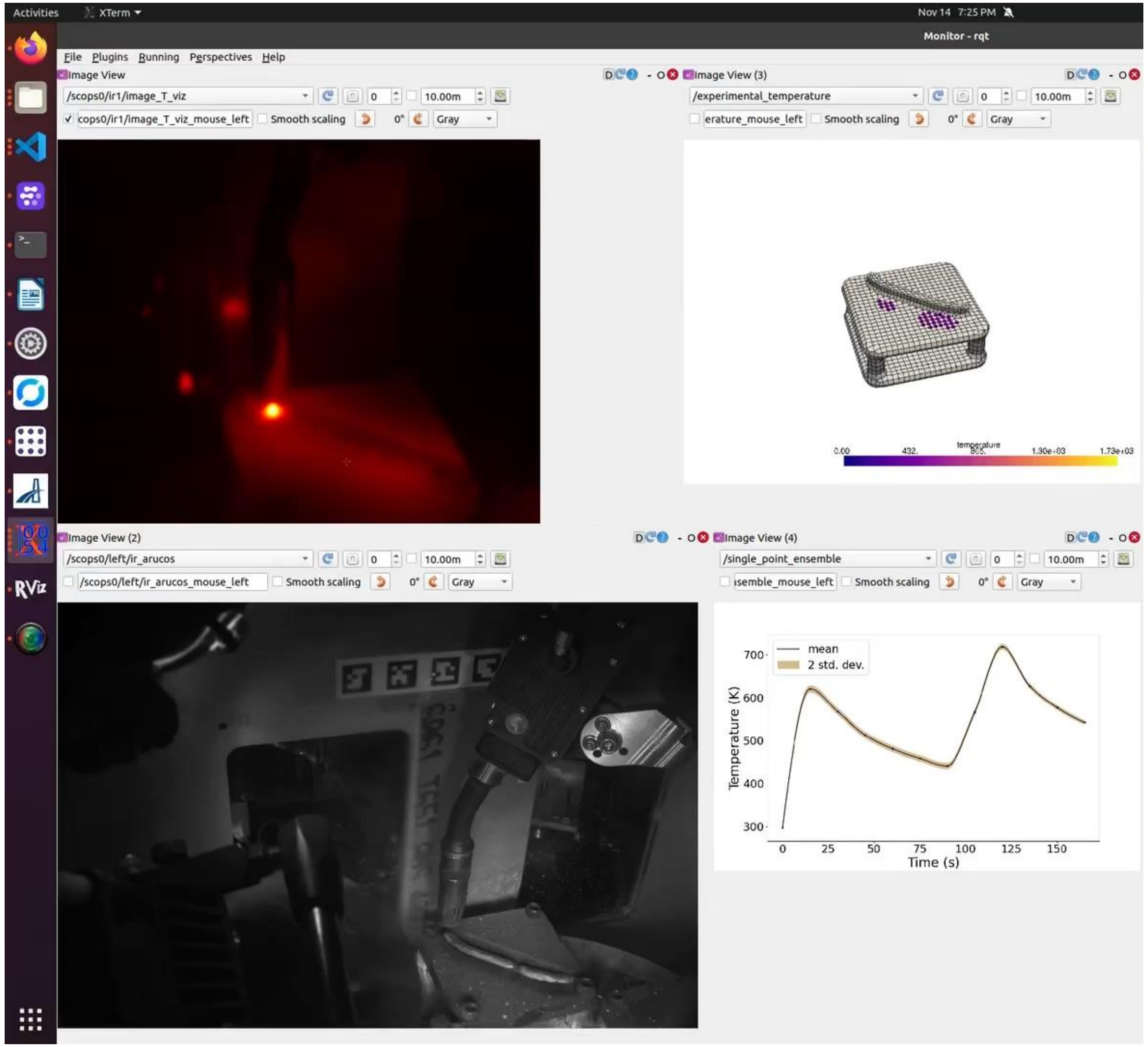




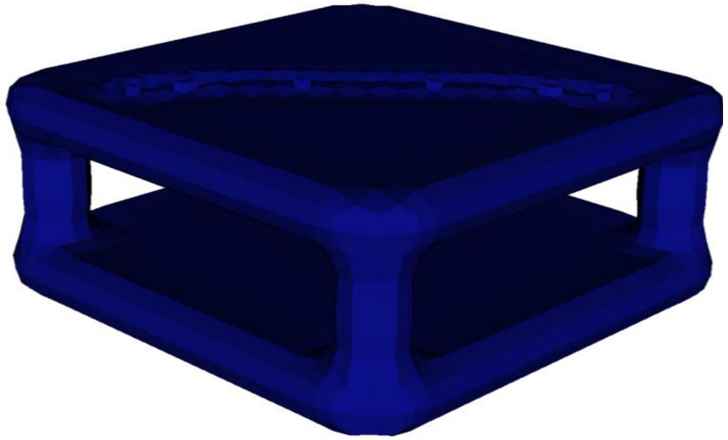


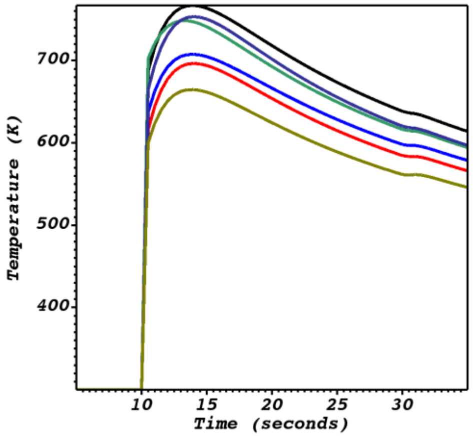
Simulation Infrared Rays Fused

Model reference control feedback established



Real-time simulation twin





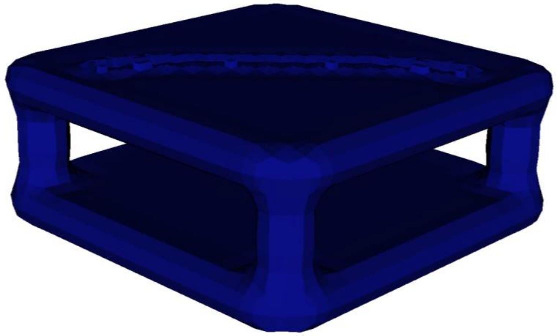
Assimilation adjusts twin based on IR
Control targets adjust to follow nominal simulation

- Nov ‘24 – SNS validation
- Scan path choice based on predicted deviation from reference simulation
- Integrated with HPC through INTERSECT

