NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

Standards Considerations Towards the In-Process Quality Assurance of AM Parts

Paul Witherell, PhD

Measurement Science for Additive Manufacturing Program

National Institute of Standards and Technology

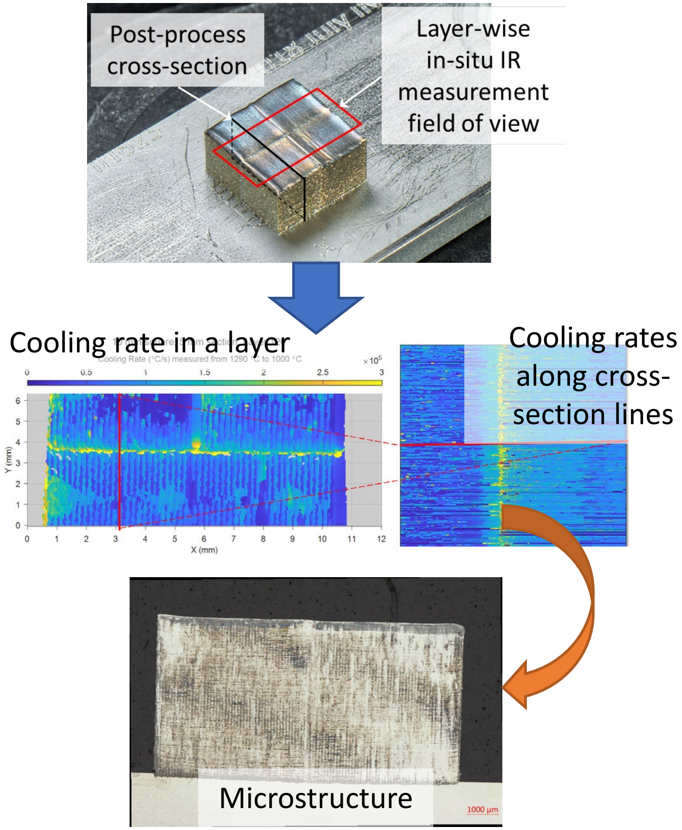
October 25, 2023

Brief Introduction to NIST AM Research

- Full spectrum of materials classes (Ceramics, Polymers, Metals, Concretes, Biological materials)
- Full spectrum of AM process categories

Focus areas:

- Unique materials and material properties
  - Comprehensive characterization of processing-structure-properties-performance (PSPP) relations
  - Determination of properties affecting printability/manufacturability
  - Provisionment of critical AM materials data to stakeholders
  - Methods to enable the insertion of new materials for additive applications
- Trustworthy in-process monitoring and control
- Verified and validated process and material models and design tools
- Rapid, inexpensive, and effective part inspection techniques
- Rapid and traditional machine and material qualification techniques
- Process and material standards and specification
- Data curation, integration, and analysis



Meeting Criteria for Part Acceptance

- Whether we are referring to qualification, certification, acceptance…
- In general, the aim is to:
  - Build confidence/trust into part
  - Establish confidence that the part will perform as designed


- Traditional manufacturing processes benefit from legacy and robustness

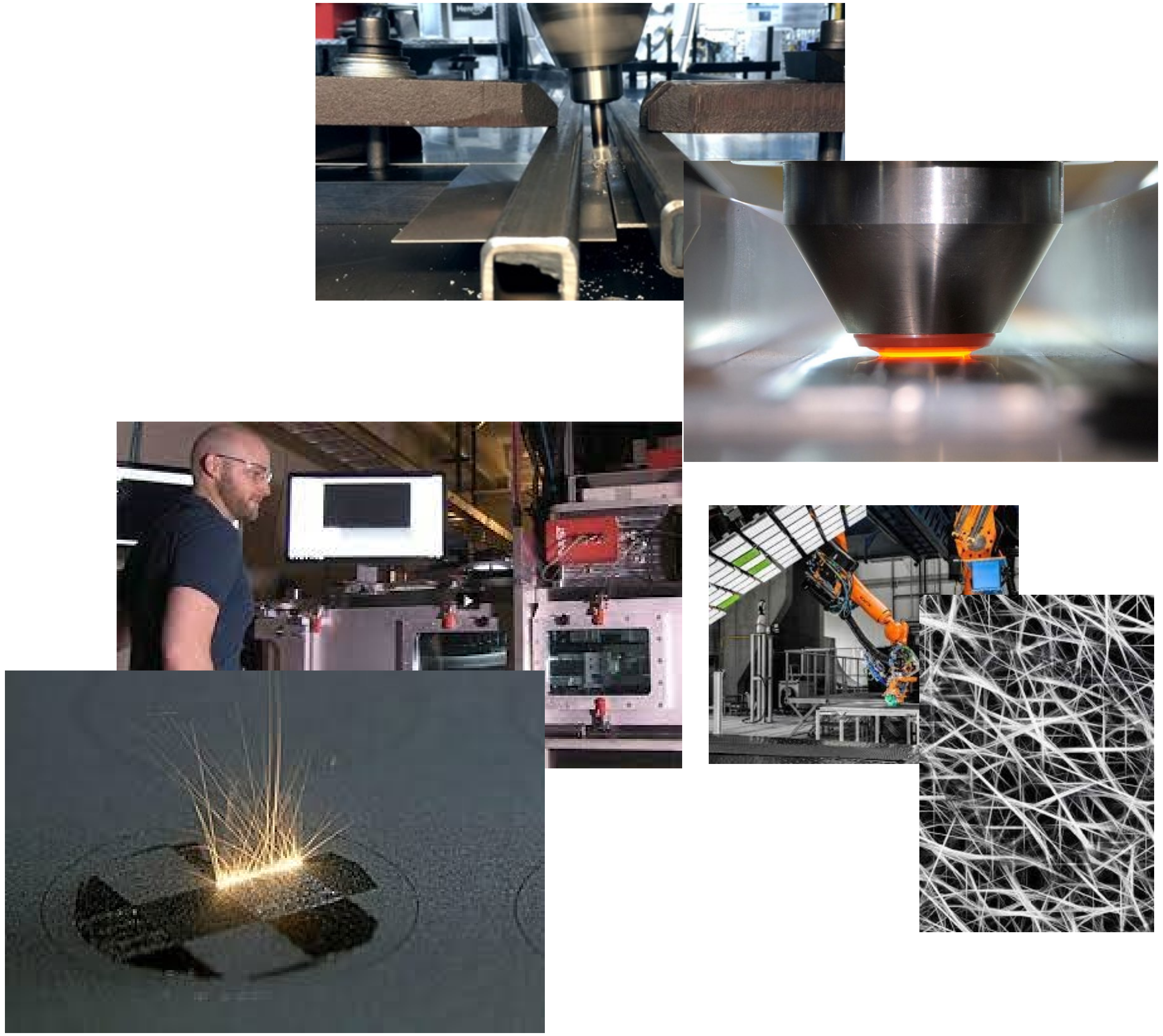
- To build trust into the part, trust must be established for the process as well

- AMTs present many challenges

Why Are AMTs so Challenging?

- Advanced usually implies improved, however:
  - Novelty often comes with new uncertainties
    - Creates challenges when repeatability and reliability are essential
  - Increased capabilities are accompanied by increased parameters
    - Large flexibility can lead to large variability
    - Less robust to disturbances

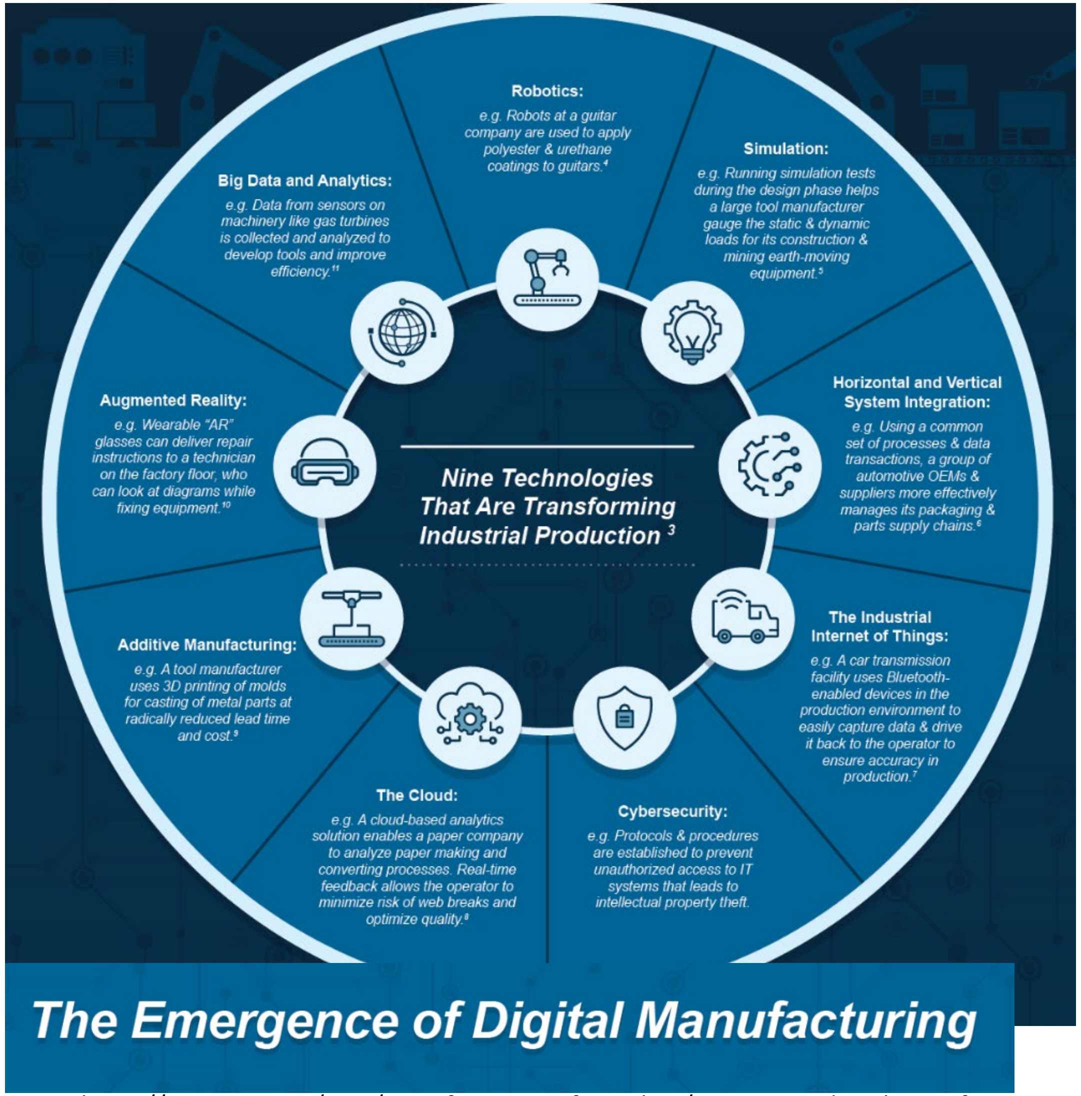
Traditional qualification methods have proven difficult to adopt for AMTs



Building Trust through the Digital Nature of Advanced Manufacturing Technologies

NIST

- Current “state-of-the-art” most often benefits from increased digitalization
- Advanced manufacturing processes are often driven by a strong digital component
- The digital, piecewise nature of many of these processes lend themselves well to more advanced analytics

