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, and geometry and surface properties, during processing
- **Lack of science-/model-based methods** for control of part attributes through measurable primary process responses
- **Lack of an existing scientific-technological foundation** for a futuristic manufacturing platform in a distributed network

Solution

- **Integrate physical process knowledge with numerical simulations** for fast, integrated framework
- Develop a **multi-loop control system** allowing users to quickly determine the process parameters needed to yield the desired part attributes in a given process chain
- Enable integration with flexible, common, **voxel-based data structure** for encoding processing information and part attributes
- Leverage **general purpose graphical processing units (GPGPUs)** that operate well on voxelate data
- Design and conduct **unique experiments to validate simulations**
- Demonstrate multi-level methods on a unique **open-architecture networked Direct Material Deposition (DMD) machine**

Progress

- Fast **part-scale thermal modeling**
- **Voxel representation** of part scale
  - Uniform voxel structure
  - Efficient method for querying arbitrary points
  - Store experimental sensor, digital modeling, microstructural information
  - Implementation of hierarchical Octree algorithm for data refinement
- **Fine scale modeling**: powder spreading and thermal-CFD
- **Translation** of thermal-CFD model into voxel data
- **3D grain-growth model** with cellular automata
- Fast, accurate **voxel-based microscale mechanical model** (Self-consistent clustering analysis)
  - Captures porosity, phases, grains (size, shape)
  - Predict influence on elastic properties, tensile strength, fatigue life, etc.
- **Process-structure-properties models** for EBM process

Ongoing and Short-term Future Work

- Capture **residual stress** in process model, mechanical model
- Implement **thermal model for GPGPUs**
- **Improve hardening law** for precipitate strengthening, grain boundary effects, and more complex mechanisms such as creep
- Develop **data-driven methods** based on fine-scale models and experiments for real-time modeling
- Perform **validation experiments** using the ARPI

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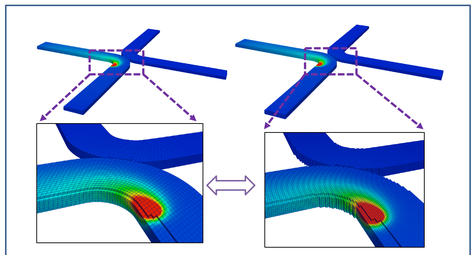
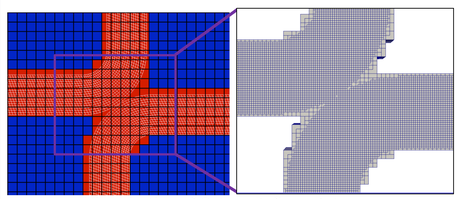
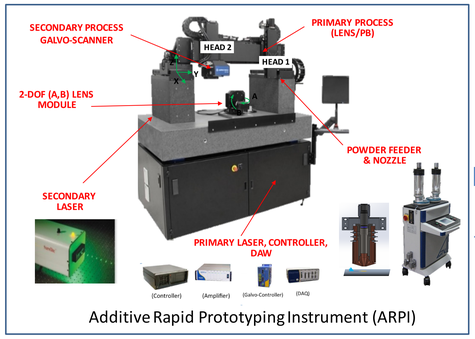


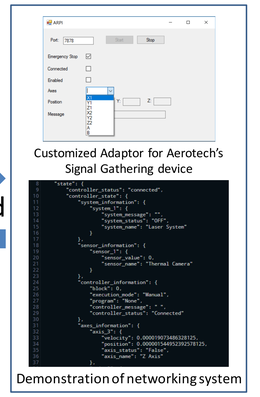
Conversion of unstructured FEM to voxel structure



Visualization of Octree-Refined Data

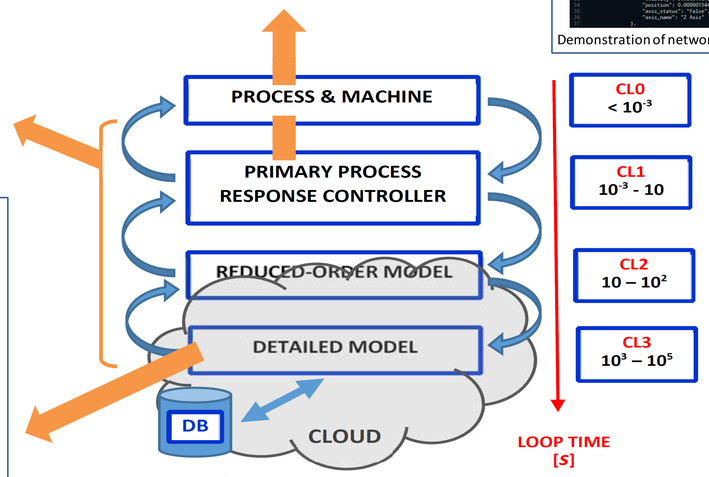


Additive Rapid Prototyping Instrument (ARPI)