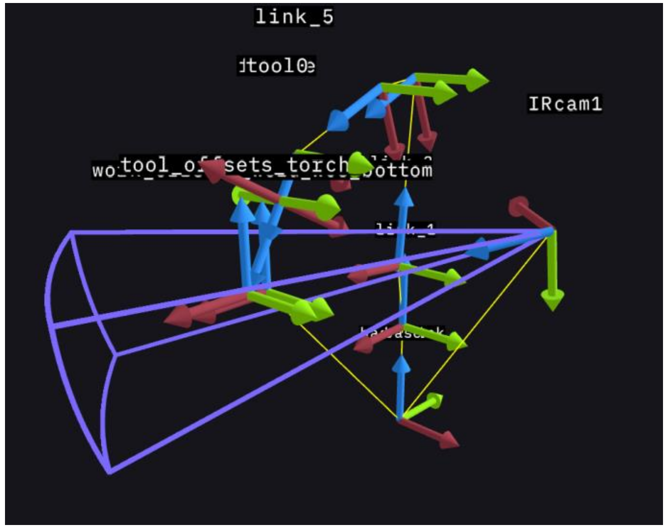
OAK RIDGE National Laboratory

Applications - Controls with Confidence

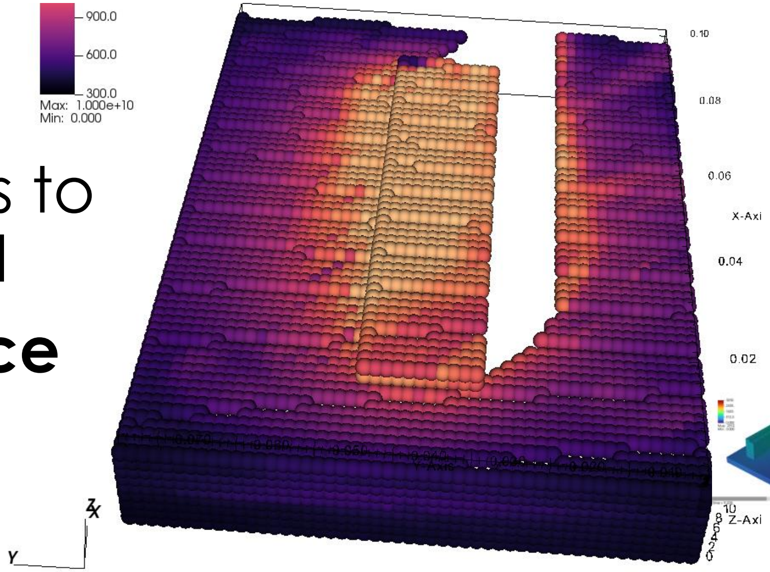
- Controls
  - Allows full state estimation of **unseen nodes**
  - Allows estimation of unmeasured quantities
    (stress instead of just strain!)
- Confidence
  - All models are wrong, etc.
  - Therefore, uncertainty needs to be estimated & propagated
  - Gives **site-specific confidence** in thermal histories & microstructure predictions