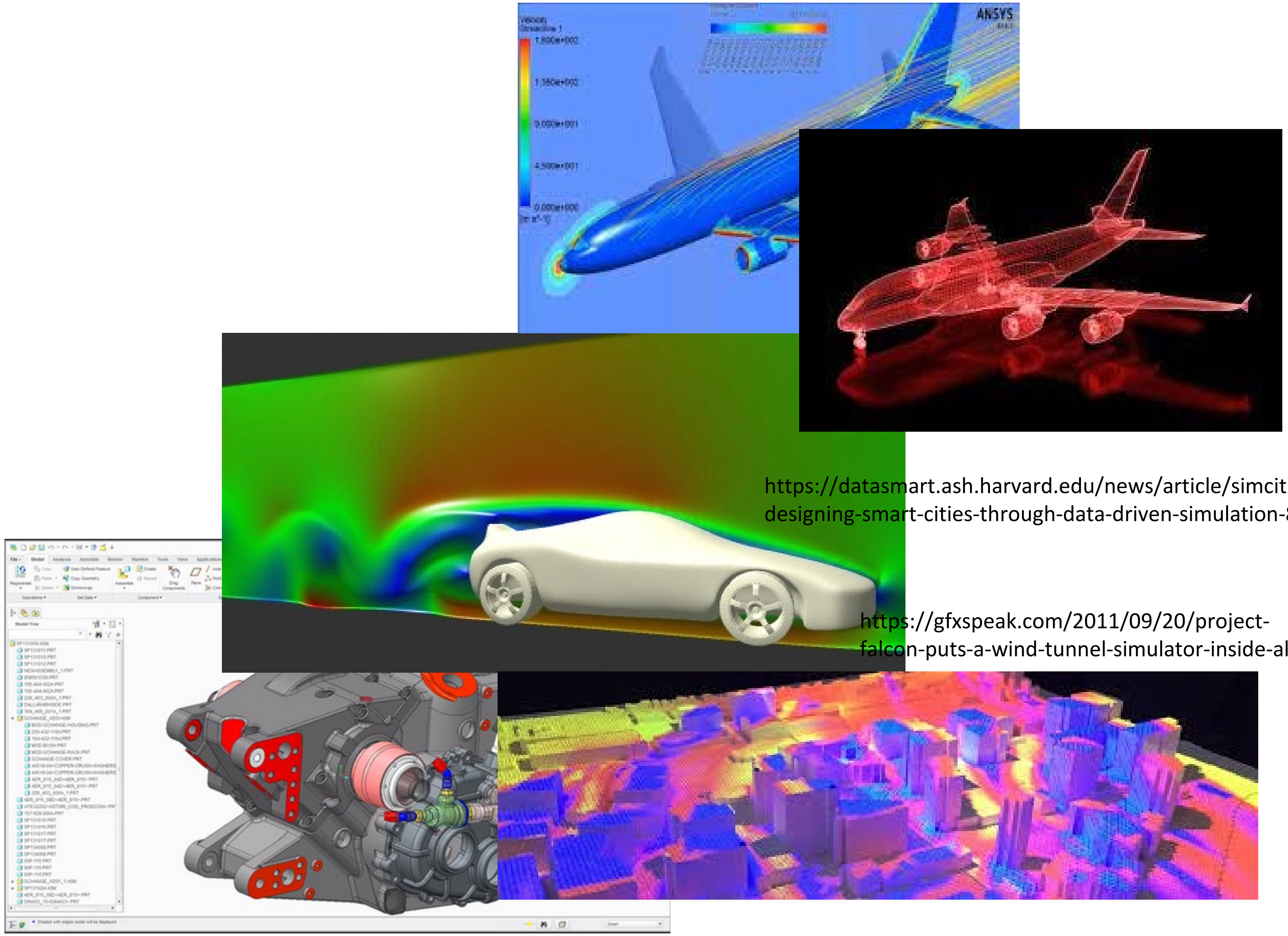


https://www.nist.gov/mep/manufacturing-infographics/emergence-digital-manufacturing

The Increasing Roles of Modeling and Simulation

NIST

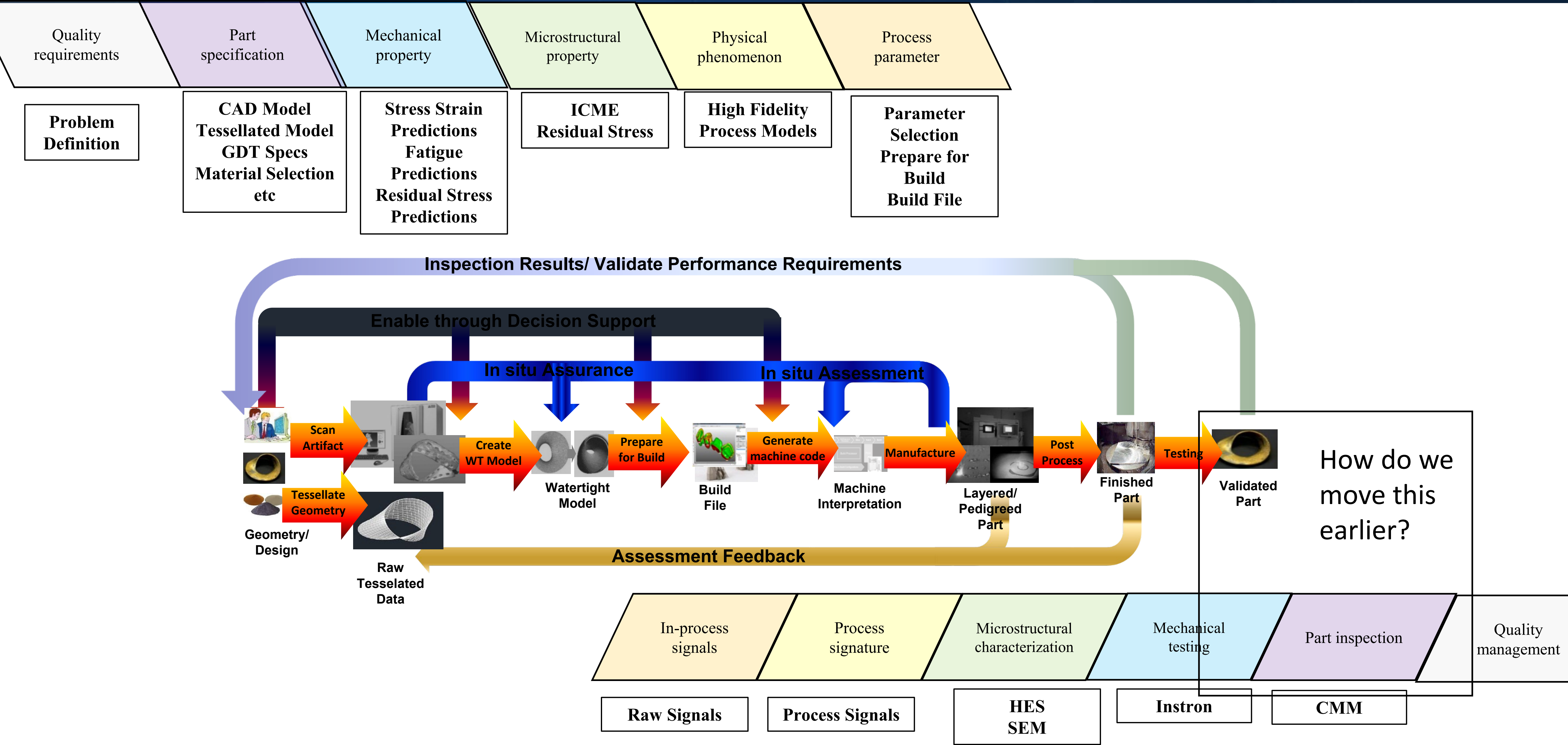
- Modeling and simulation are being used to:
  - Digitally realize a desired state of a part or process
  - Provide insight into physics interactions of parts and processes
  - Set expectations of expected performance through observed interactions
  - Provide a foundation for predictive analytics and course corrections during design, manufacture, and use phases of a part or subject



https://datasmart.ash.harvard.edu/news/article/simcities-designing-smart-cities-through-data-driven-simulation-893

https://gfxspeak.com/2011/09/20/project-falcon-puts-a-wind-tunnel-simulator-inside-alias/

M&S Sets Expectations, but When Does the Quality Assurance Occur?



Quality Assurance through Observation and Measurements: Exploring the Digital Twin

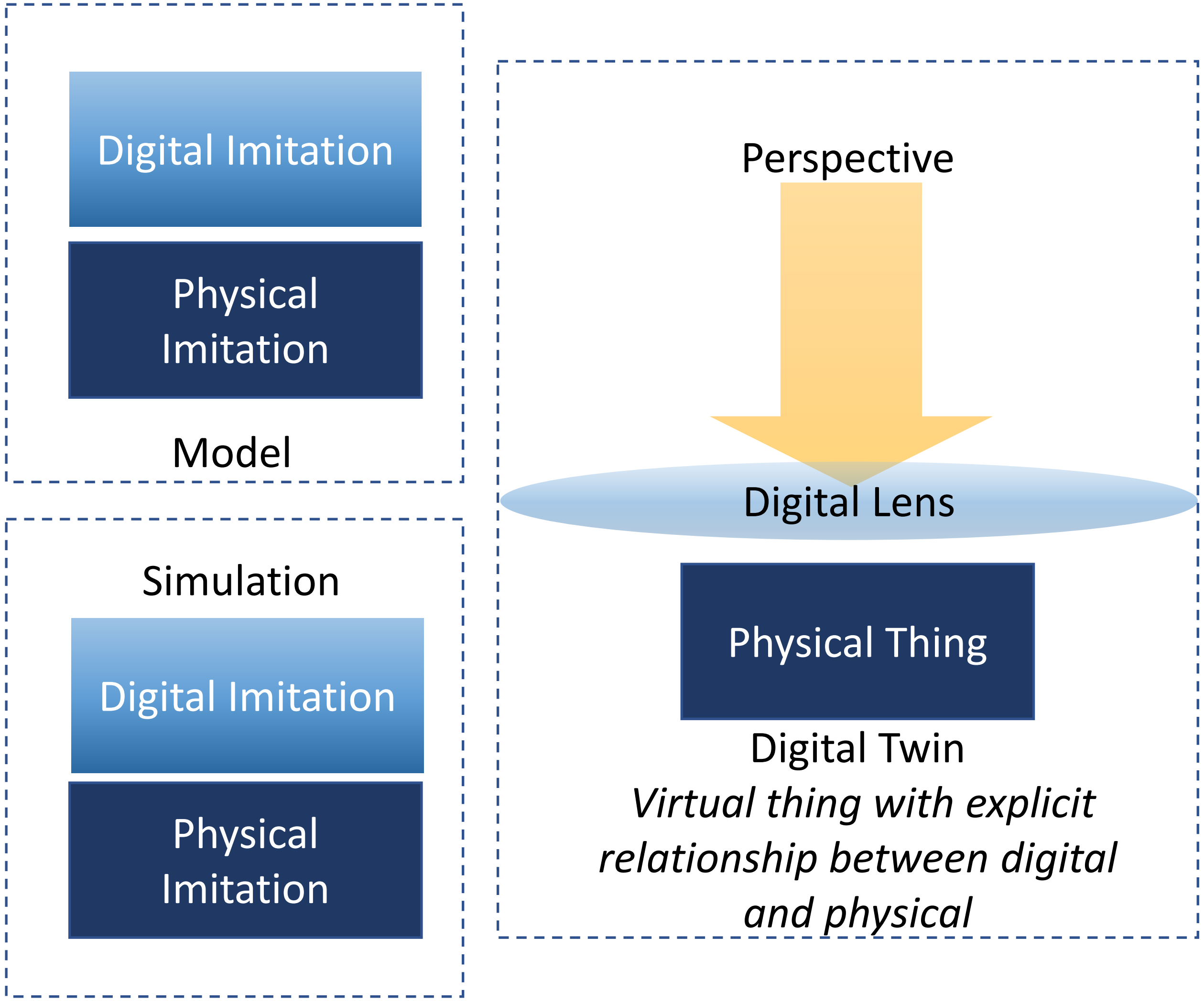
Model - Simulation- or a Digital Twin?

Modeling and Simulation

- Can exist in physical world, digital world, or both
- Represent parts, processes, behaviors…
- Context/Perspective greatly influence to what extent they are representative

Digital Twin

- Exists only in digital world– but with an explicit relationship to the physical
- Digital twin links to the physical world do **NOT** have to exist as models or simulations
- Explicit links between physical observations and digital counterparts



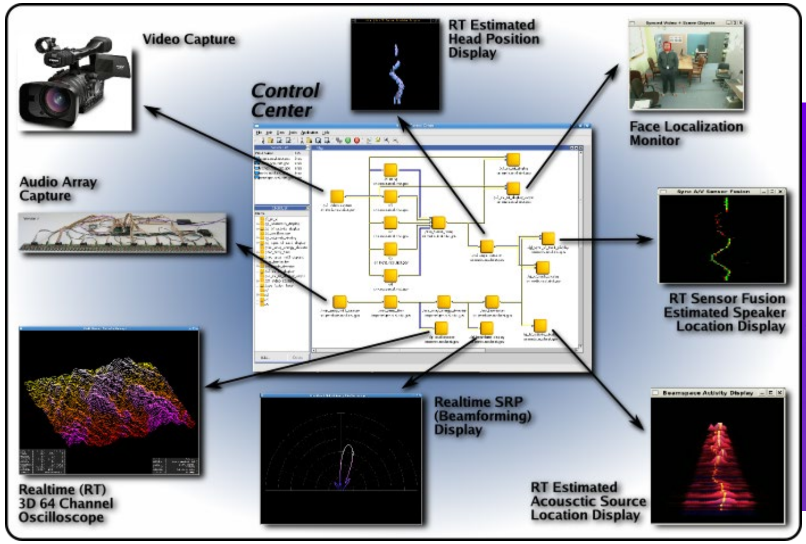
Emerging Digital Twin Opportunities

"a digital informational construct of a physical system as an entity on its own"
-Grieves and Vickers (2017)

https://www.ccad.uiowa.edu/military/warfighter-simulation

Characteristics of a Digital Twin:

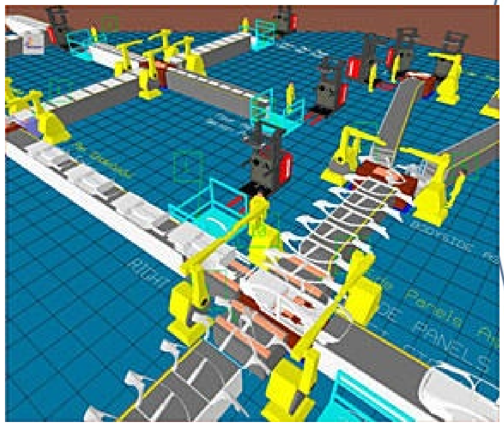
- A virtual representation of a thing
  - Many different definitions
- Scalable
  - A twin can exist within a twin
- Flexible
  - Simulation and emulation
- Purposeful
  - Context dependent adaptations



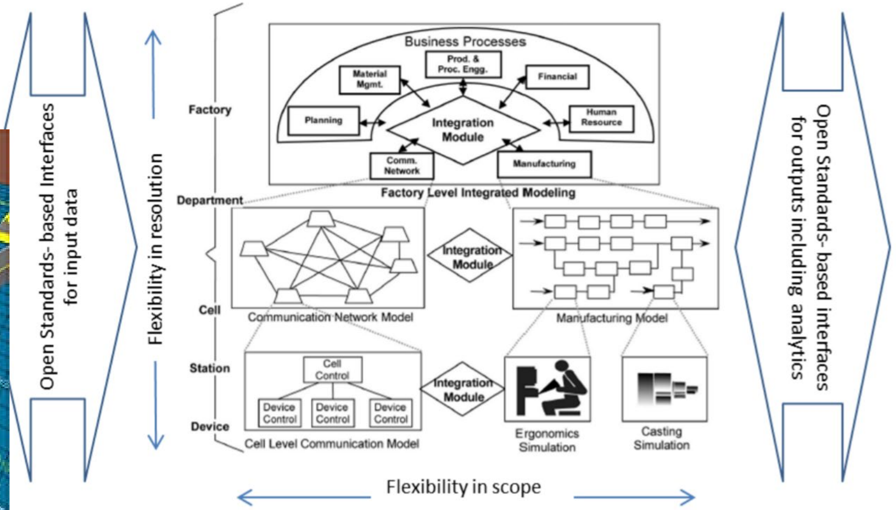
https://www.nist.gov/itl/iad/mig/nist-smart-space-project/nist-smart-space-project-data-flow/nist-data-flow-system

Leveraging the Digital Twin in Manufacturing

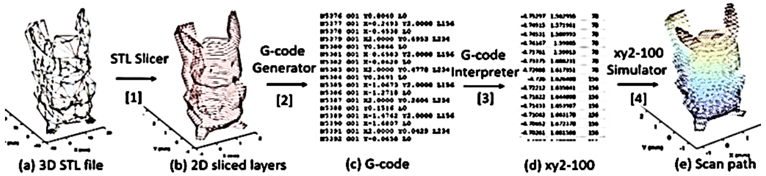
- Multi scale in manufacturing:
  - Part, machine, factory, supply chain
- Common uses in manufacturing
  - To assess behaviors of parts or processes during operation
    - M&O of machines and parts
  - To configure systems on component-system levels
    - Production system design, complex product integration
  - To establish provenance and/or control during the fabrication of a part
    - Quality control mechanism

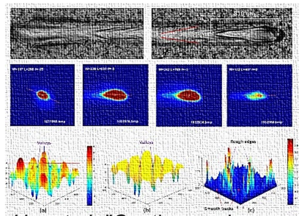


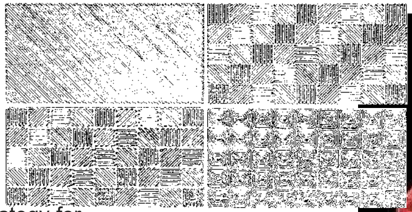
https://www.nist.gov/topics/manufacturing/nist-led-standard-enables-agility-cost-and-time-savings



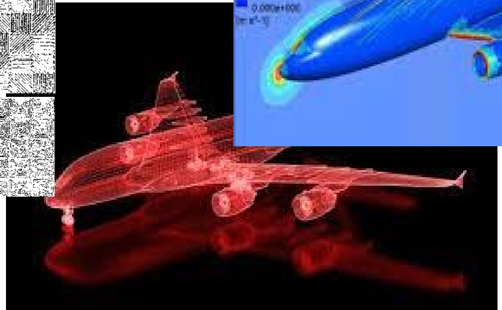
Shao, Guodong, et al. "Digital twin for smart manufacturing: The simulation aspect." *2019 Winter Simulation Conference (WSC)*. IEEE, 2019.

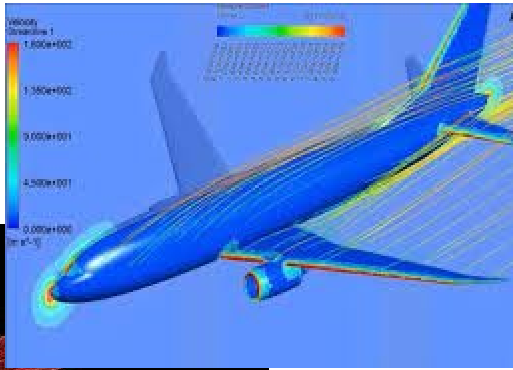






Yeung, Ho, et al. "Continuous laser scan strategy for faster build speeds in laser powder bed fusion system." *Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium*. 2017.



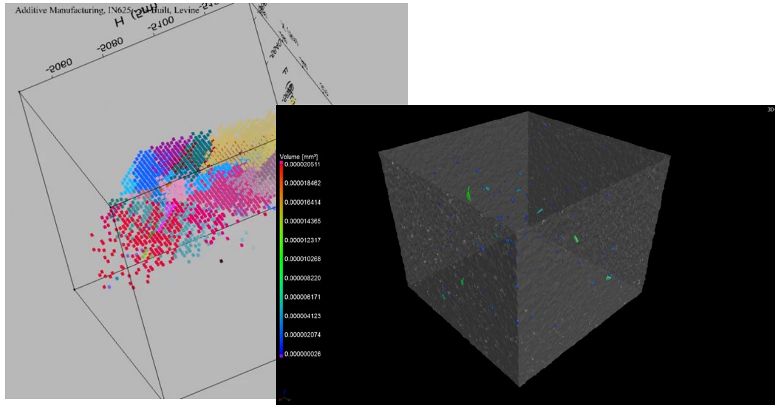


Leveraging the Digital Twin in AMTs

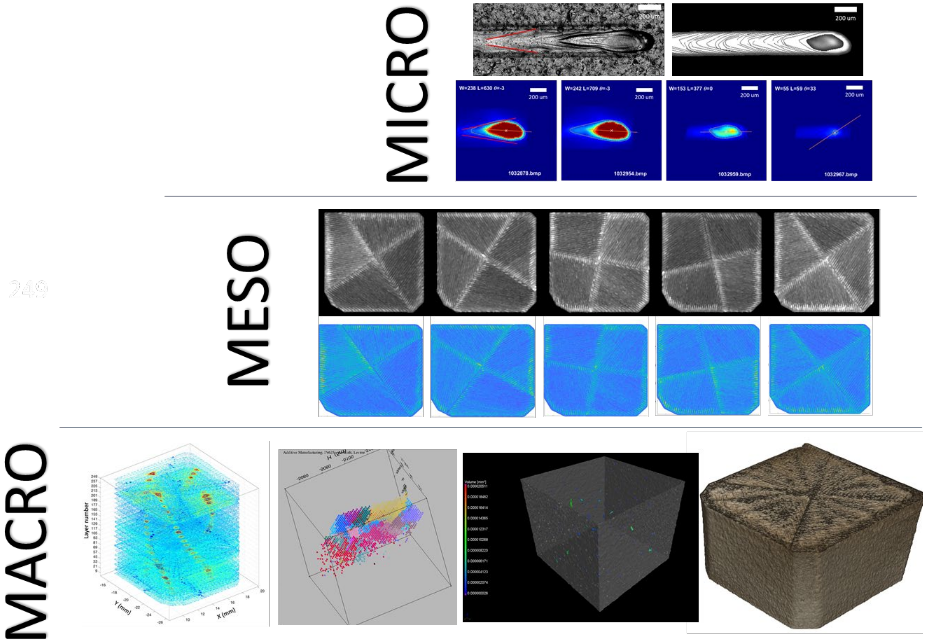
With the increasing significance of data in manufacturing, the digital twin has become an important concept:

- Implications due to perspective/connotation;
- Couple to a physical counterpart;
- Often spatial and temporal components

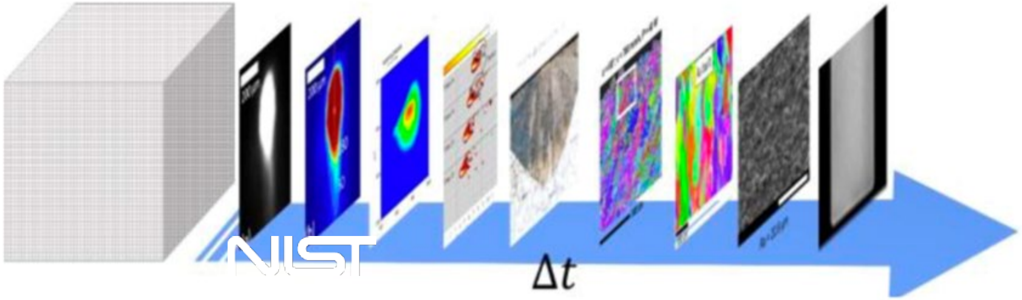
The digital twin approach can be used to provide a basis on which detailed analyses and assessments can be performed



Obtaining Micro-scale Residual Stresses Using Synchrotron X-Rays



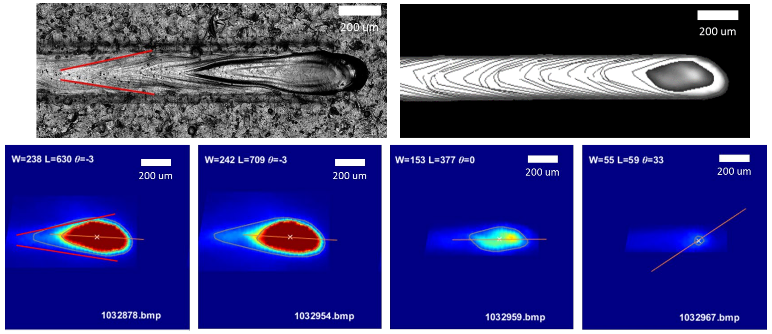
From NIST EL Measurement Science for Additive Manufacturing Program
Precursor Materials Qualification : Thien Phan



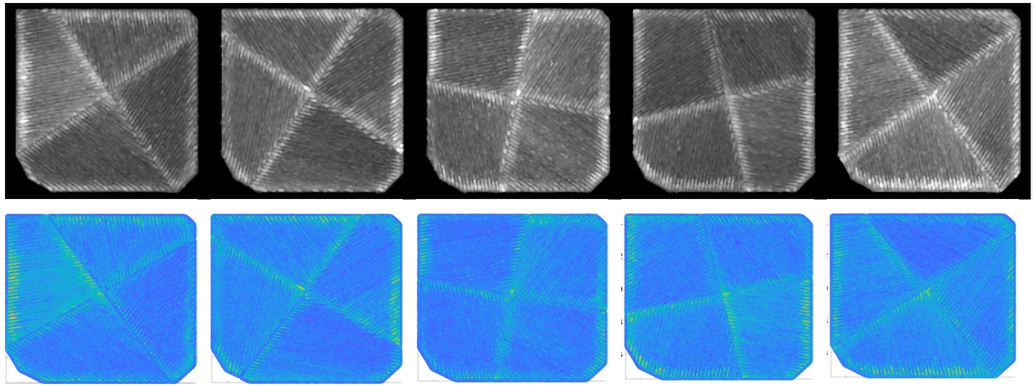
Measurements Through the Context of a Digital Twin

- Much of the research measurements in AM at NIST can be related through a digital twin approach

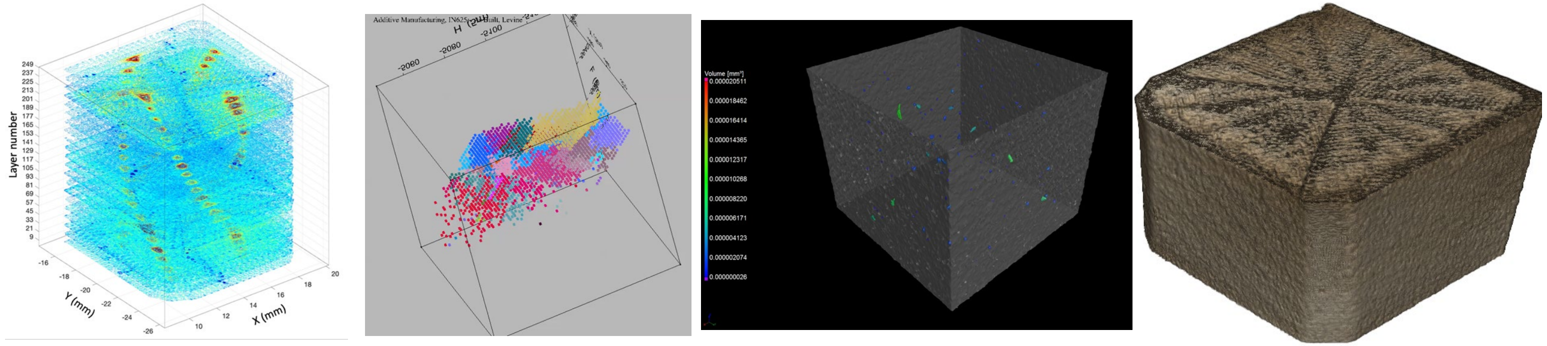
MICRO



MESO

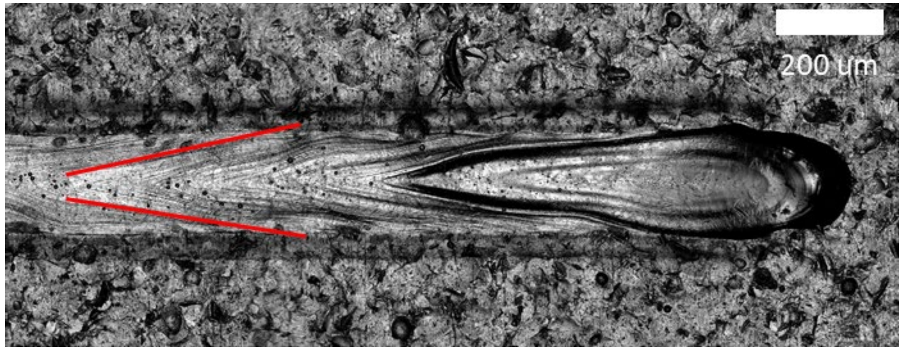


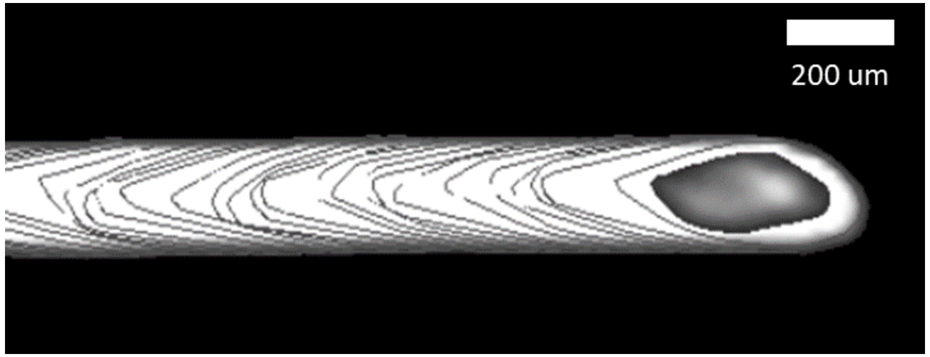
MACRO

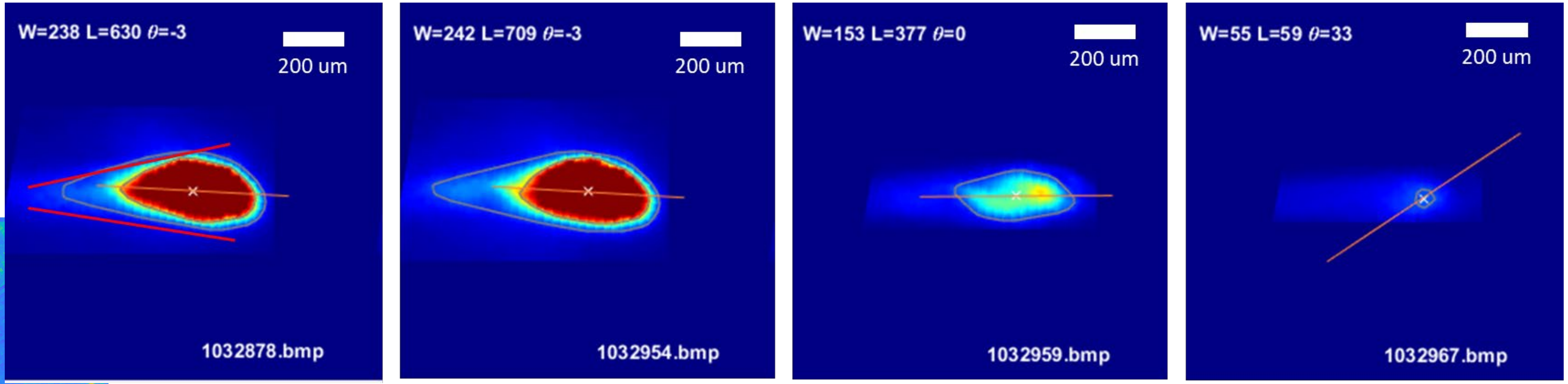


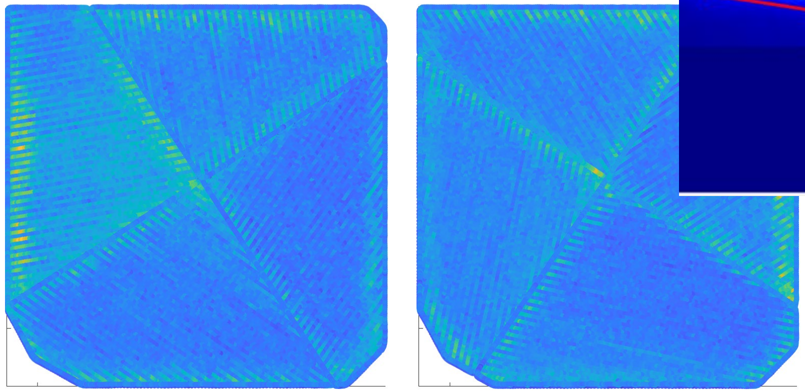
NIST Measurements in AM

- The digital twin approach can be used to map measurements taken at different times with different instruments







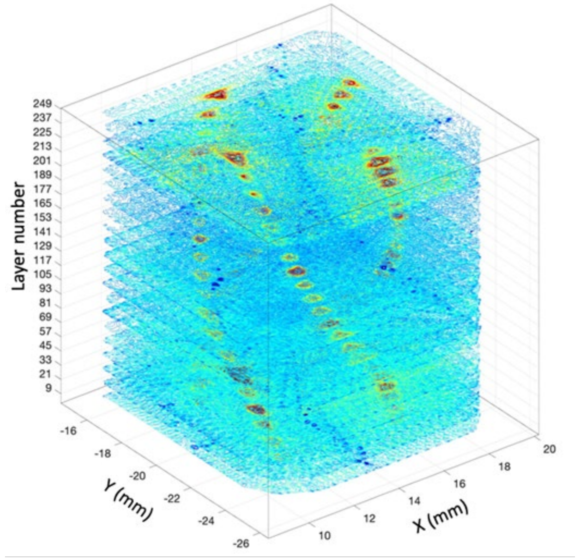


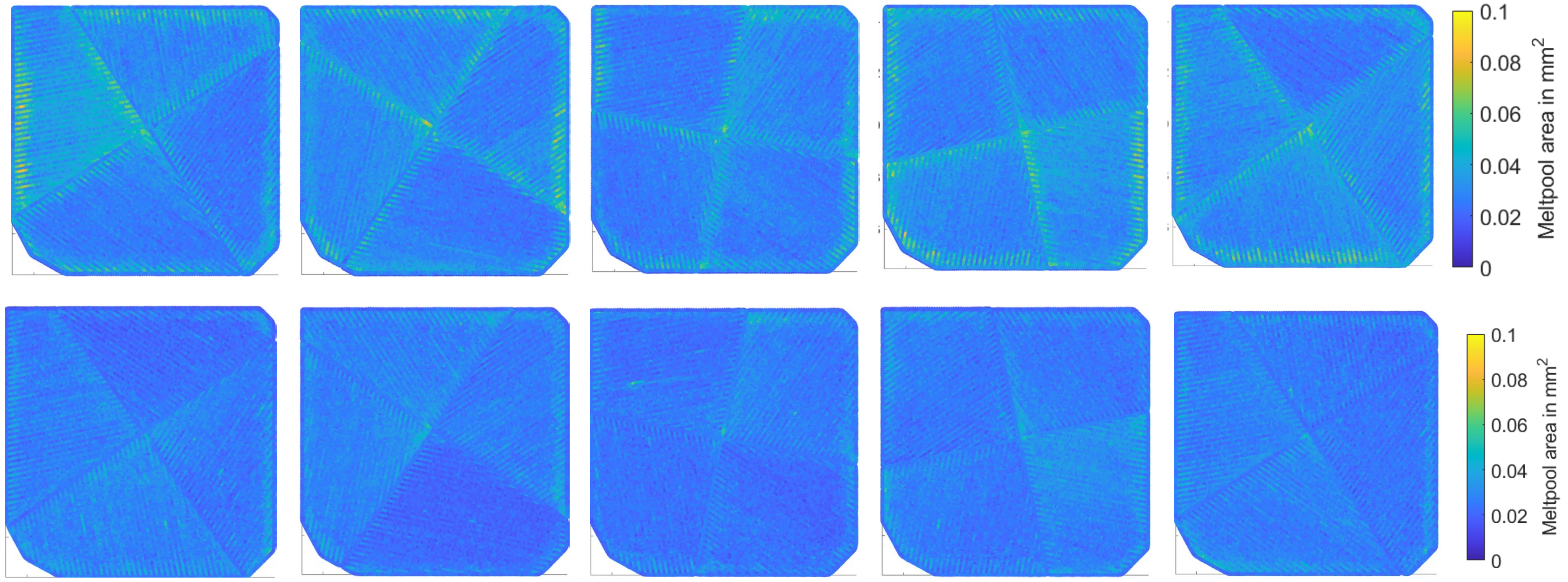
In-situ melt pool observation an analysis is mapped from tracks to layers

From NIST EL Measurement Science for Additive Manufacturing Program
AM Machine and Process Control Methods for Additive Manufacturing
Ho Yeung, Project Lead

NIST Measurements in AM

- The digital twin approach can be used to map these measurements across scales



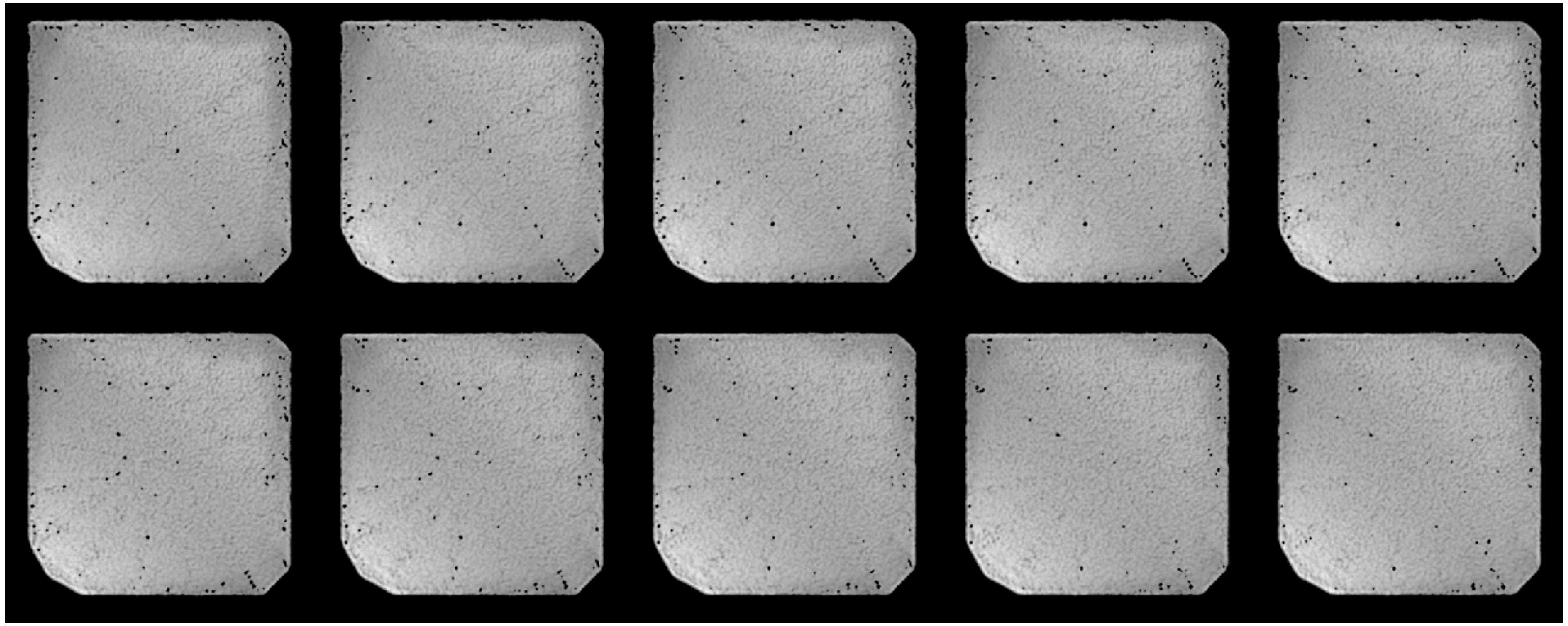


In Situ layer-wise observations can be mapped back to volumes

From NIST EL Measurement Science for Additive Manufacturing Program
AM Machine and Process Control Methods for Additive Manufacturing
Ho Yeung, Project Lead

NIST Measurements in AM

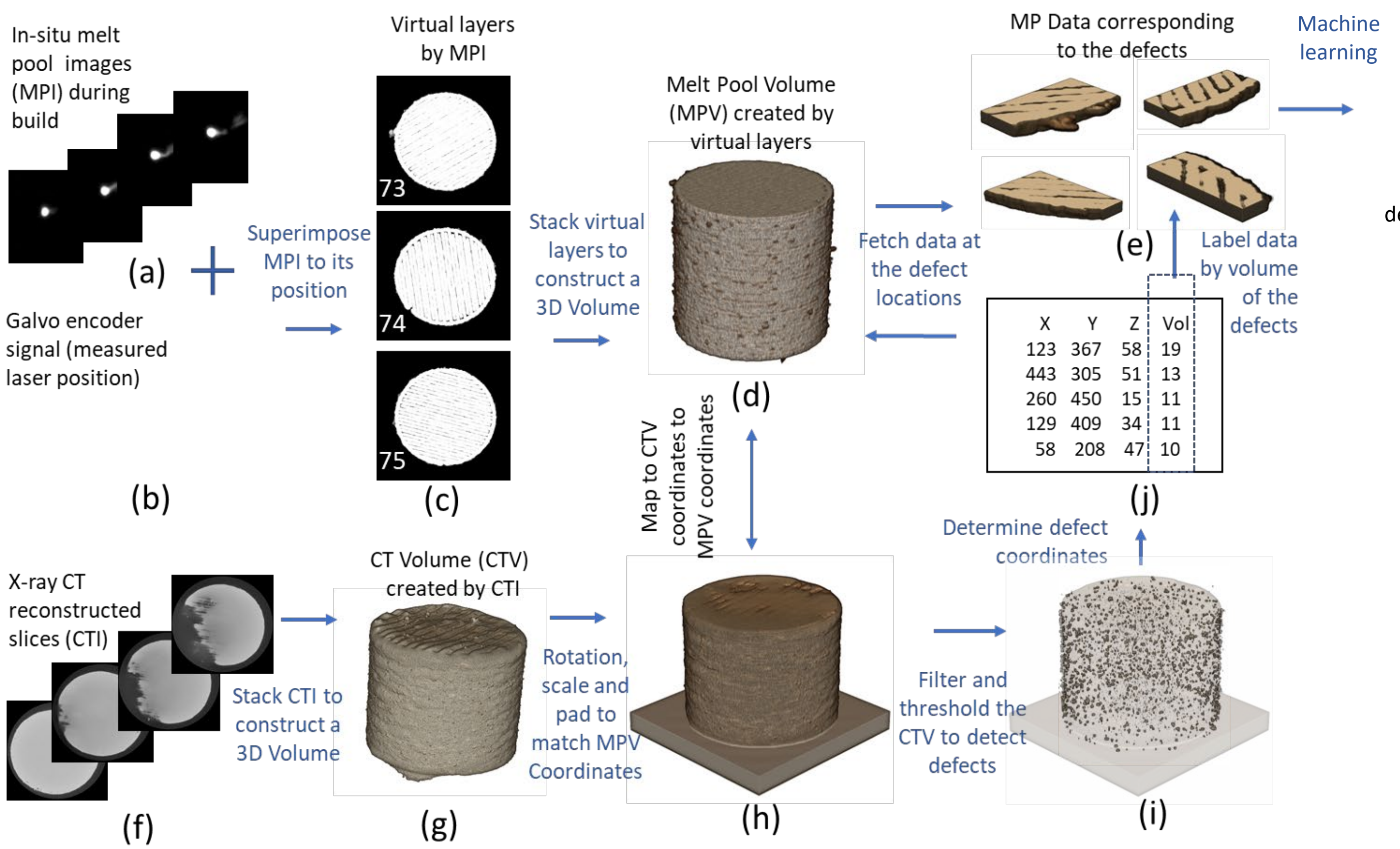
- The digital twin approach can be used to map in situ and ex situ measurements

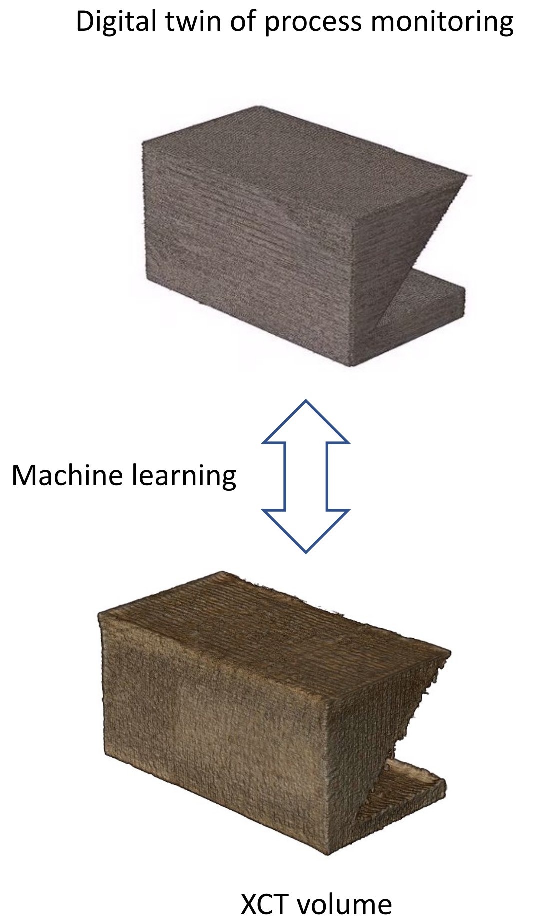


Ex Situ layer-wise observations can be mapped back to volumes

From NIST EL Measurement Science for Additive Manufacturing Program
Additive Manufacturing Part Qualification
Jason Fox, Project Lead

NIST Defect Detection with Digital Twin





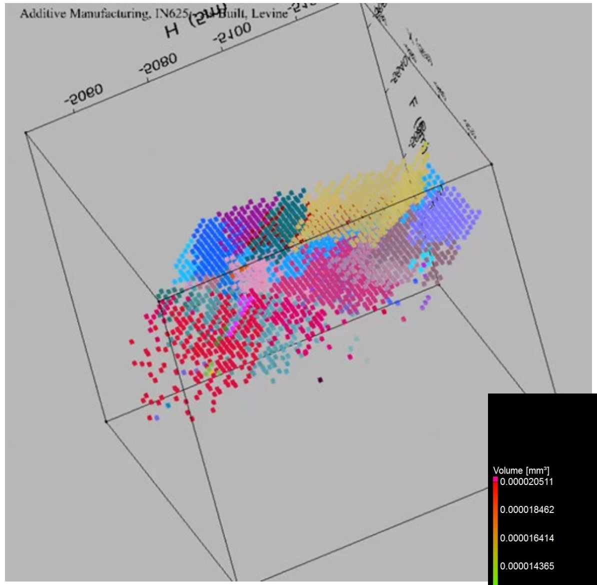
Qualify as build – defect prediction model

- Correlate the process monitoring digital twin and XCT detected defects.
- Train machine learning model to predict pores from the digital twin.

From NIST EL Measurement Science for Additive Manufacturing Program
AM Machine and Process Control Methods for Additive Manufacturing
Ho Yeung, Project Lead

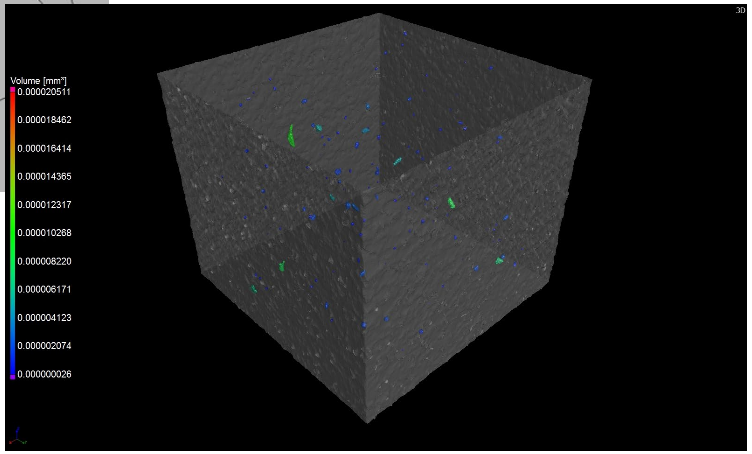
Standards Considerations to Address In-Process Assurance

- The digital twin approach can be used to provide a basis on which detailed analyses can be performed
- Acceptance requires agreement in
  - Identification of relevant data and meaning of data
  - Repeatability of data registration and fusion
  - Methods for curation and presentation for consistent analysis
  - Establishment of fundamental correlations between observations and meanings
    - E.g., design allowable and beyond



Obtaining Micro-scale Residual Stresses Using Synchrotron X-Rays

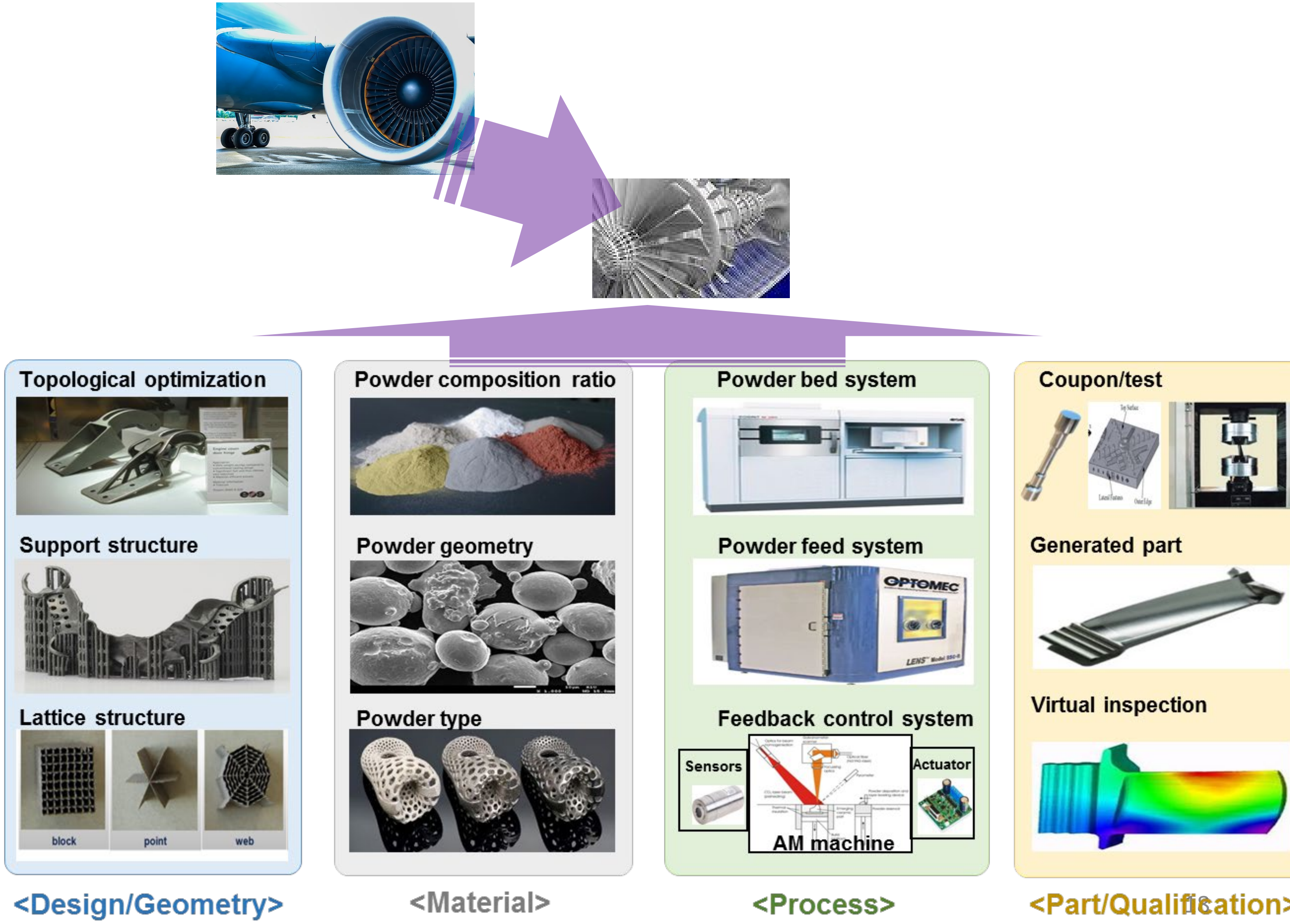
36 μm × 63 μm × 60 μm



From NIST EL Measurement Science for Additive Manufacturing Program
Precursor Materials Qualification
Thien Phan, Project Lead

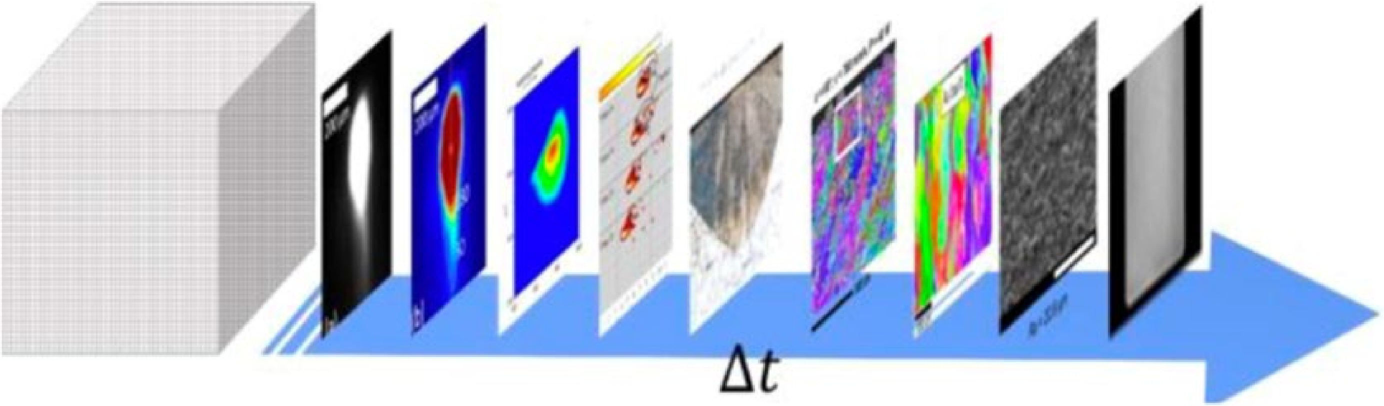
Thinking Back to Acceptance—Do Process Observations Reflect the Quality of the Part?

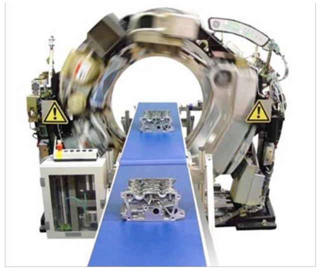
- Process assurance versus part quality assurance
- Digital twins can build confidence in processes and parts using:
    - Digital twin criteria that focuses on establishing provenance of part-process interactions
    - Digital twin criteria that focuses on establishing expectations of part within context of specific application



The Reconciliation Challenge: Process vs Part

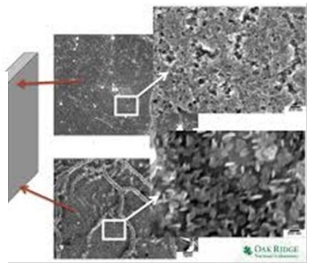
- Distinguishing between process characteristics(fundamental criteria) and part characteristics (context specific criteria)
- FC and CSC measurements often established at different scales
  - Inherent differences in measurements do not always allow for one-to-one mappings
  - Integration will depend on application requirements and focusing on observable behaviors
  - Expansion of scope to system-of-system digital twins may be necessary to facilitate integration
- CSC performance criteria may not easily map to observable part characteristics
  - Process signatures and key performance indicators must be leveraged
  - VVUQ must be accounted for





<Industrial CT scanning>

<Ultrasonic testing>



grain morphology>

<Tensile strength>

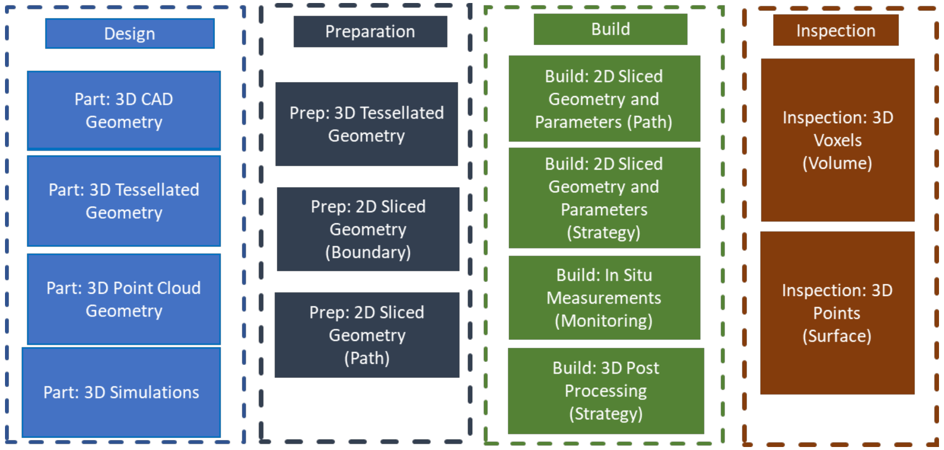
Fundamental Criteria (FC)- Process Assurance

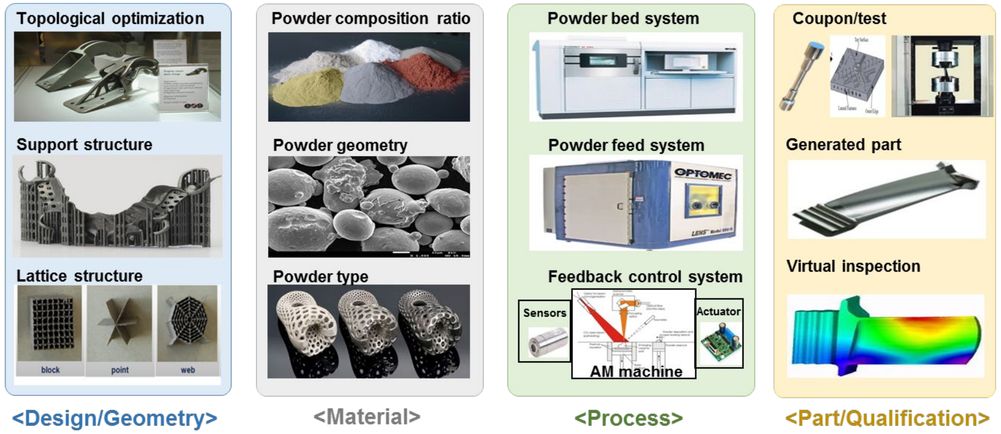
NIST

Establish Fundamental Criteria

Five Fundamental Criteria (FC) for establishing digital twin of part:

1) Definition of successful fabrication process
   -e.g., validation against predictive model
2) Definition of what a “quality” part is
   -e.g., no crack formation
3) Established links between process characteristics and part characteristics,
   -e.g., data registration
4) Identification of process or part signatures of note
   -e.g., microstructure or surface roughness
5) Determination of acceptable metrics and measurement techniques for observation
   -e.g., grain orientation or average roughness



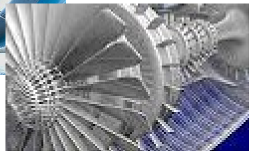


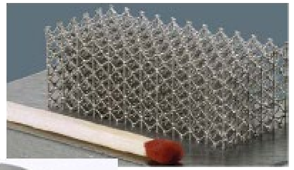
Context-Specific Criteria (CSC)- Part Assurance

Establish Context Specific Criteria

Five Context Specific Criteria (CSC) for establishing digital twin of part:

1) Identification of performance requirements
   - -e.g., cyclic loading requirement
2) Identification of part characteristics that directly or indirectly will affect part performance
   - -e.g., surface roughness
3) Identification of metrics to quantify noted part properties
   - -e.g., average roughness
4) Establishment of baseline thresholds
   - -e.g., Maximum surface roughness
5) Incorporation of uncertainty
   - -e.g., safety factor

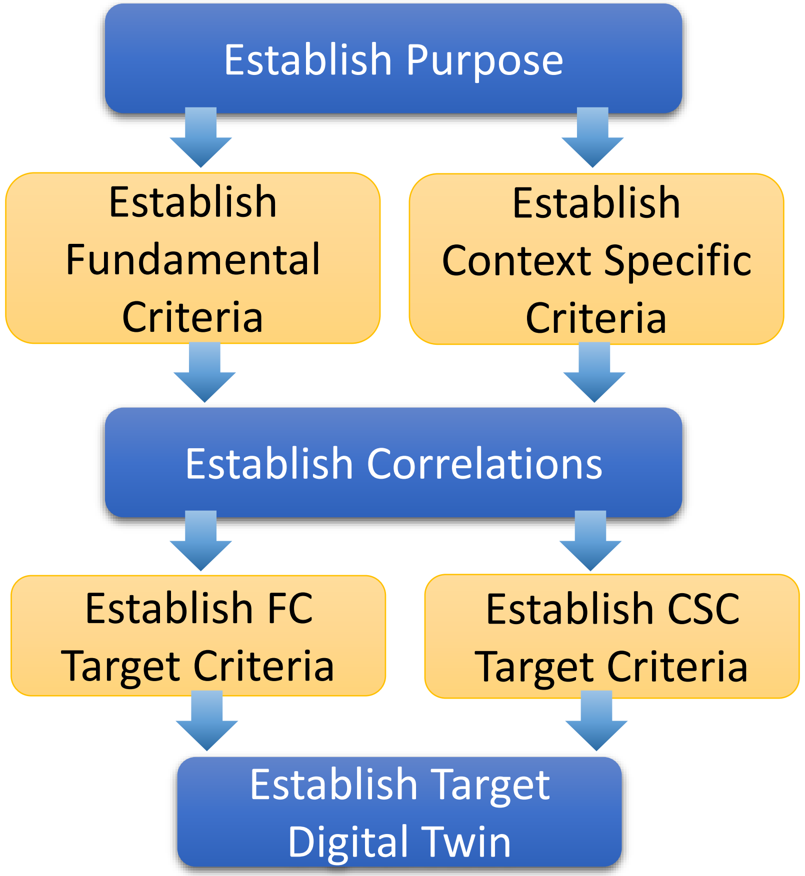






Towards a Digital Twin for the In-Process Quality Assurance of AM Parts

Establishing purpose

- Setting scope
  - Focus on appropriate lifecycle stages of development and use
- Setting context
  - Focus on Performance Requirements and Part Characteristics
- Setting target expectations
  - Focus on measurable quantities

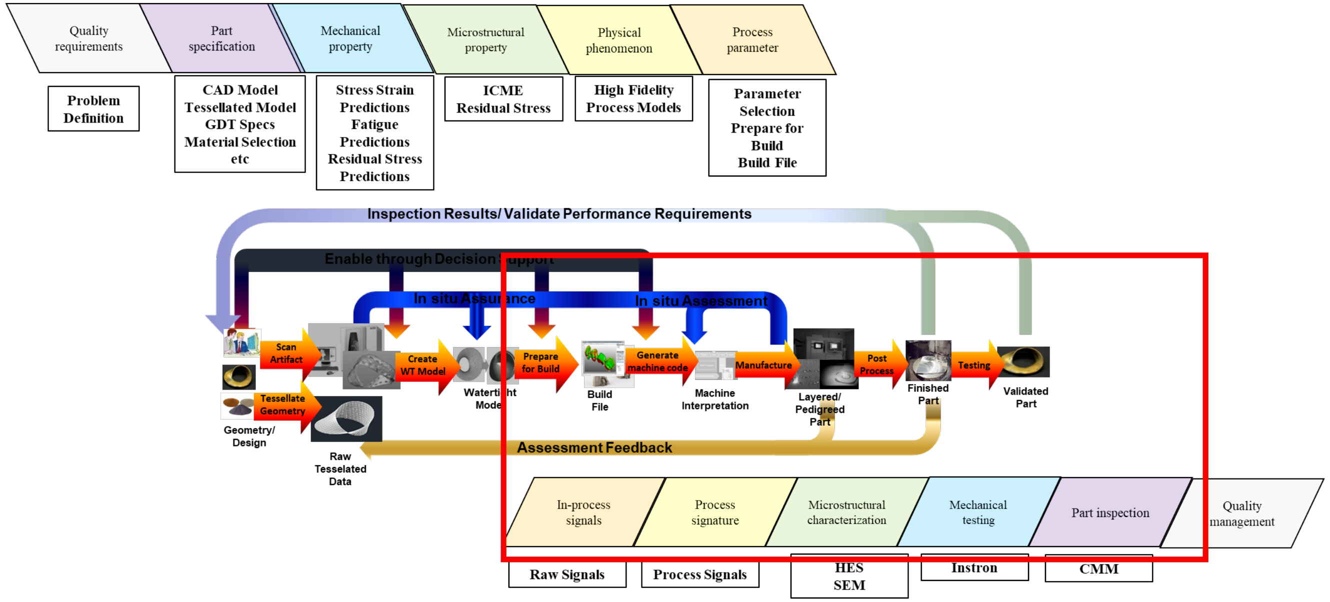


Witherell, Paul. "Digital Twins for Part Acceptance in Advanced Manufacturing Applications with Regulatory Considerations." The 46th MPA Seminar, Stuttgart, DE, 2021.

https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=933613

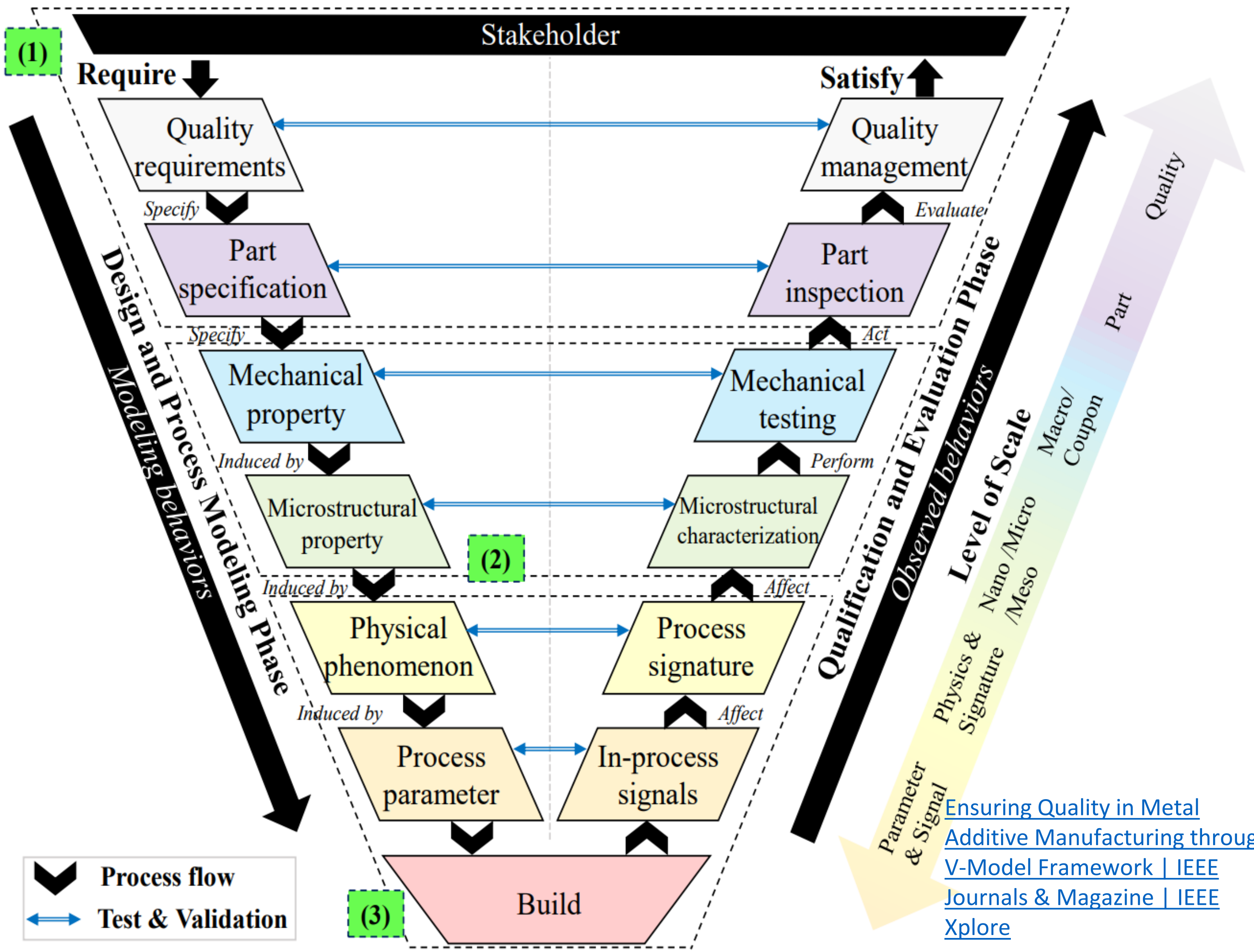
Standards Considerations to Address In-Process Part Quality Assurance

- Adopting digital twins for part quality assurance requires additional considerations in:
  - How we establish provenance at different stages
  - How we establish acceptance thresholds
  - How we test and validate for performance at earlier stages
  - How we explicitly address VVUQ at each stage
  - How we establish best practices
    - Context and application specifics
    - Case studies



Towards Establishing In-Process Acceptance

- Moving the box earlier requires
  - Accounting for specifications at all stages
  - Ability to traverse different scales
  - Ability to test and validate at all stages



[Ensuring Quality in Metal Additive Manufacturing through a V-Model Framework | IEEE Journals & Magazine | IEEE Xplore]

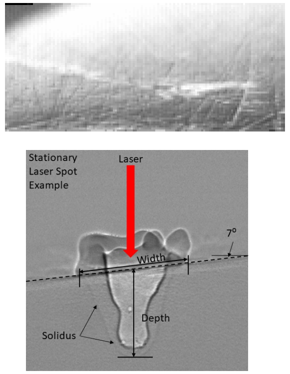
One Approach: Building a Scalable Framework through Standards

NIST ENGINEERING LABORATORY

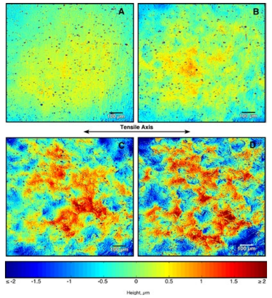
NIST Additive Manufacturing Metrology Testbed:

- Open PBF-LB/M platform,
- Metrology of process controls.

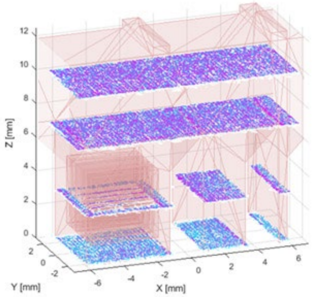
Melt pool monitoring



Surface profiling



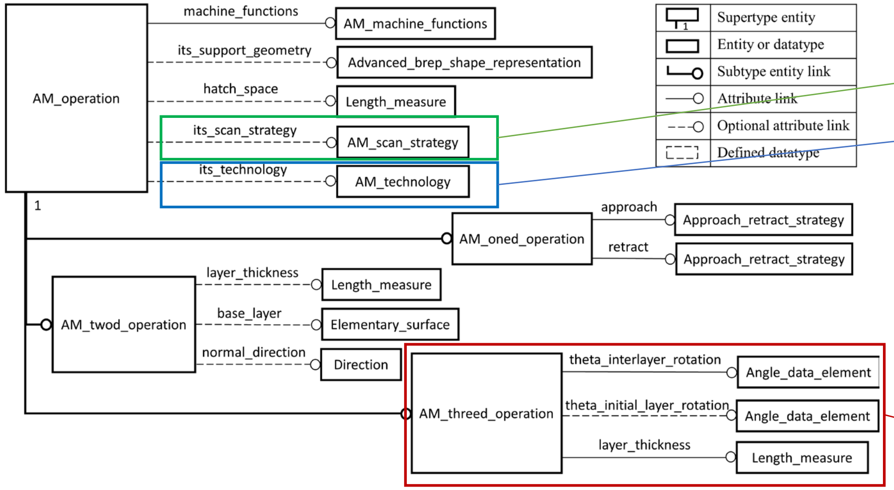
Cooling rates



Source: https://www.nist.gov/ambench

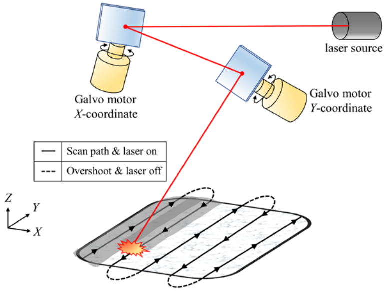
Previous Work:

Extend STEP-NC ISO 14649-17
Proposed for ISO 10303-238 ed. 4

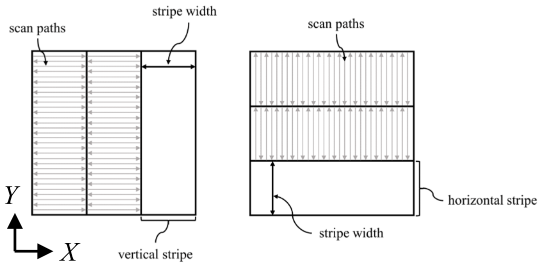


AM_scan_strategy

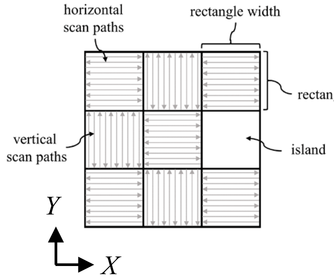
AM_technology (PBF-LB)

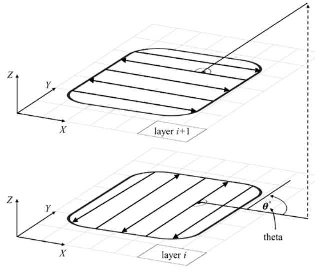


AM Stripe Strategy



AM Chess Strategy





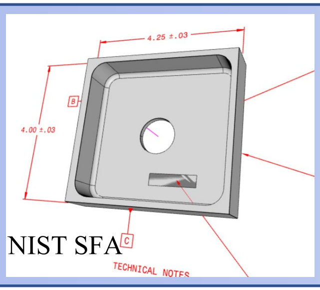
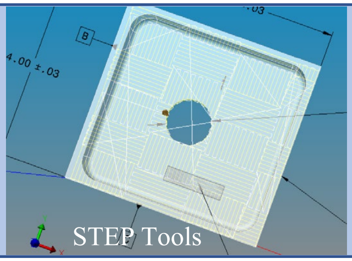
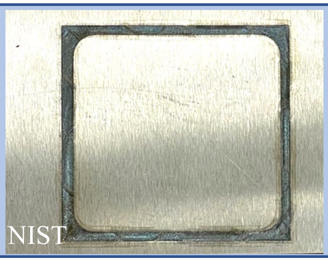
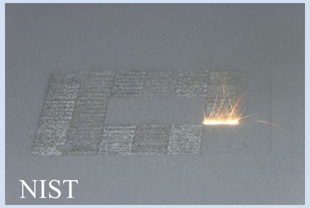
AM_threed_operation

Milaat, Witherell, Yeung et. al. : https://doi.org/10.1115/1.4055855
Milaat, Witherell, Yeung et. al. : https://doi.org/10.1115/DETC2022-90673

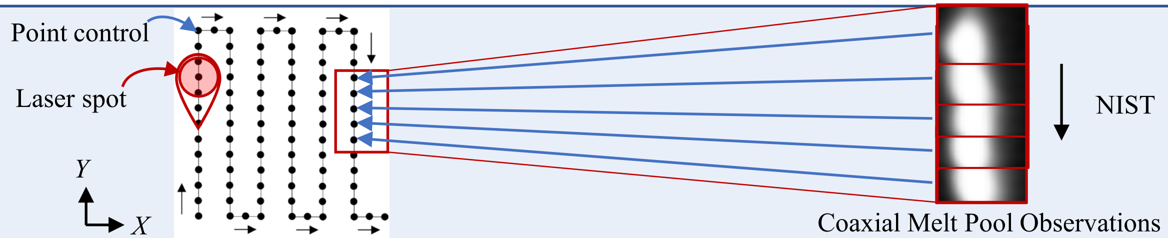
Approach: AM Discretization (PBF at Scale)

NIST ENGINEERING LABORATORY

Processing Discretization

	Specification	Observation
3D Orientation (X,Y,Z) Coordinates		
2D Sliced Layers, Scan Strategies		
1D Scan Paths, Contour		

0D
Time Stepped
Digital Command



Thinking Out Loud

NIST ENGINEERING LABORATORY

3D Geometry:
Full Part Representation
Sacrificial Geometry

3D to 2D:
Layer/Slice Discretization (Layer thickness)
Anchored Orientation
Interlayer rotation

2D to 3D

2D Geometry:
Layer geometry
Island Geometry

2D to 1D:
Scan Vector/Path
Infill Pattern, Interlayer rotation
Spot Size, Hatch Spacing
Pre/Post Contouring (Boundaries)
Layer to Island discretization strategy
List vs Bag- Order of Operations

1D to 2D

1D Geometry
Polyline Geometry
Island Geometry

1D to 0D
Sampling/Discretization Rate
Time Step
Start and Stop Times

0D to 1D

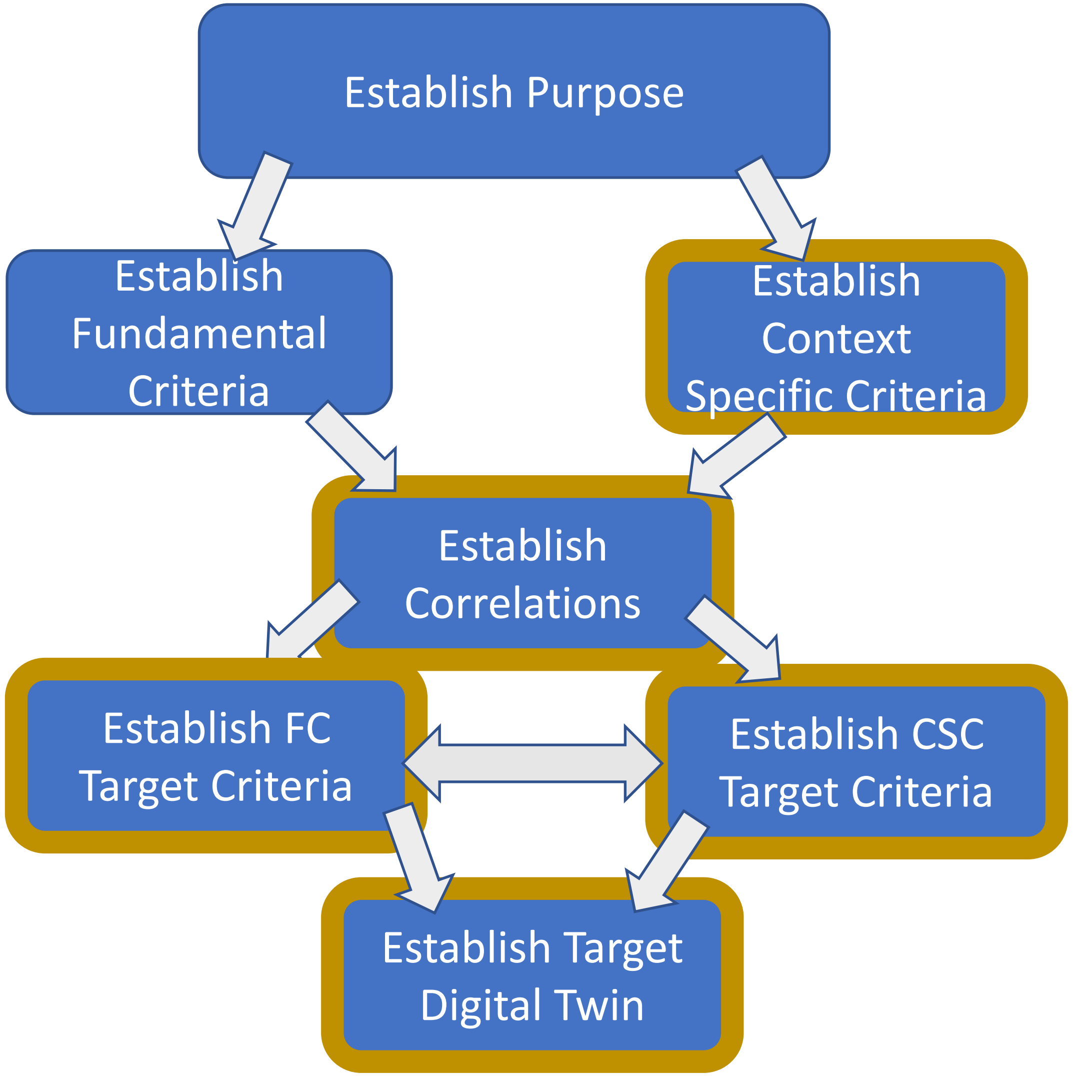
0D
Spatially Located Point

X

Final Thoughts

- Digital twins allow for assessing a part in virtual environment
  - Expected performance must be established
  - Target thresholds must be established
- Digital twins support compositionality in evaluation of parts
  - Crosslinks and reconciliation must be established
- Digital twins support analysis of reconfigured processes and designs
  - Data formats and platforms must be determined

Standards play a key role in realization



NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

Thank You!

Paul Witherell, PhD

Measurement Science for Additive Manufacturing Program

National Institute of Standards and Technology

October 25, 2023