Synergy: An Integrated Simulation and Process Control Platform for Distributed Manufacturing Process Chains

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Challenge

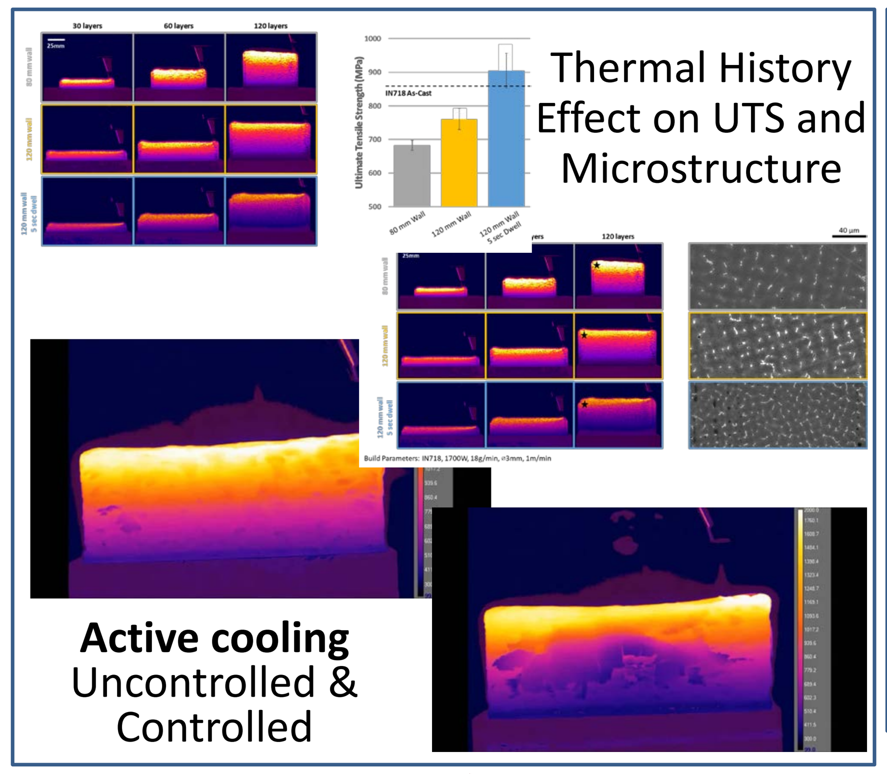
- **Need for high performance, rapidly constructed custom part realization**, not achievable with current methods
- **Inability to directly measure and control desired part attributes/properties,** such as microstructure, porosity, residual stresses, surface properties, etc. during processing
- **Lack of science-/model-based methods** for the control of part attributes through measurable primary process responses
- **High computational cost** of existing predictive physics-informed predictive methods
- Lack of means for the **rapid storage and query of process and simulation data**

Solution

- **Integrated physical process knowledge with numerical simulations** for a fast, integrated framework
- **Multi-loop control system** for quick setting of process parameters that yield the desired part attributes in a given process chain
- **General purpose graphical processing units (GPGPUs) to accelerate** physics-informed analysis of Directed Energy Deposition – DED - processes
- **Unique experiments to validate simulations**
- **Link between the CAD engine and FEM** for mapping unstructured simulation data into a structured voxelized grid
- **Efficient and accurate solidification model to predict microstructure** of grains and build a relationship to material properties