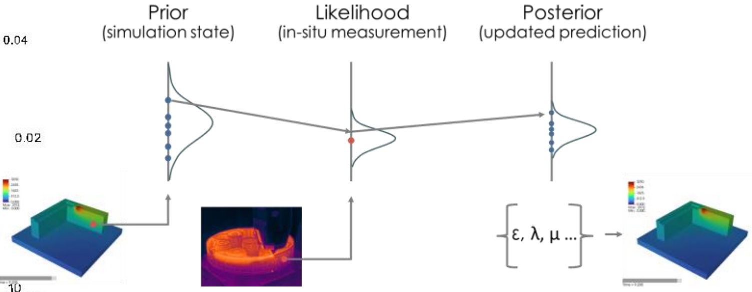
Adamantine FEA simulation



Camera coordinate transforms

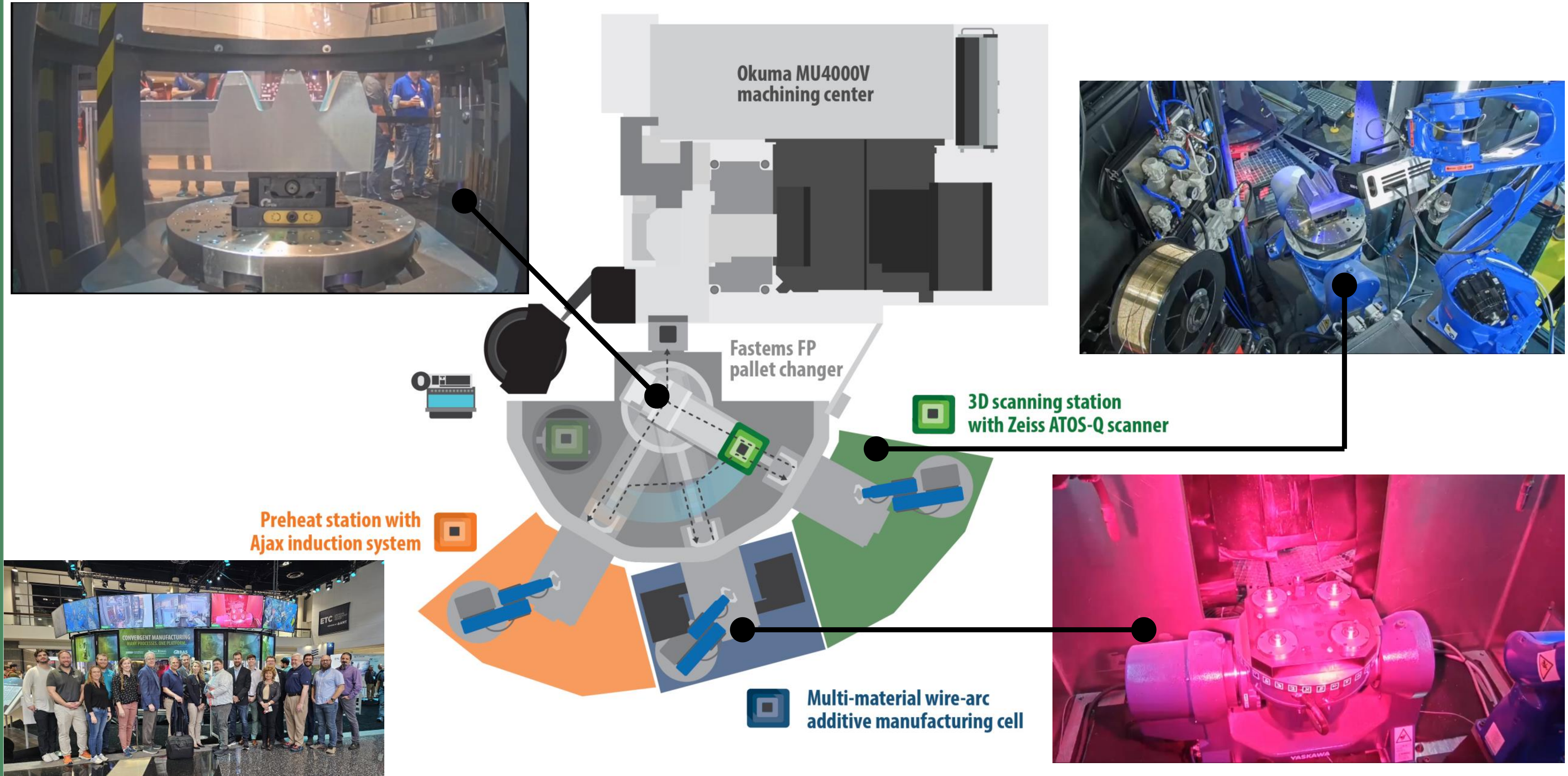