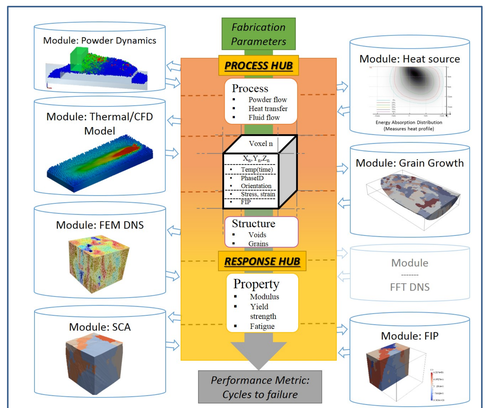


Customized Adaptor for Aerotech's Signal Gathering device

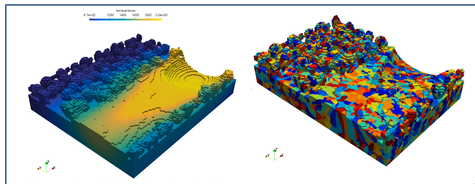
Demonstration of networking system



Proposed multi-loop control system

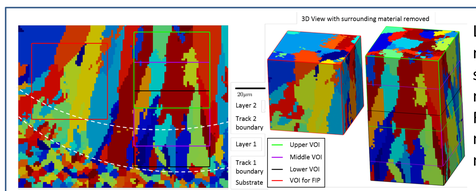


Computational framework for modeling process-structure-property-performance relationships in AM

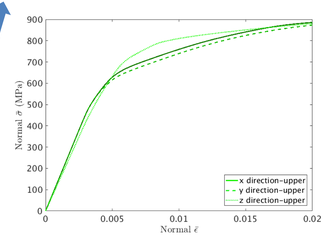


Thermal and fluid flow simulation for a powder-bed process

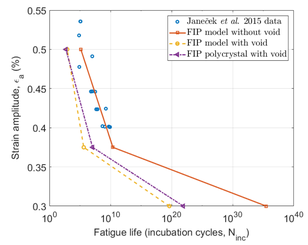
Grain growth model based on thermal history



Left: Slice of a 3D CAFE model for grain growth, showing VOIs for microstructure analysis. Right: the 3D microstructures used for mechanical analysis



Stress-strain curves for microstructures from: layer one, inter-layer, layer two



Fatigue life prediction with microstructure from microscale process simulation

DMD Process Chain Hardware

State-of-the-art open-architecture Direct Material Deposition (DMD) machine, called ARPI, being designed and equipped with various sensors to verify this framework:

- Computer-controlled **high-precision multi-axis Cartesian gantry-type motion platform** with dual Z-axes to support a range of DMD processes and melt-pool or cooling rate manipulation
- **Two powder delivery subsystems**: commercial Fraunhofer and NU-designed-and-built system
- Two **high-resolution IR cameras**; embedded **thermocouples** and **acoustic emission sensors**, situated on a calorimeter; **galvo-scanner**

Networking Framework

- Machine capable of **distributing data over a network**, using the MTConnect standard: an essential component for running the ARPI control system in a distributed network
- Covers **wide range of data** including axes information, sensor data, ARPI controller information, warnings, and time series data
- Data can be received and saved on an **online repository** as well as other computers

Scientific Impact

- **General framework for linking simulation data throughout the process-structure-properties workflow**: applicable to material performance assessment, not just AM
- System for **network-controlled advanced manufacturing**
- **Efficient data structure** for combining information from experiments and simulations, applicable to GPGPU computing

Broader Impact

- Potential for **guiding future advanced manufacturing**, to be tested on the ARPI
- Method **extensible to other manufacturing processes**, particularly those using digital representations of the geometry and the process
- Heighten **awareness of GPGPUs for numerical modeling**, and their ability to reduce computational performance bottleneck
- **Education and Outreach**
  - Provides a setting for graduate students to conduct interdisciplinary research, leveraging the Predictive Science and Engineering Design cluster at Northwestern
  - Advanced modeling methods taught in a grad course; 15 students
  - 5 HS students mentored in Summer 2017, working on material and thermal modeling (by Liu's students)