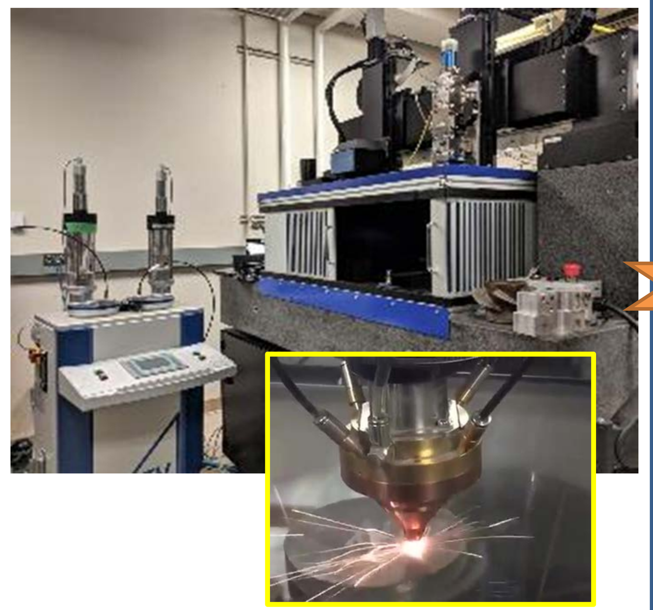
Progress

- Developed data-driven design of microstructure and mechanical properties based on **Self-Organizing Maps** (SOM)
- **Predicted melt pool geometry, surface topography, grain structure, and dendric microstructure**, all validated by AM-Bench (NIST) experimental data
- Investigated a **hierarchal data-driven** network for **real-time prediction of residual stress and thermal profile** that is generalized across geometries using semi-supervised signals through a shared network
- Examined **multi-scale modeling** of AM by **combining machine learning and macro-scale** modeling for melt pool dynamics
- Developed a preliminary DED setup and experiments to demonstrate **cooling-rate and temperature gradient control**
- **Redesigned** and upgraded **ARPI optical system** and **environmental chamber**

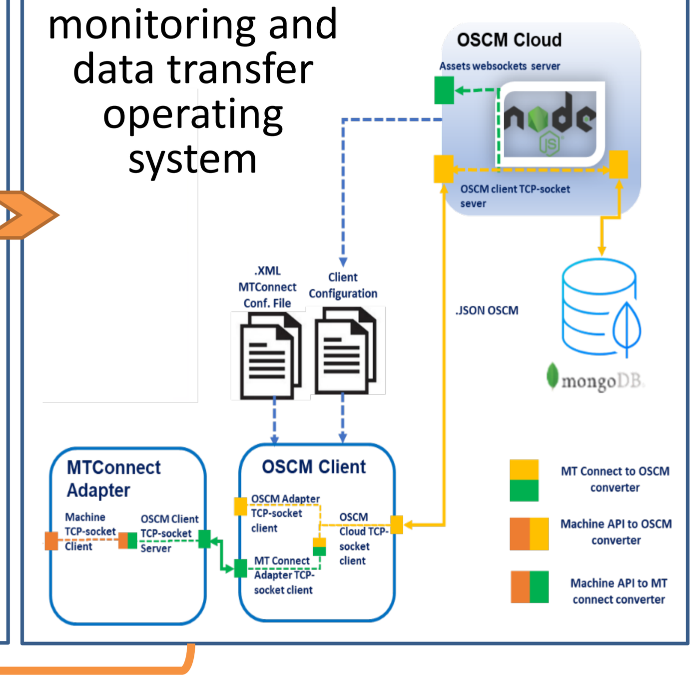


Thermal History Effect on UTS and Microstructure

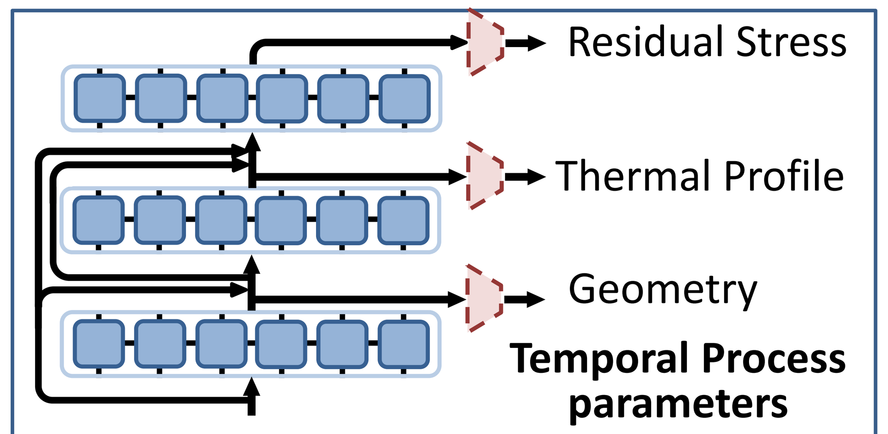
Active cooling Uncontrolled & Controlled