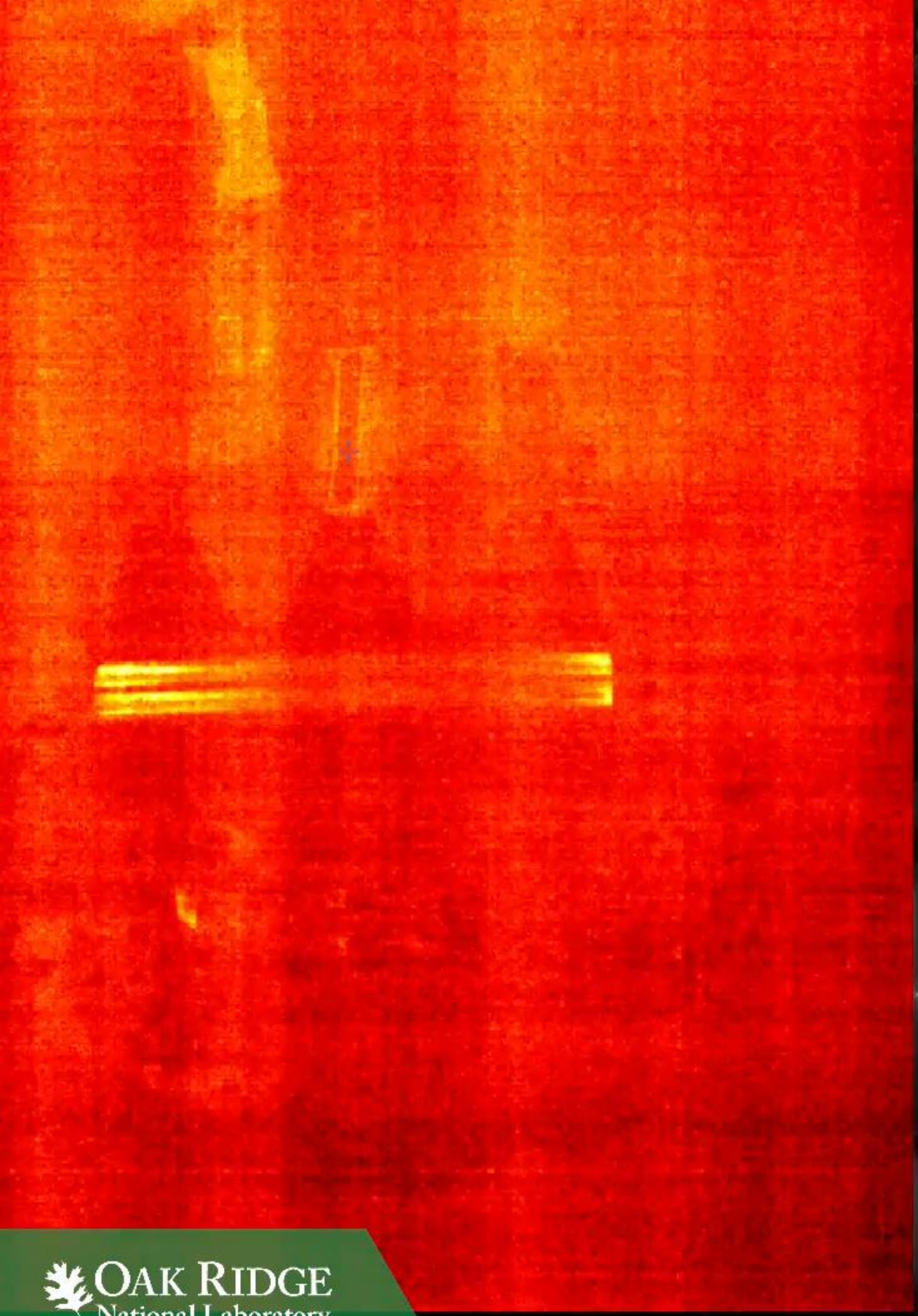
Mapped temperature to simulation mesh

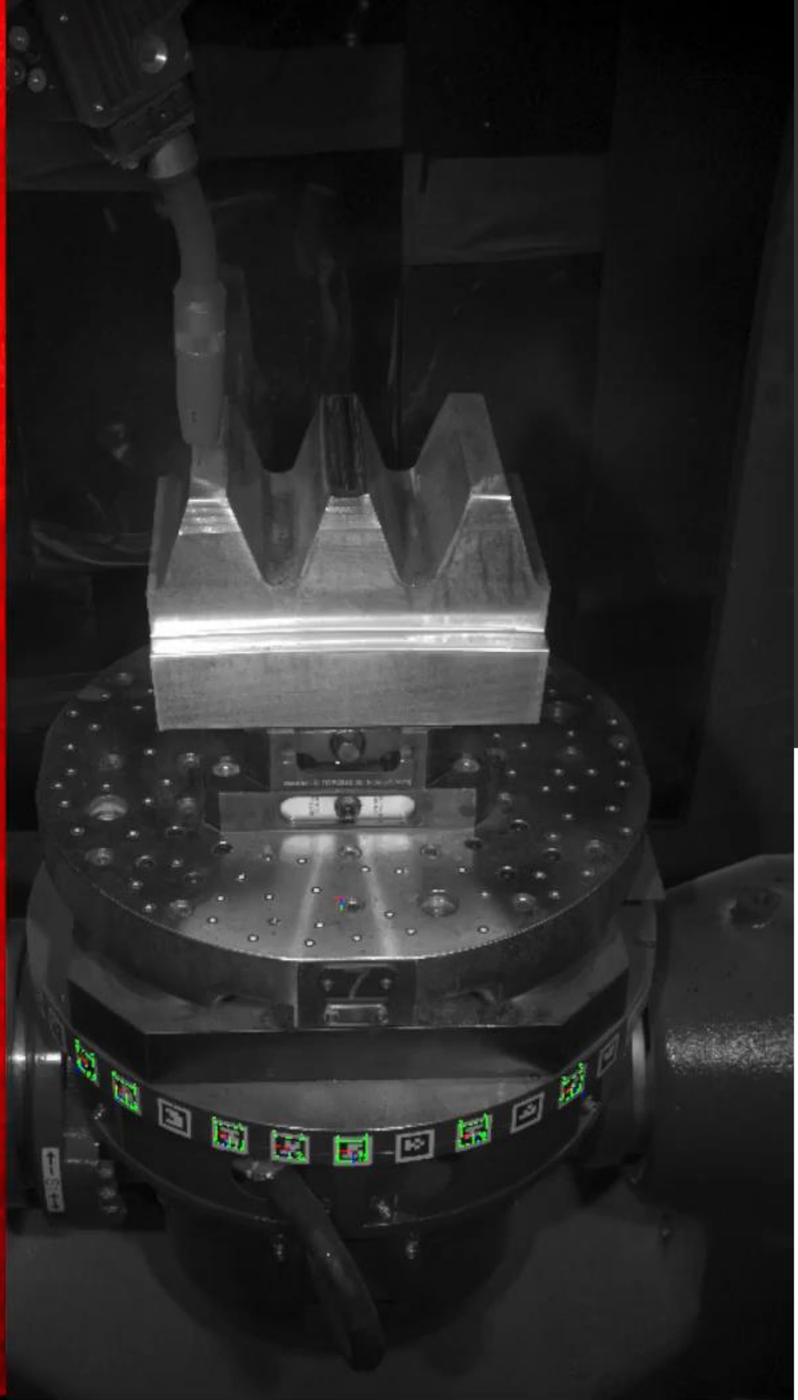


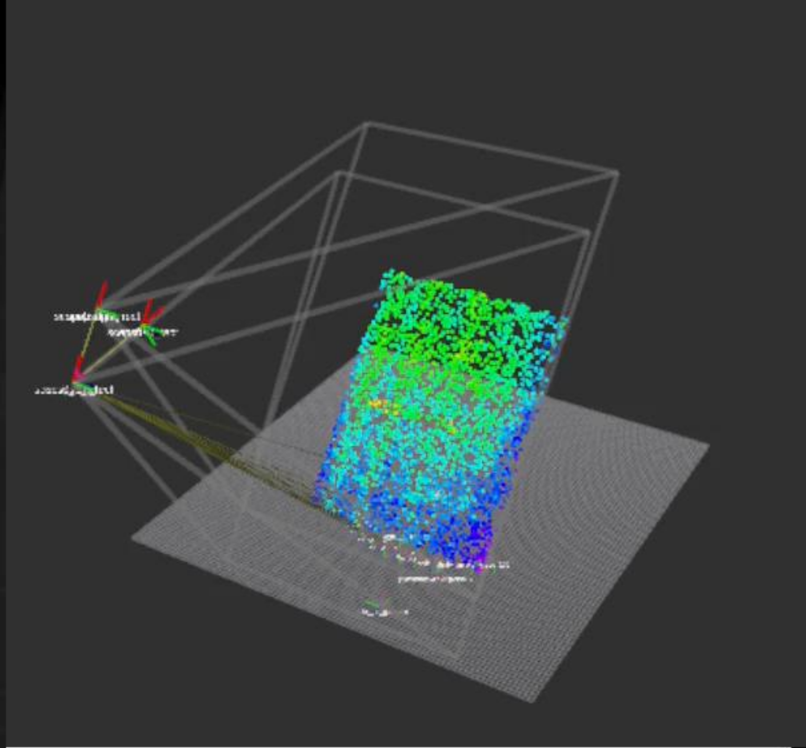
ENKF updates assumptions

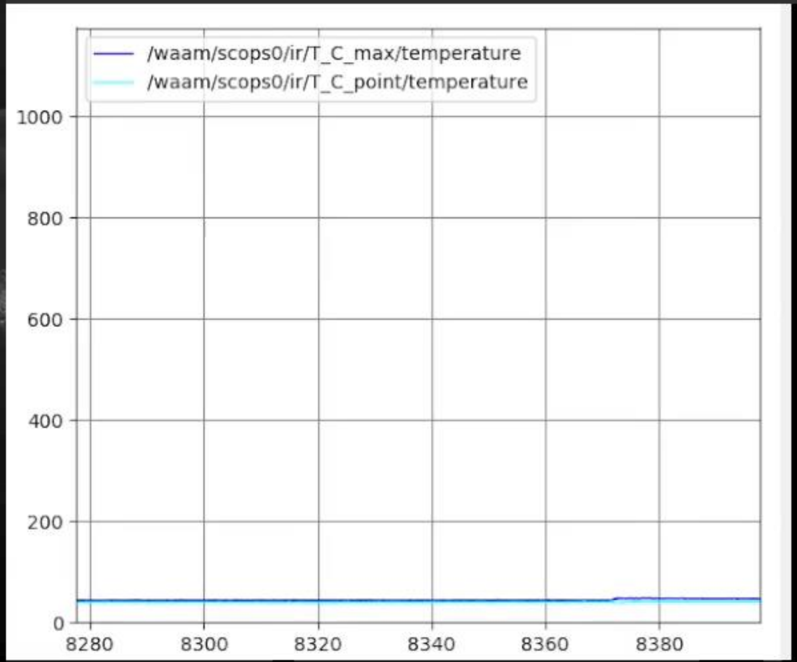
A Demonstration – IMTS Emerging Technology booth
Future Foundries *Convergent Manufacturing platform*