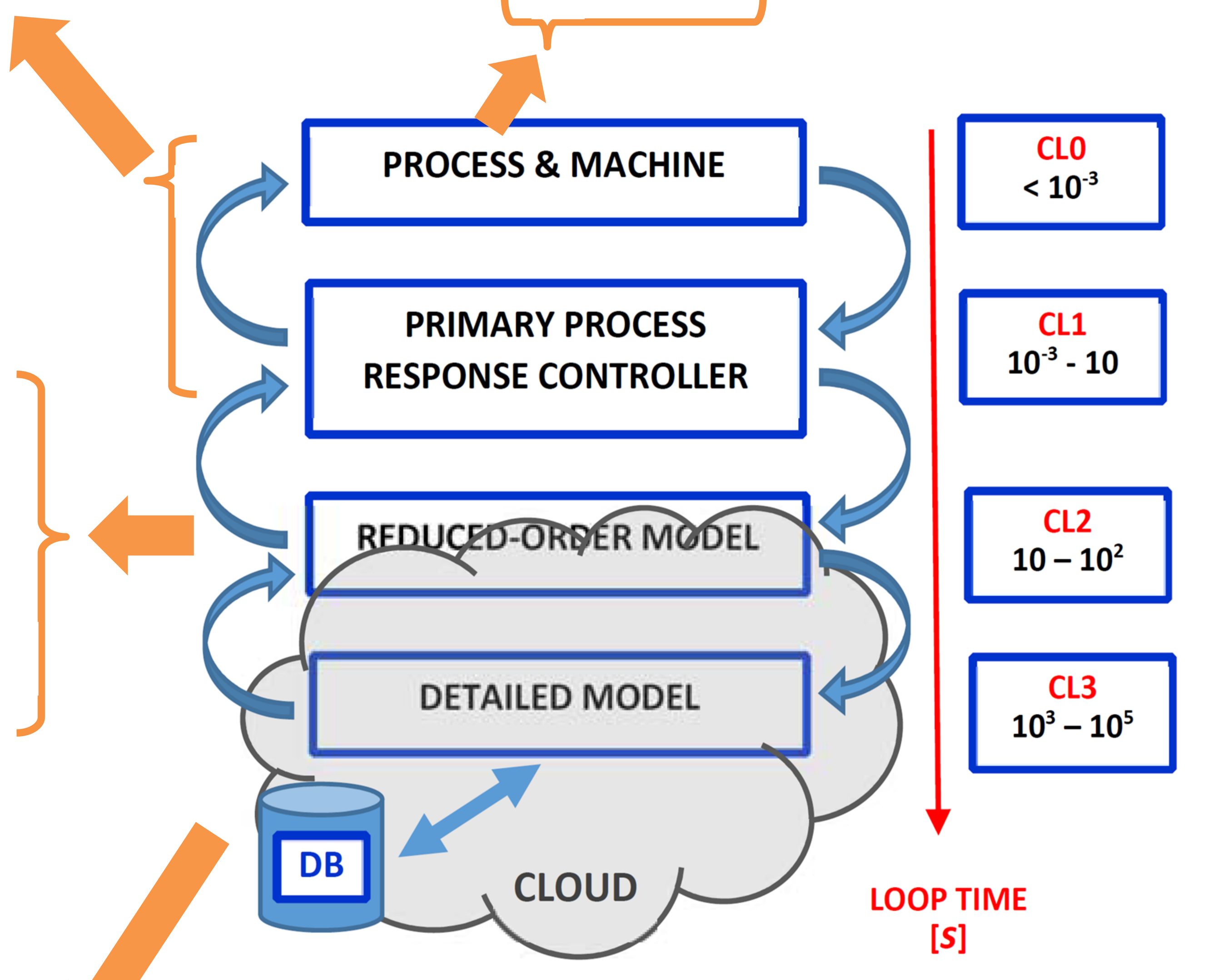
Additive Rapid Prototyping Instrument - ARPI



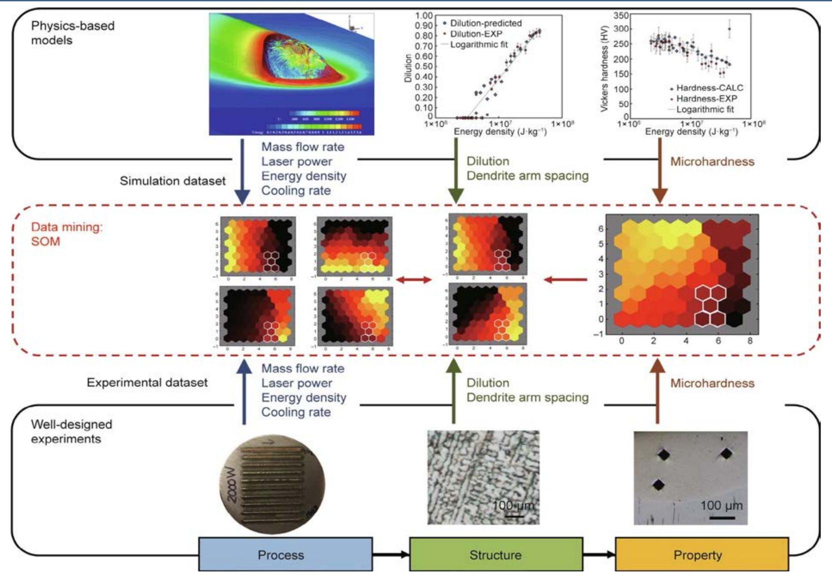
Cloud-enabled monitoring and data transfer operating system



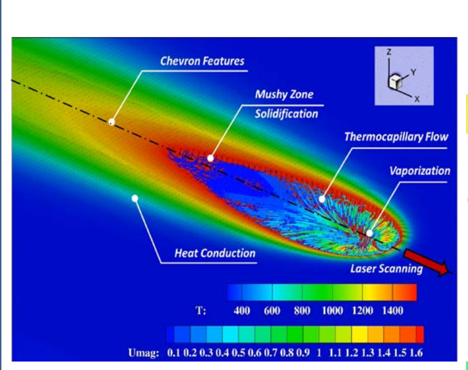
Data-Driven modeling of residual stress and thermal history by recurrent neural networks



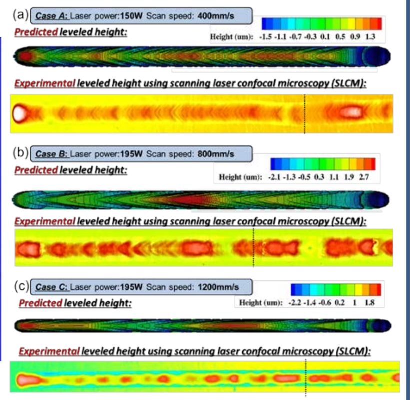
Proposed multi-loop control system



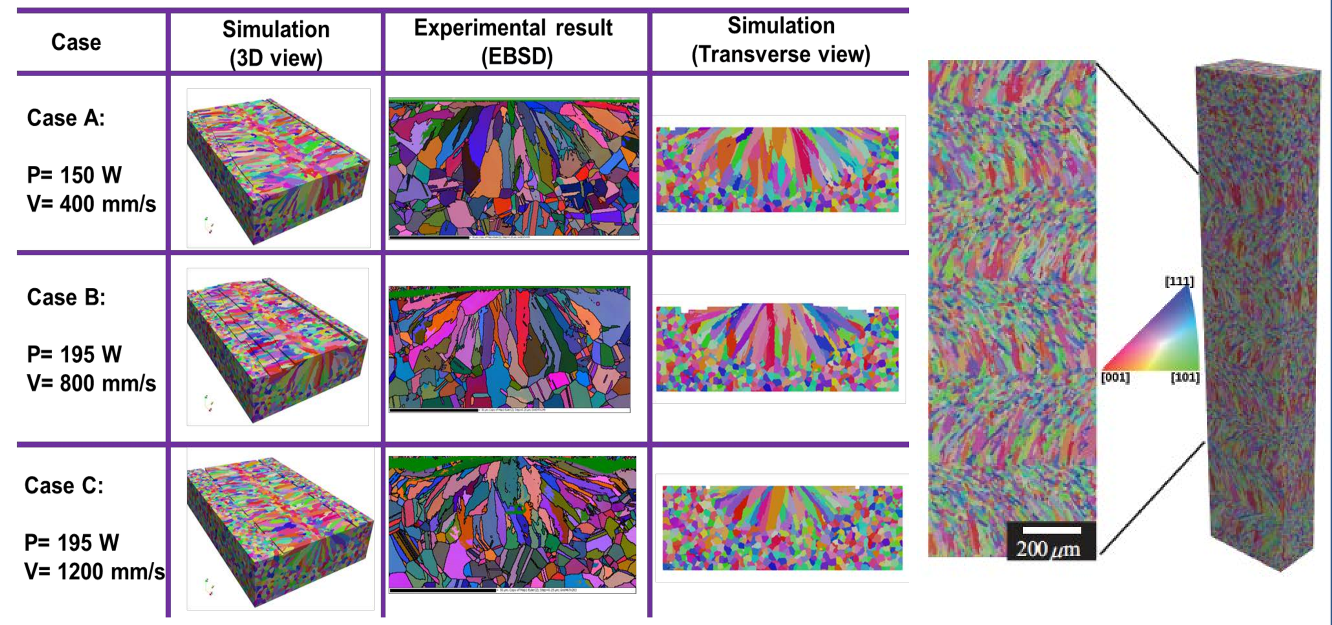
Reduced-order model of Process-Structure-Properties relationships using self-organizing maps



Detailed CFD thermo-fluid modeling



Surface topography prediction and validation



Cellular Automaton (CA) modeling of grain structure

Scientific Impact

- **General framework for linking simulation data throughout the process-structure-properties workflow** applicable to material performance assessment
- **Fast hierarchical analysis** of advanced manufacturing processes using data-efficient neural networks to capture temporal and spatial features of the process
- **FEA analysis integrated with data-driven modeling** to achieve multiscale simulations
- **Computationally efficient physics-informed material analysis models** to predict and manipulate material performance in **advanced manufacturing processes**
- **Active control of cooling rates and temperature gradients** on a unique open-architecture DED machine (ARPI)

Broader Impact

- **Advancing manufacturing capabilities** through seamless integration of the physical process with fast process simulations on GPUs through a new data structure
- **Extensibility to other manufacturing processes**, particularly those that use digital representations of the geometry and process for future Industry 4.0 factories
- Physical platform for **guiding future advanced manufacturing process controls** (demonstrated for DED**)**
- Advancing **AI-based prediction and design** solutions for industrial manufacturing
- **Part attribute/property- rather than process response-driven manufacturing process control**

Education and Outreach

- Undergraduate projects in **Capstone Design** course (design of ARPI subassemblies and temperature control)
- Undergraduates in **REU projects**
- **Subject matter taught in graduate manufacturing courses**
- Provided a setting for graduate student projects through the **Predictive Science and Engineering Design cluster** at NU
- Published/prepared over **18 journal papers and numerous conference presentations**
- Co-organized **Women in Manufacturing with 130 participants** with mHUB, MxD, Women Tech Founders, and others

Women in Manufacturing

2019 NSF Cyber-Physical Systems Principal Investigators' Meeting
November 21-22, 2019 | Crystal City, Virginia

Northwestern University

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