Oak Ridge National Laboratory

Thank you!

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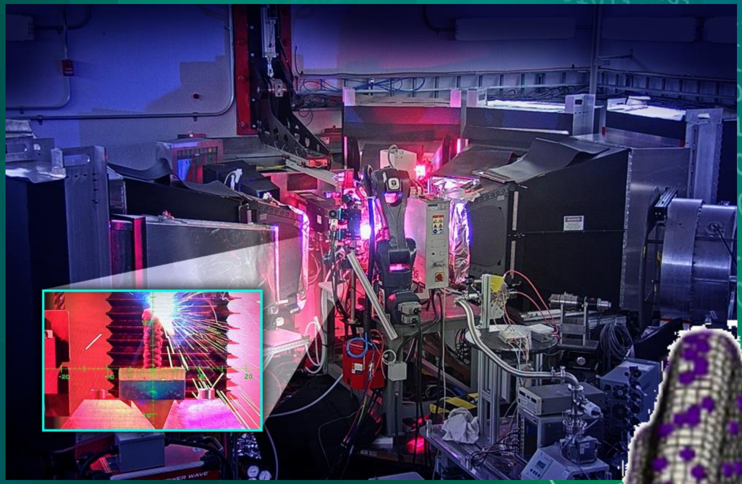

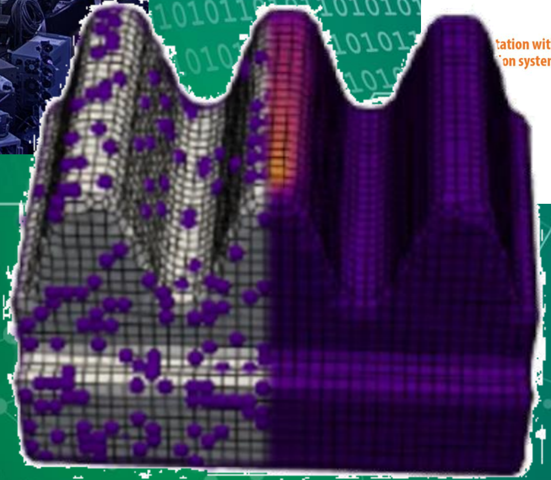

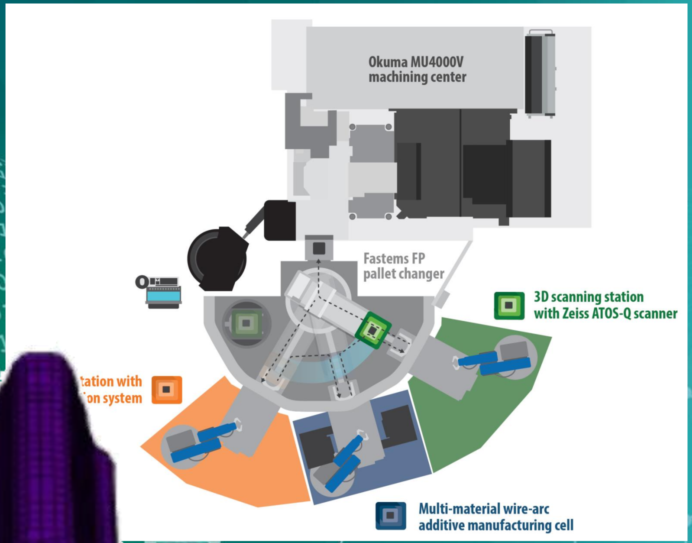

SCOPS :

Adamantine :

ORCID: