Digital Twin Simulation for Manufacturing Processes

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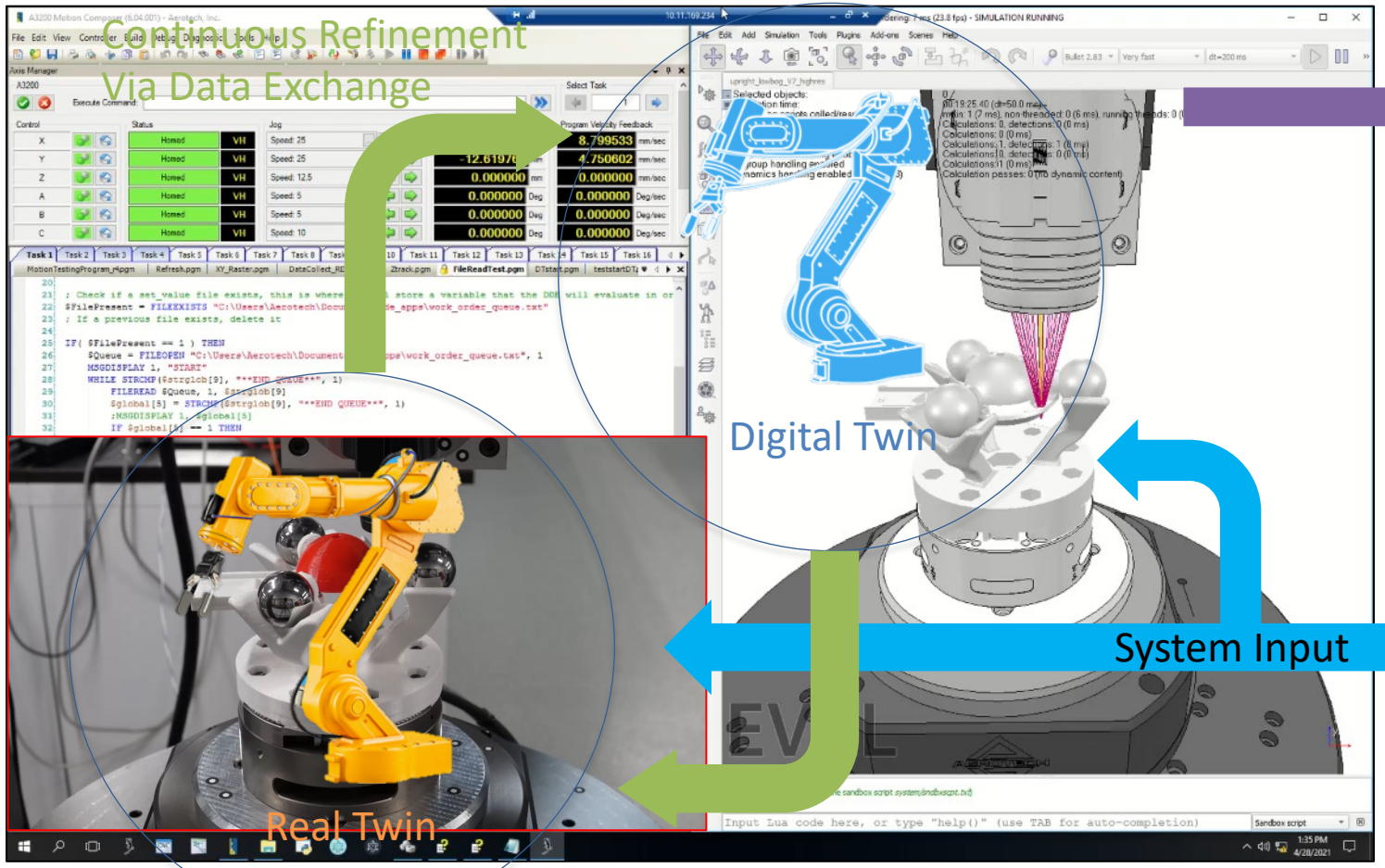
Our objective for digital twins is to replicate real manufacturing systems from command inputs through data stream outputs



Optimizations

A digital twin is the confluence of physics-based models, sensing, and advanced analytics:

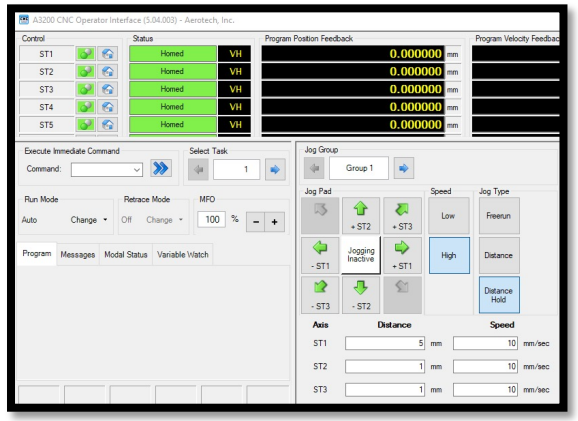
- Intrinsically evolves from *in-situ* and *ex-situ* data streams
- Replicates machine health and aging behavior, providing actionable insights on lifetime performance
- Reduces time, risk, and cost associated with process development and training

System Control:

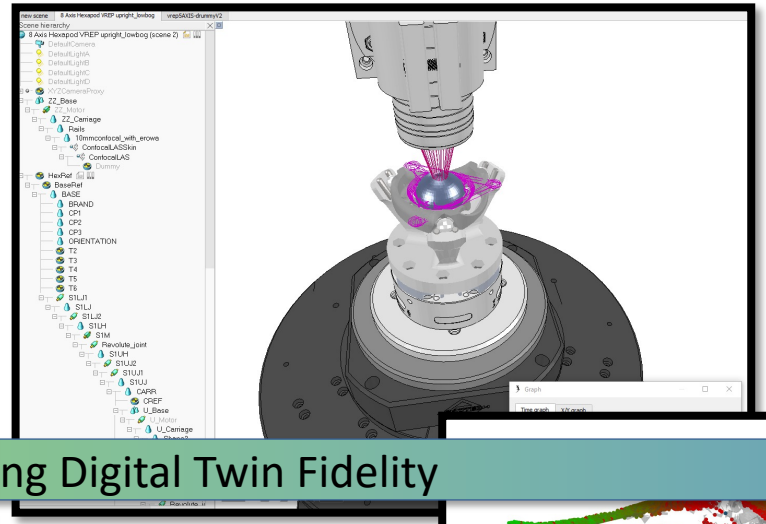
Digital twin is a living model that is continuously refined by data from its real-world counterpart

We are actively exploring numerous applications for Digital Twins for our DIW manufacturing systems.

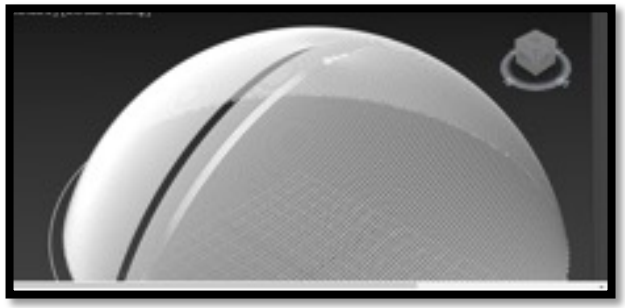
Operator Training



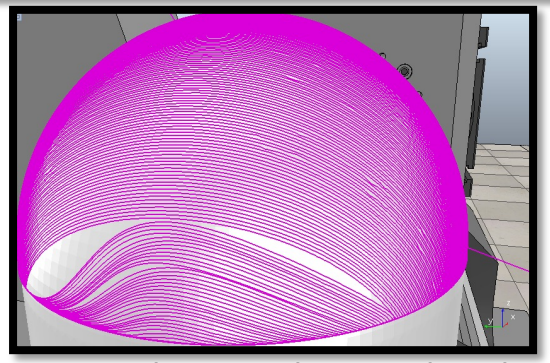
Virtual Fabrication and Metrology



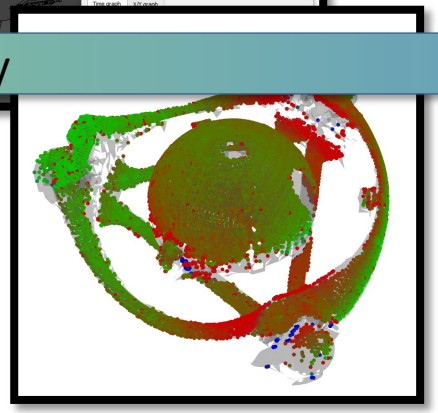
Creating simulated parts



Increasing Digital Twin Fidelity



De-risk complex toolpath



As Digital Twins evolve and improve, new use cases continue to arise and deliver value.

We are developing a modular approach, combining custom code from LLNL and commercially available tools

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G1 F2100 E-0.8
;LAYER_COUNT:183
;LAYER:0
M107
G0 F3600 X113.574 Y78.036 Z0.2
;TYPE:SKIRT
G1 F2100 E0
G1 F1800 X113.975 Y77.564 E0.0206
G1 X114.434 Y77.149 E0.04118
G1 X114.943 Y76.795 E0.0618
G1 X115.493 Y76.511 E0.08239
G1 X115.989 Y76.325 E0.10001
G1 X116.402 Y76.196 E0.1144
G1 X116.543 Y76.155 E0.11928
G1 X117.389 Y75.919 E0.1485
G1 X117.6 Y75.865 E0.15574
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G1 X118.824 Y75.585 E0.1975
G1 X119.653 Y75.42
G1 X119.819 Y75.39
G1 X120.604 Y75.26
G1 X120.763 Y75.24
G1 X121.81 Y75.115
G1 X121.974 Y75.09
G1 X122.583 Y75.04
G1 X122.739 Y75.03
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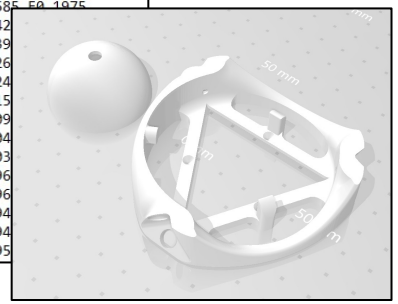

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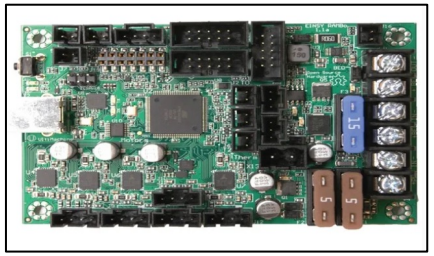
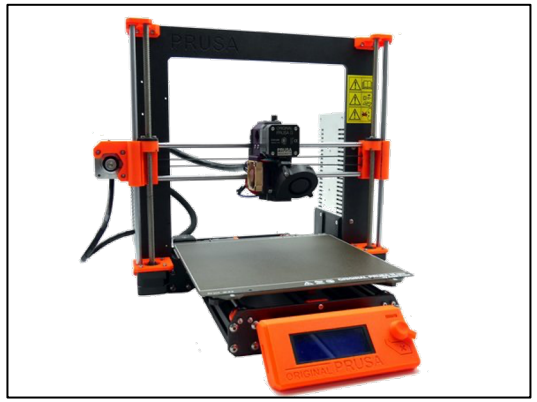
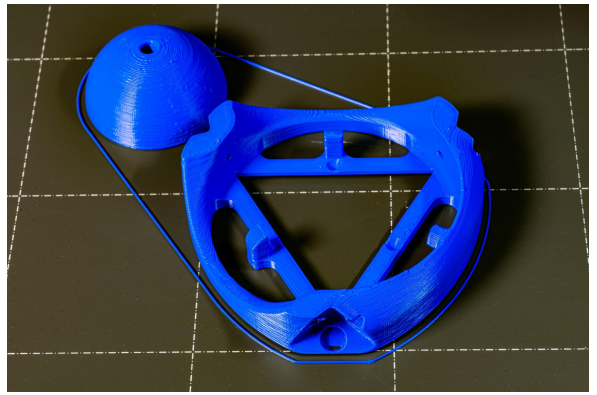
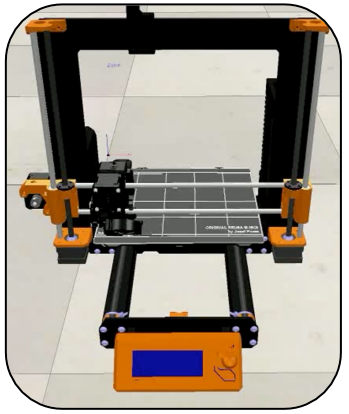


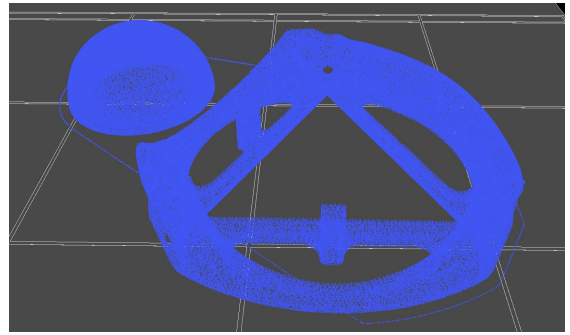




Firmware → Printer → Real Part

Virtual Firmware → Virtual Printer → Virtual Part





'Real' toolpath, executed on a Digital Twin of a fabrication system, produces a Digital Part

Leveraging Digital Twin Fabrication Data to Create 3D Representations of Components

Digital Twin Machine Encoder Data

```
Time X Y Z Extruder BedTemp ExtruderTemp
1605632472.1960719 -79.99905626667015 -129.998466433339 0.0 0.0 60.0 215.0
1605632472.2329726 -78.4832378714949 -130.01540295172083 0.0 0.0 60.0 215.0
1605632472.2828386 -76.48872392222567 -130.0376880237797 0.0 0.0 60.0 215.0
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1605632472.3825727 -72.4996101983558 -130.08225912683972 0.0 0.0 60.0 215.0
1605632472.4334357 -70.465216078418 -130.10498978739767 0.0 0.0 60.0 215.0
1605632472.4833028 -68.47065444840909 -130.12727539220225 0.0 0.0 60.0 215.0
1605632472.5332034 -66.51456163917422 -130.14913117778028 0.0 0.0 60.0 215.0
1605632472.583038 -64.48149304379953 -130.17184702800793 0.0 0.0 60.0 215.0
1605632472.6329024 -62.48704584756587 -130.19413135422283 0.0 0.0 60.0 215.0
1605632472.6827688 -60.49251282600076 -130.21641663938 0.0 0.0 60.0 215.0
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1605632472.7825017 -56.50344678287057 -130.2609872096943 0.0 0.0 60.0 215.0
1605632472.833366 -54.46900498219309 -130.28371840299795 0.0 0.0 60.0 215.0
1605632472.8832347 -52.474376599148634 -130.3060047536465 0.0 0.0 60.0 215.0
1605632472.9330988 -50.47993893906289 -130.32828897331225 0.0 0.0 60.0 215.0
1605632472.982968 -48.48529148372256 -130.3505755370591 0.0 0.0 60.0 215.0
1605632473.0328317 -46.4908728959327 -130.37285954362656 0.0 0.0 60.0 215.0
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1605632473.2831645 -36.47818457521959 -130.48473315614848 0.0 0.0 60.0 215.0
1605632473.3330314 -34.483632481358626 -130.50701865440394 0.0 0.0 60.0 215.0
1605632473.3828945 -32.48923296586463 -130.52930244787314 0.0 0.0 60.0 215.0
1605632473.4327617 -30.494671335855728 -130.5515880526777 0.0 0.0 60.0 215.0
1605632473.482632 -28.49998573592365 -130.57387504262107 0.0 0.0 60.0 215.0
```
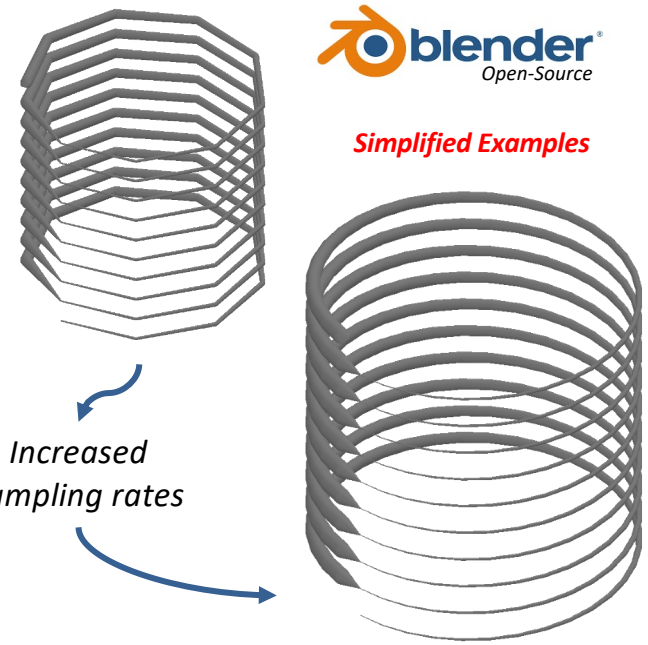

X, Y, Z, Extruder, *+ more*

Extract Point Cloud and Extruder Values from Encoder Data

-

These values provide enough information to create a 3D as-built reconstruction.



Create 3D Reconstruction with Creation Software

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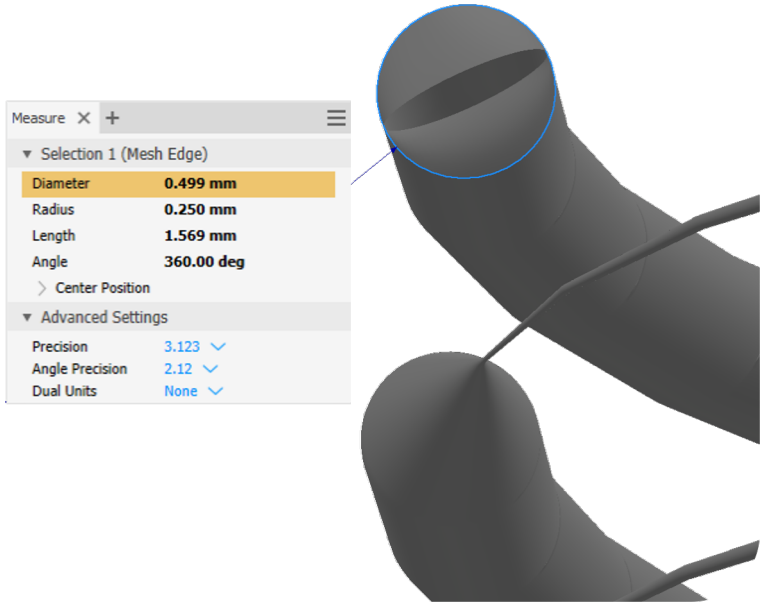
*Fused deposition modeling 'FDM' parts are reconstructed with a **spline** and **diameter** derived from DT data to represent extruded filament.**



Measure the Diameter at Specified Location or Specific Point

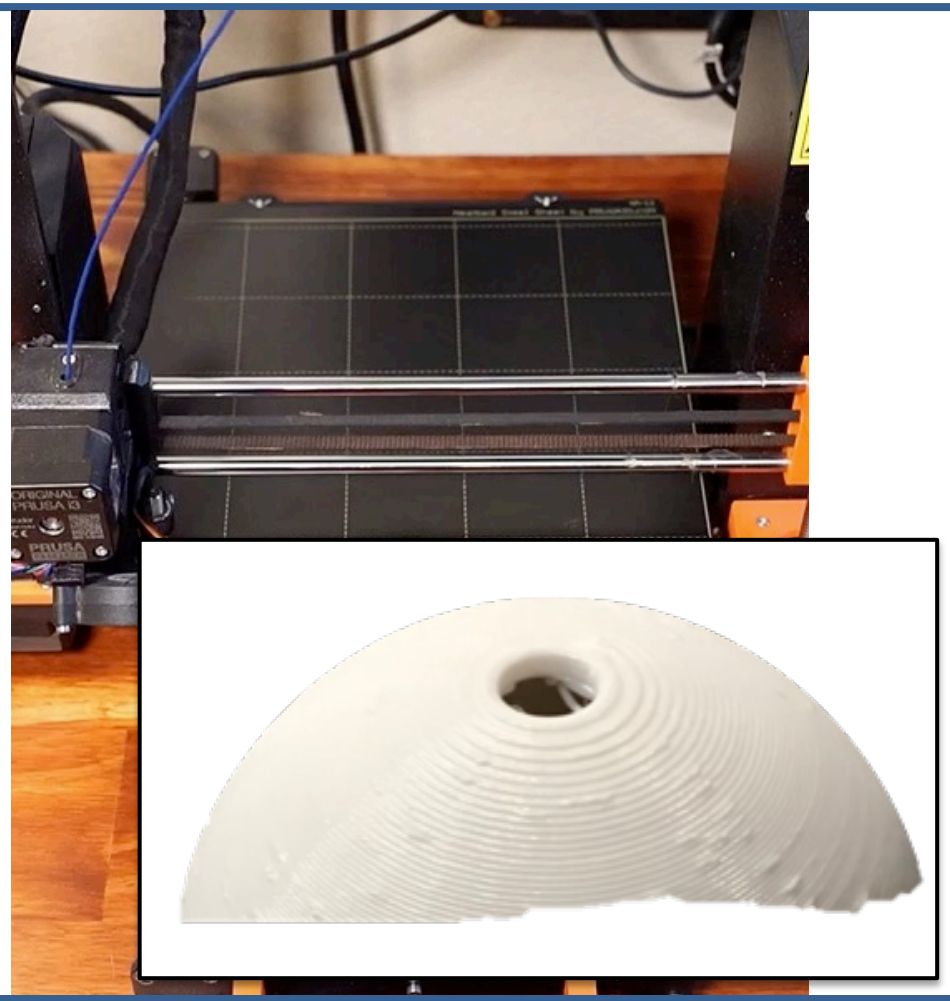
-

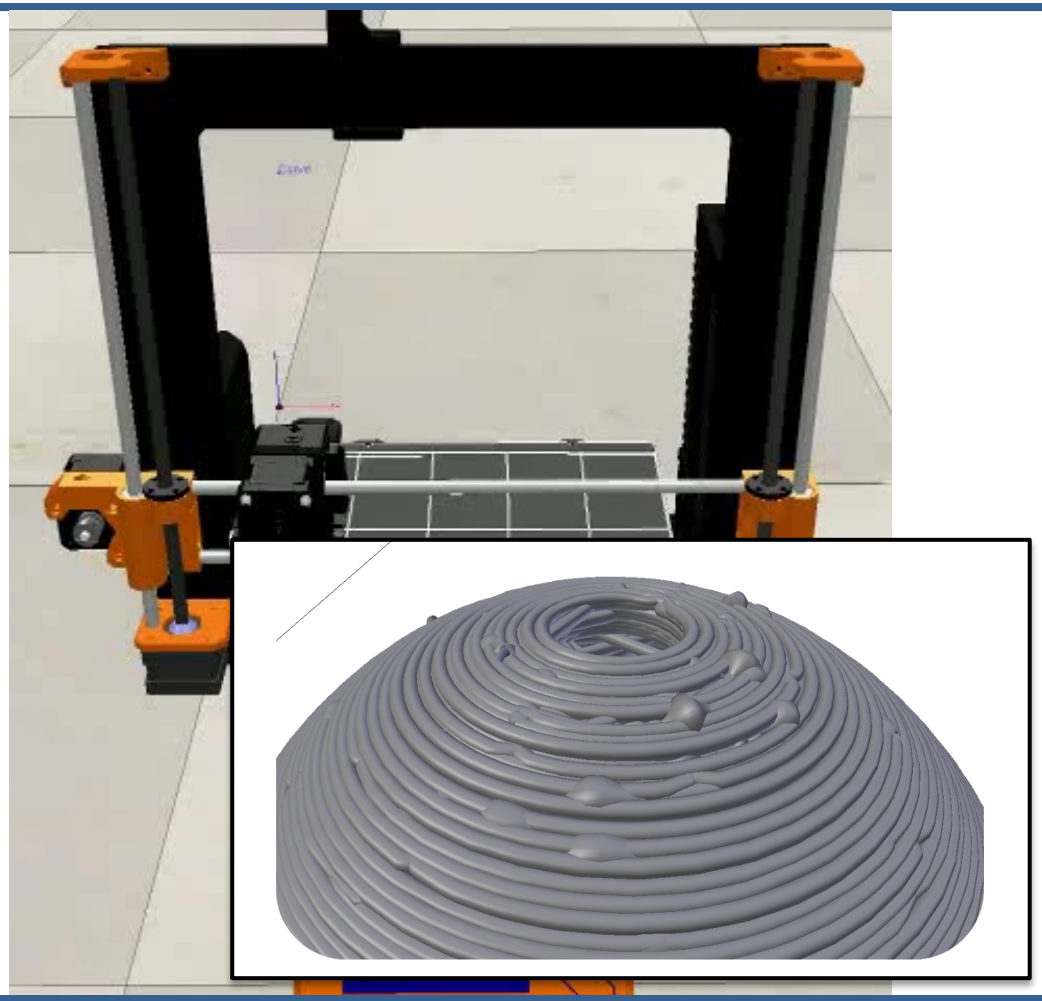
Confirm the diameter is correctly dimensioned in a standard CAD package to validate reconstruction process.

*Additional effort is being routed to more accurately model extruded filament.

DT manufacturing can predict as-built components, inform process improvement, and signal approaching errors.

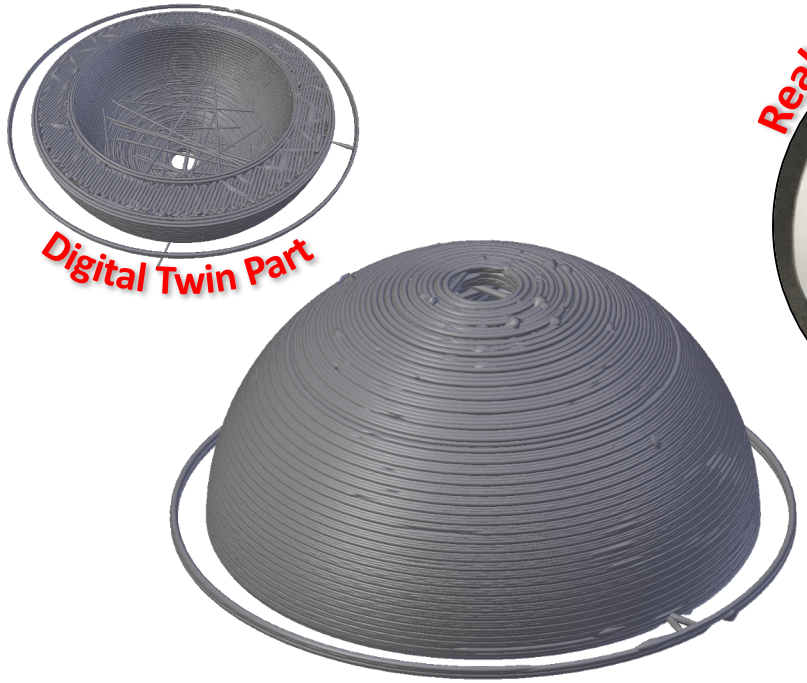
Early-stage digital twins already provide insights into fabrication processes.



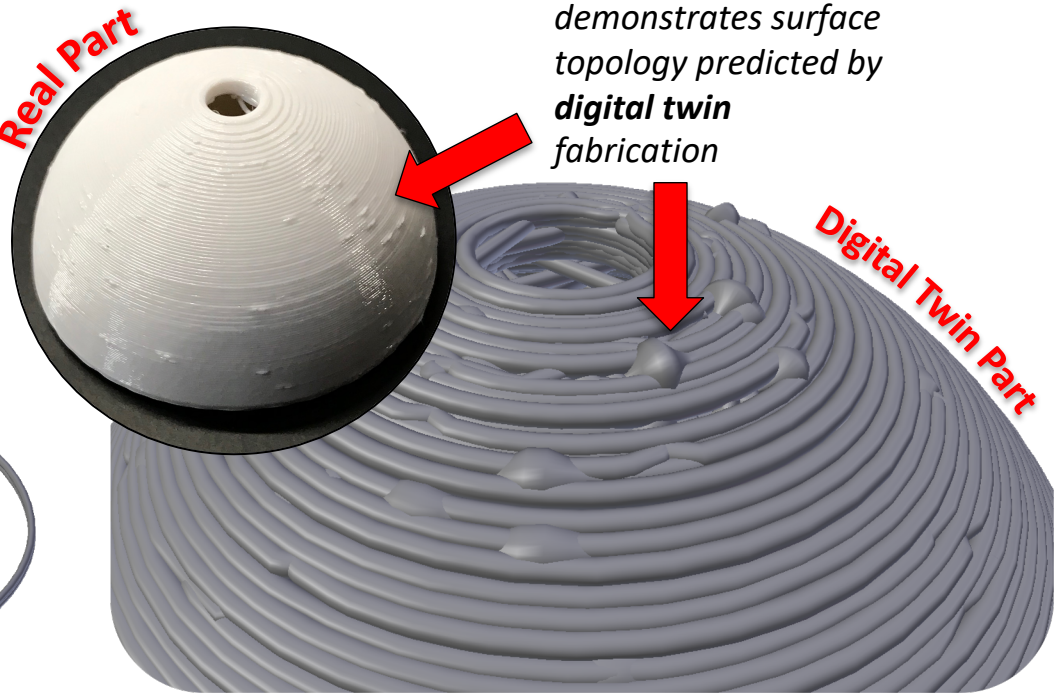


Digital twin fabrication provides an ‘offline’ method to *rapidly improve* the manufacturing process.

3D Representation Predicts Real Component

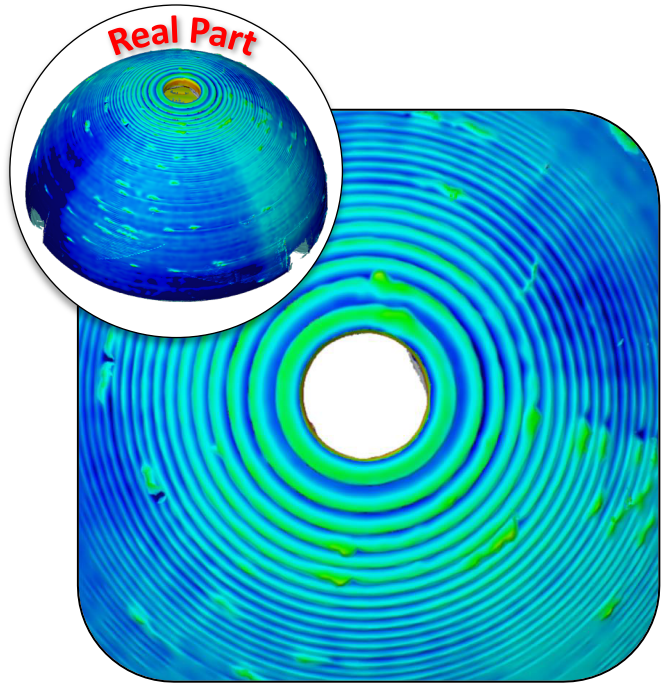


3D Representation of As-Built AM Component



Real *component demonstrates surface topology predicted by* ***digital twin*** *fabrication*

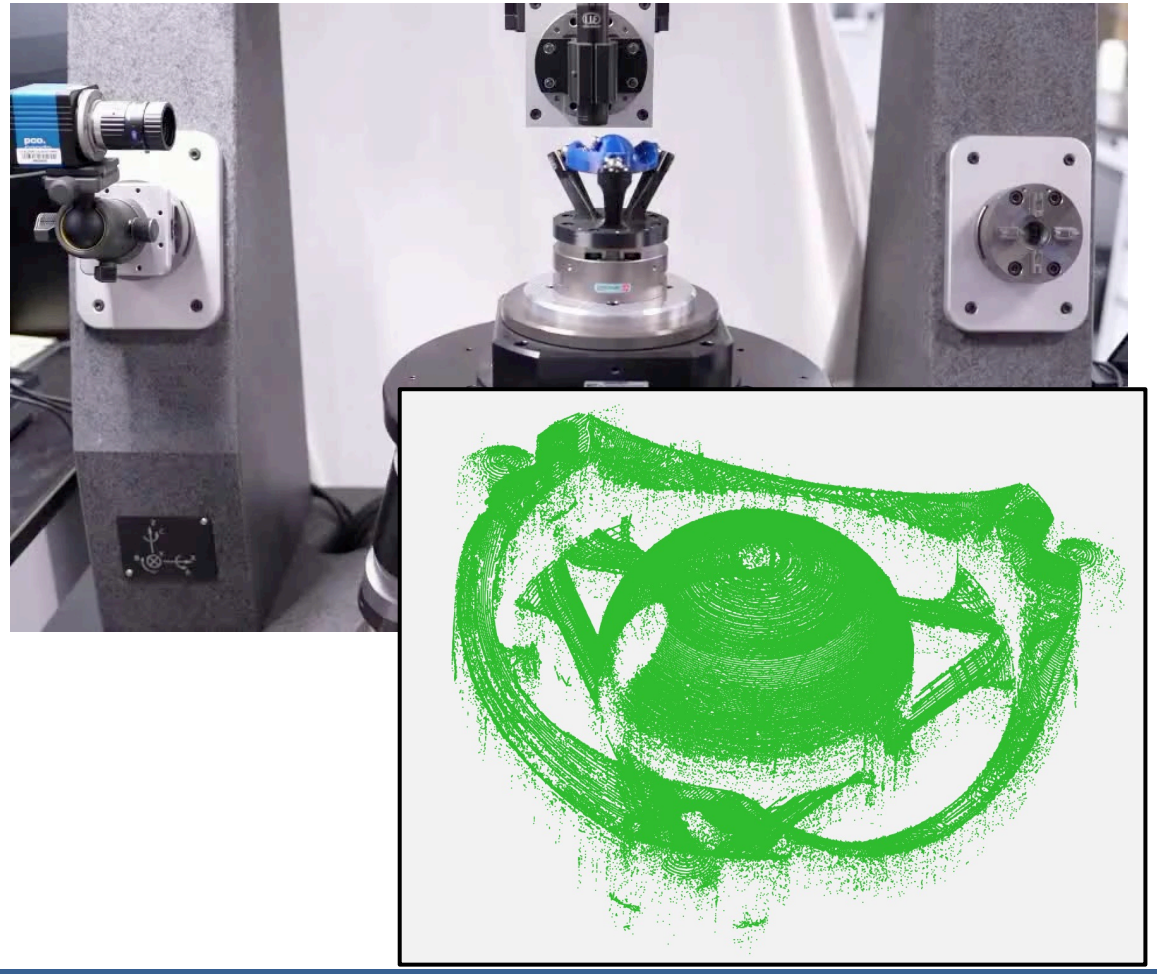
Capture Fine Details and the Nuances of the Manufacturing Process

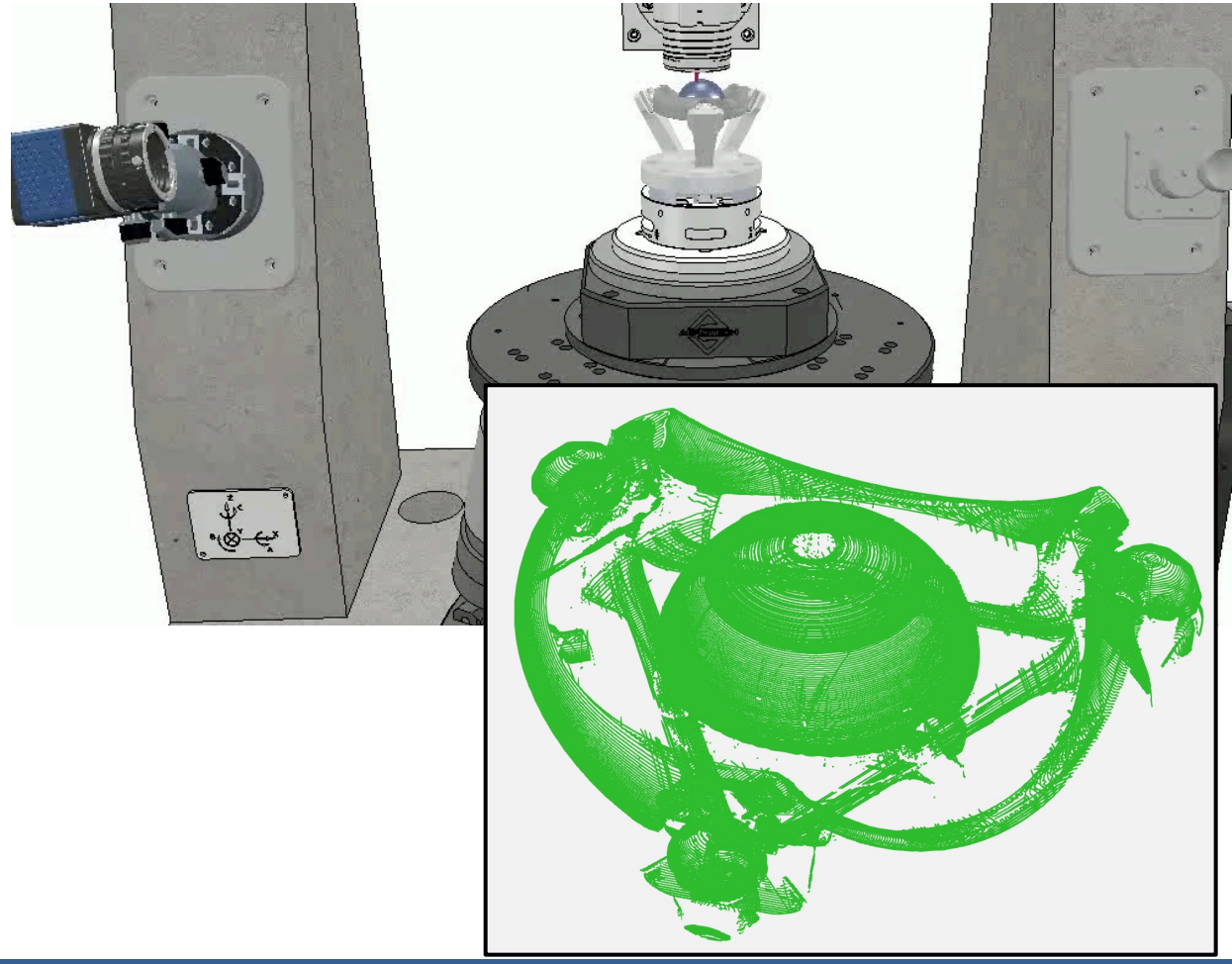


Metrology Data Quantifies the Deviations from Nominal

Digital twin fabrication provides an 'offline' method to *rapidly improve* the manufacturing process.

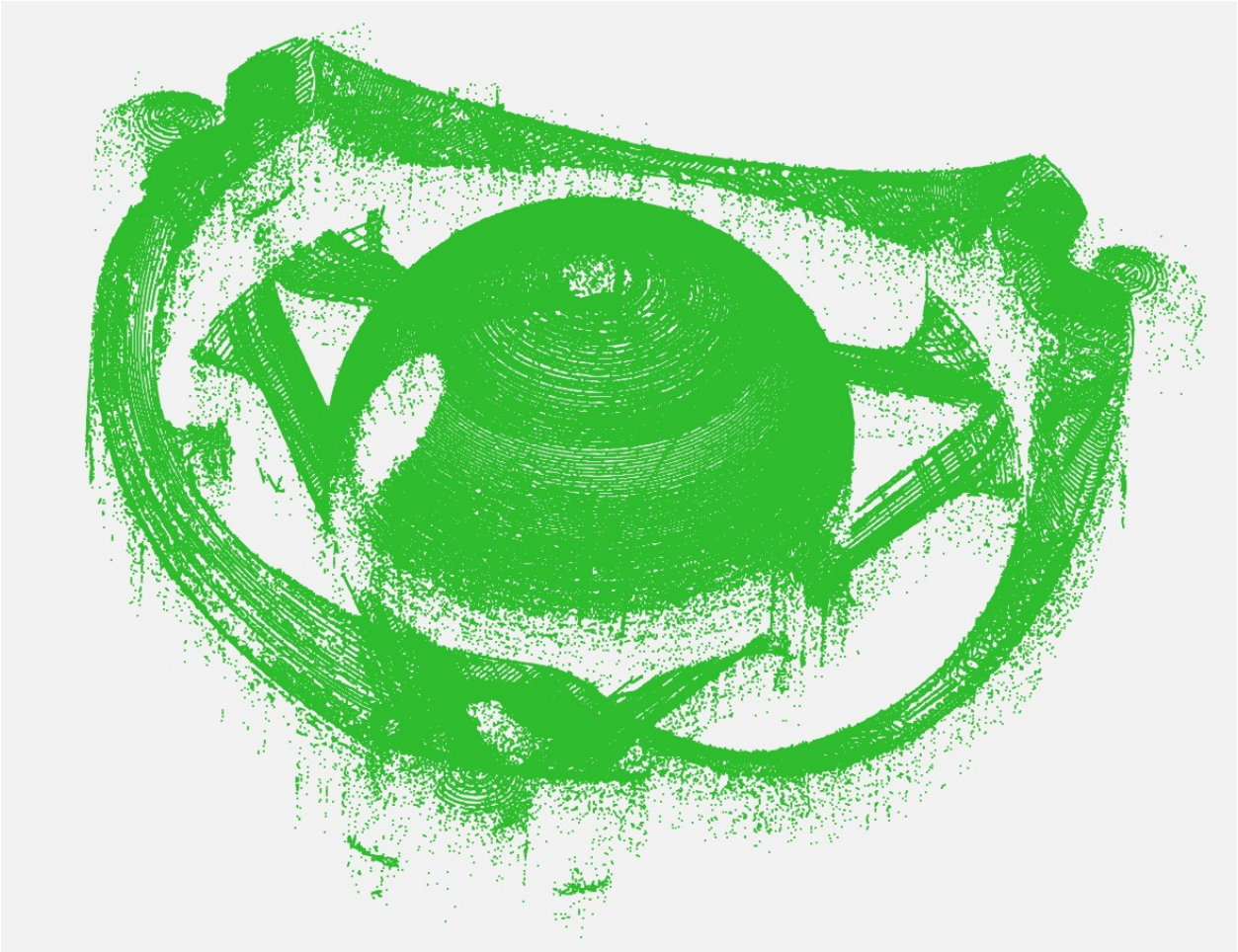
Digital twins for inspection:
RT/DT metrology toolpaths & sensor data are structurally identical

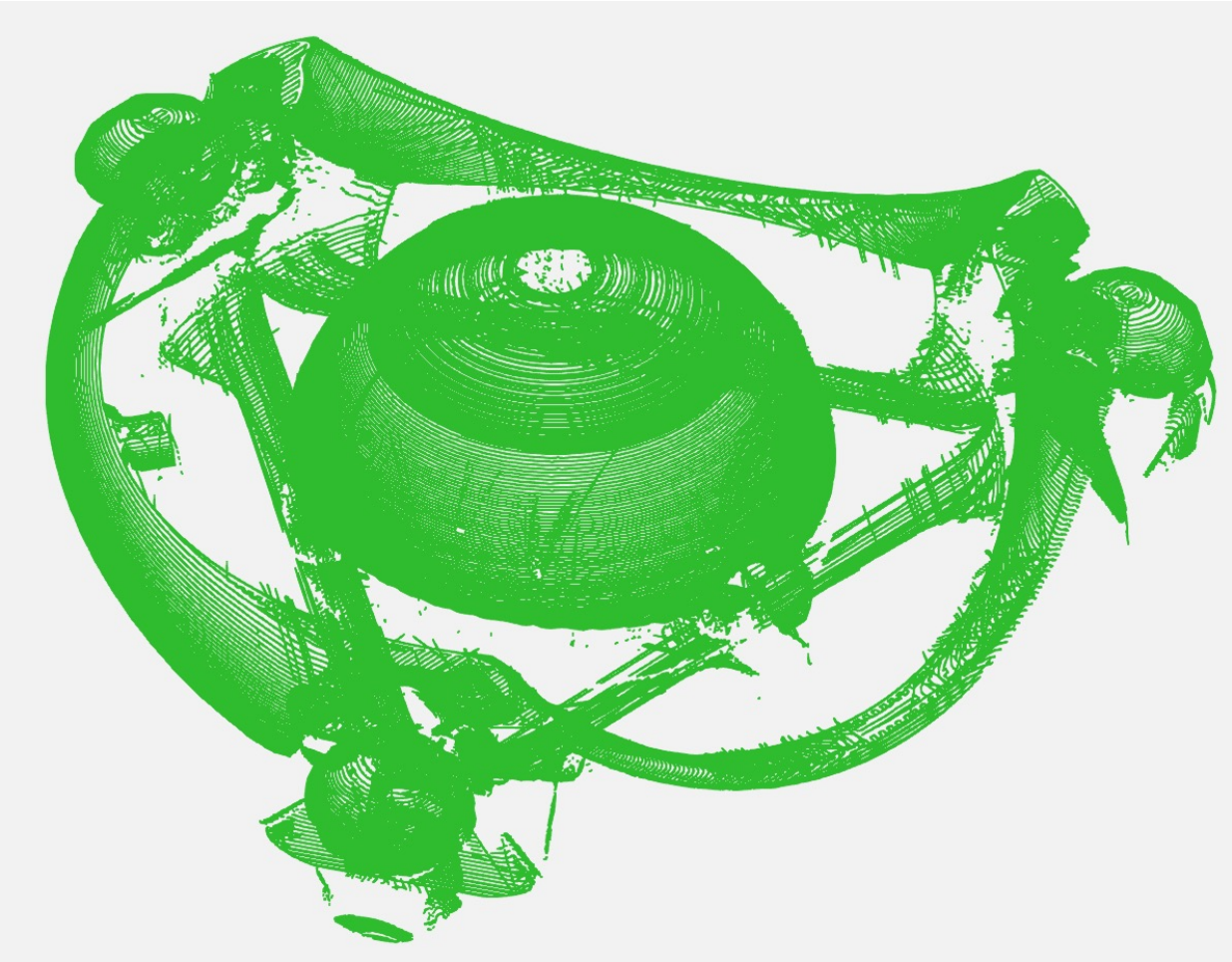




Next generation digital twins that mimic real world uncertainties will be used to optimize inspection speed and data quality

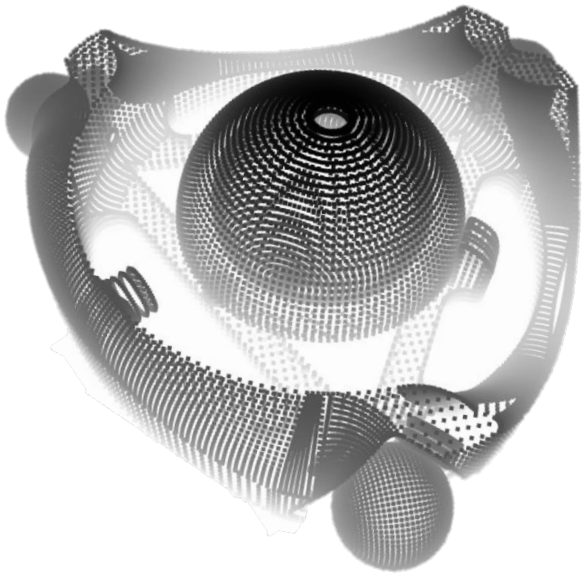
To define DTs of tools that reflect their RT counterparts, we need methods to characterize and compensate them relative to each other



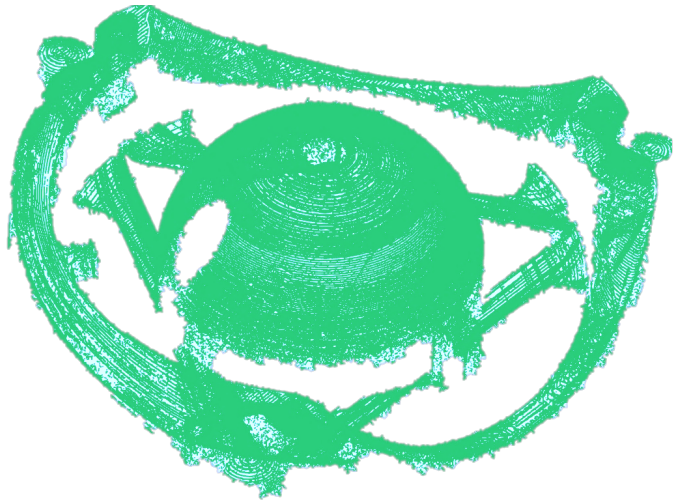


How can we leverage various datasets to improve process and part characterization?

Nominal Part

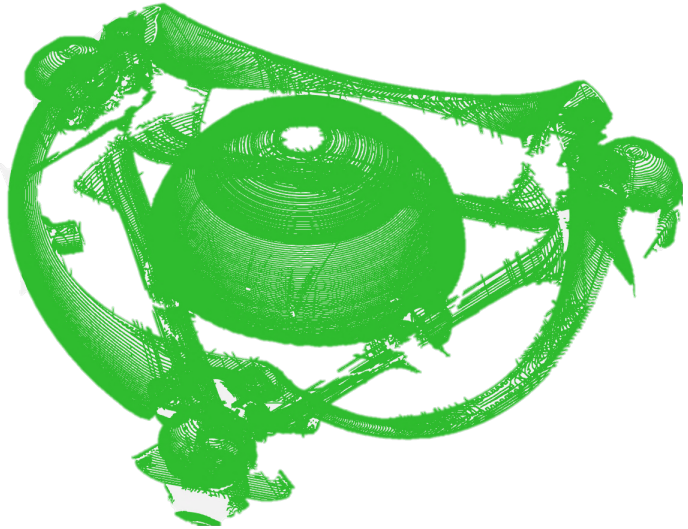


Real Twin Data



Characterization of system and sensing modalities to **reduce** uncertainty of resulting data

Digital Twin Data



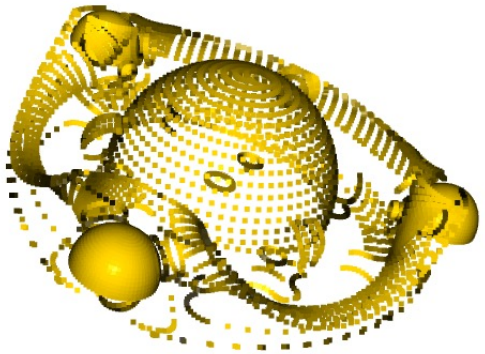
Characterization of system and sensing modalities to **introduce** uncertainty to resulting data

Comparing these data sets first requires registering against the nominal part

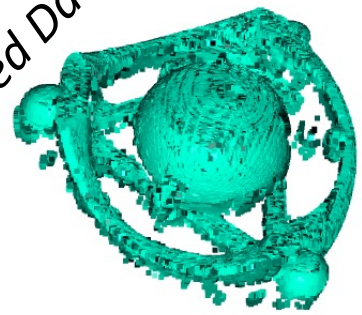
Robust registration pipeline that aligns pairs of point clouds

Before Registration

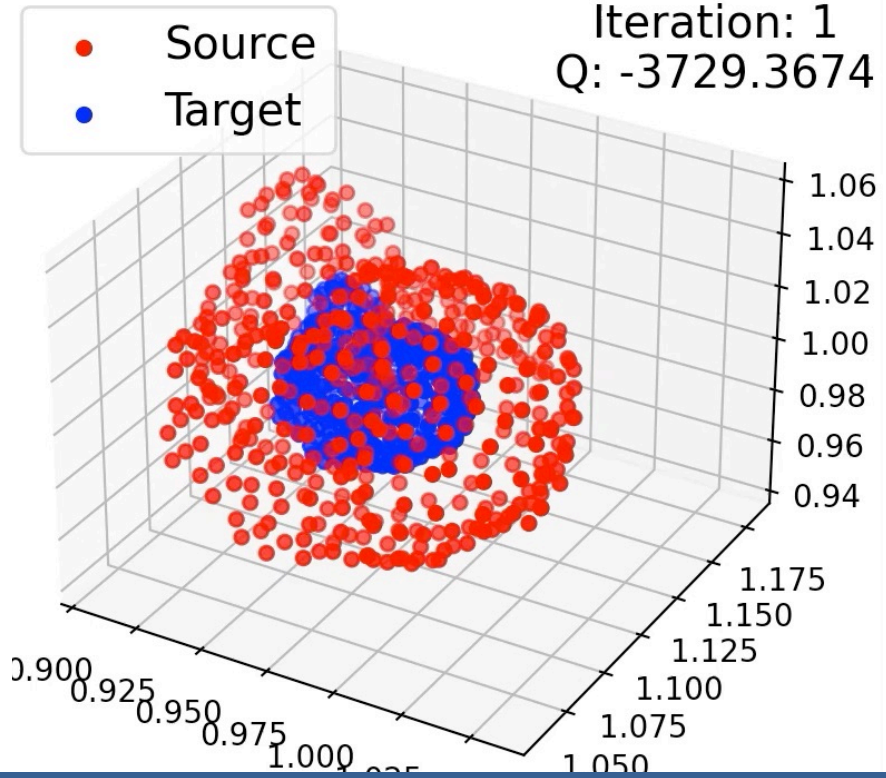
Nominal



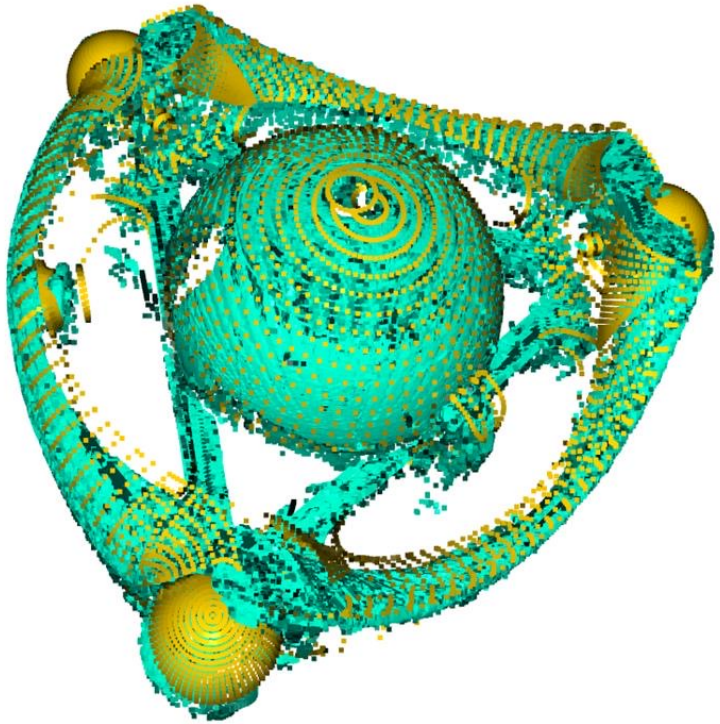
Collected Data



Rigid body rotation module that operates on two arbitrary point clouds



After Registration

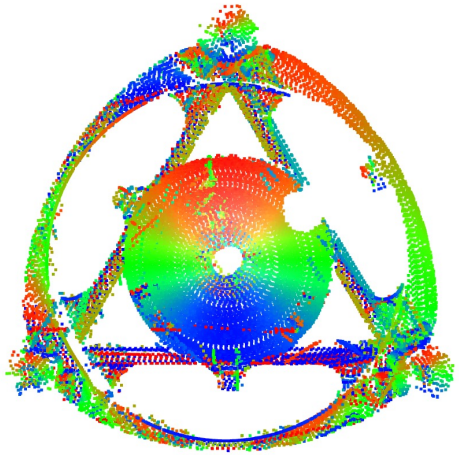


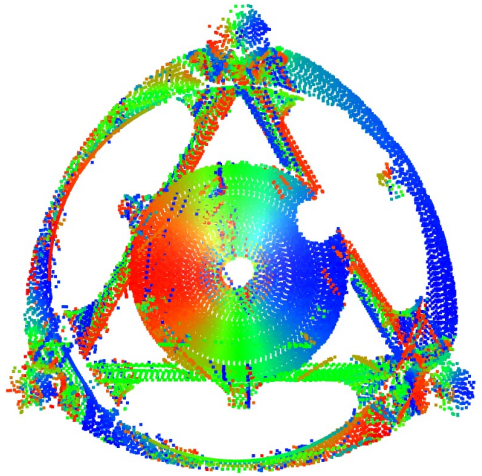
Registered clouds in same

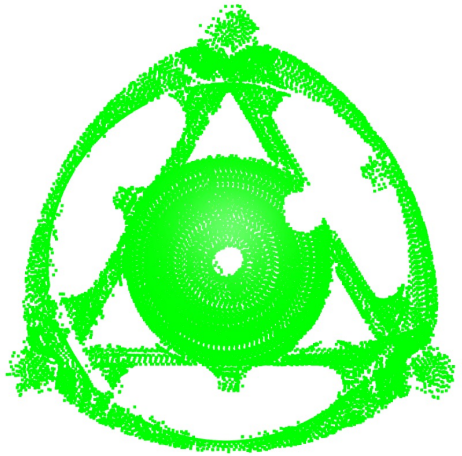
Dataset pairs can be readily compared after registration

Our data structure encompasses everything about confocal scan measurements in a general way

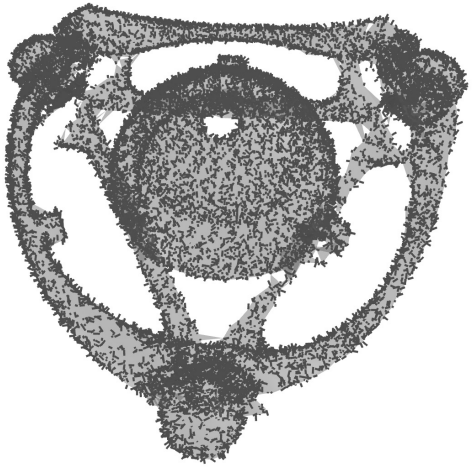
Real Twin







Surface normal field

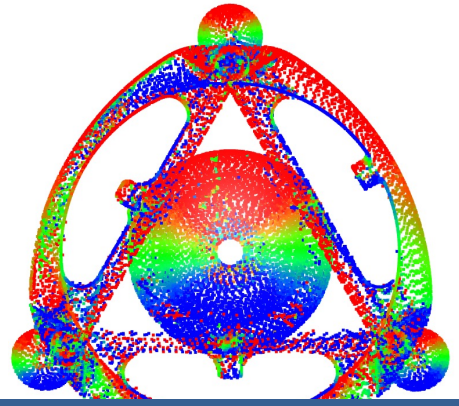


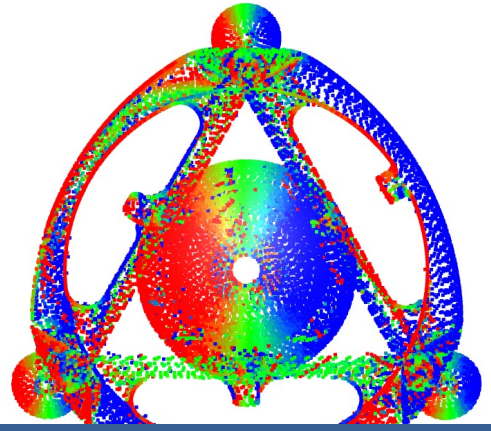
Horizontal sensor velocity, V_x

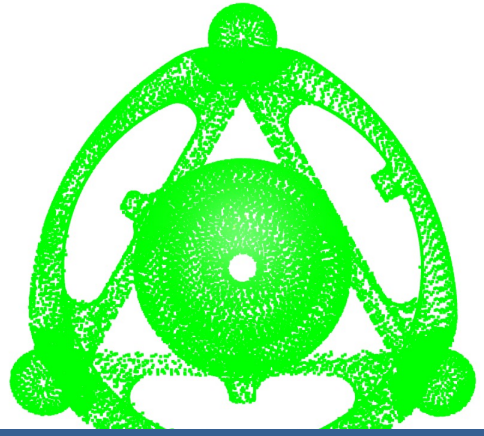
V_y

V_z

Digital Twin

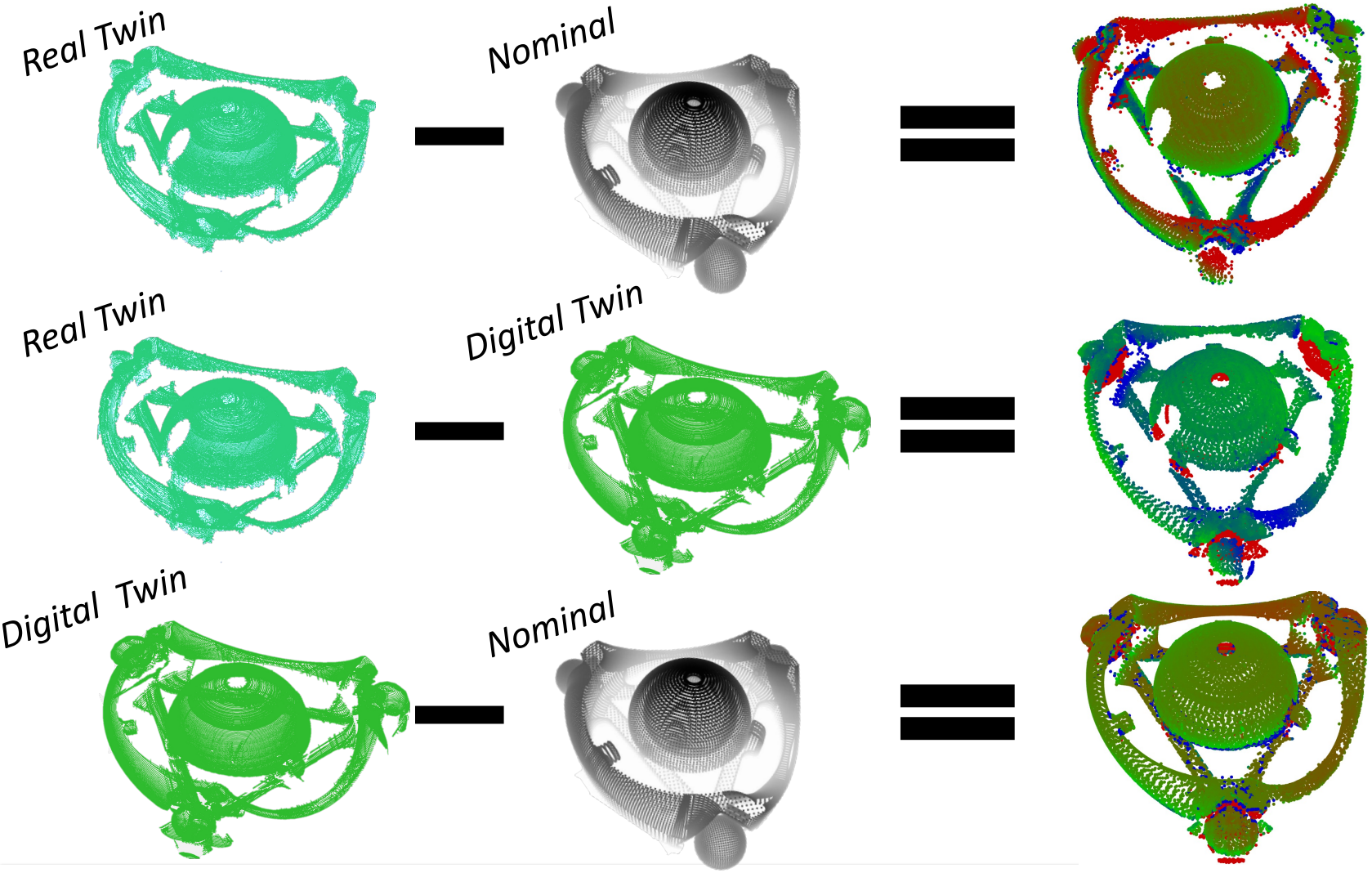






We capture several key parameters that impact Chromatic Confocal measurement fidelity

Point cloud comparisons are key to part and process characterization, digital twin refinement, and process optimization



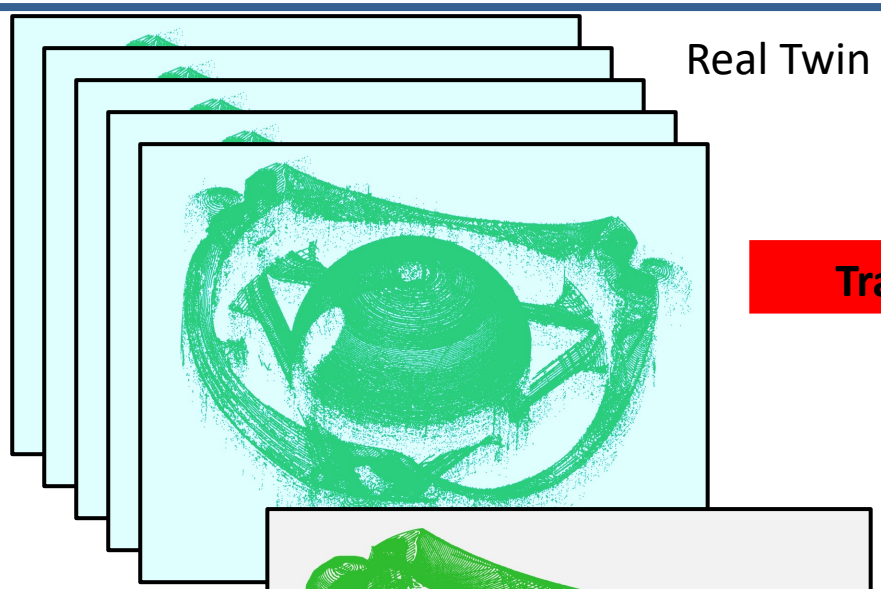
This represents the actual measurement.

If Real – Digital = 0, digital twin is perfect
If Real – Digital ≠ 0, we want to leverage real data to improve digital twin

This represents the virtual measurement.

This comparison is useful when evaluating various fabrication-inspection in a virtual environment **when DT is accurate**

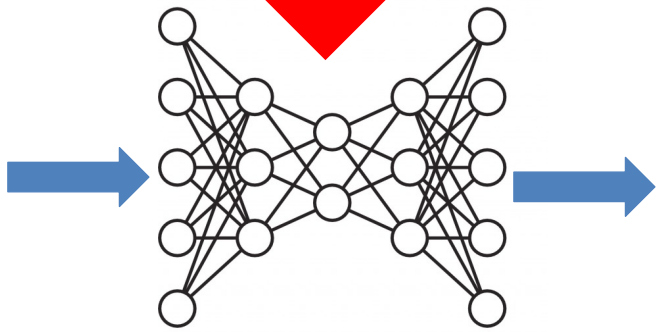
Rapid training of digital twins via integrated corrective ML layer



Real Twin Data

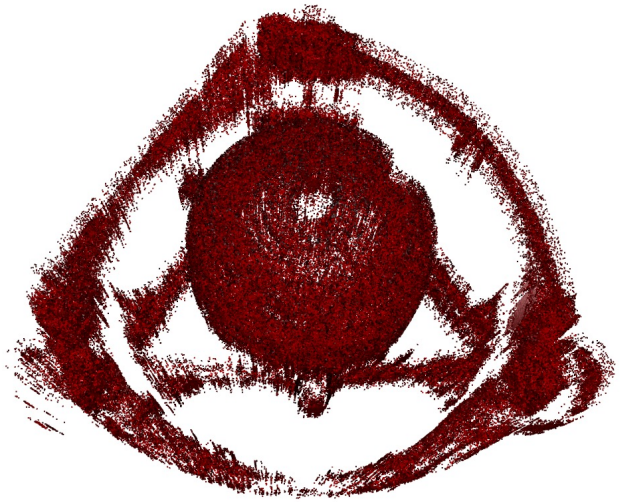
Digital Twin Data

Train on RT Data



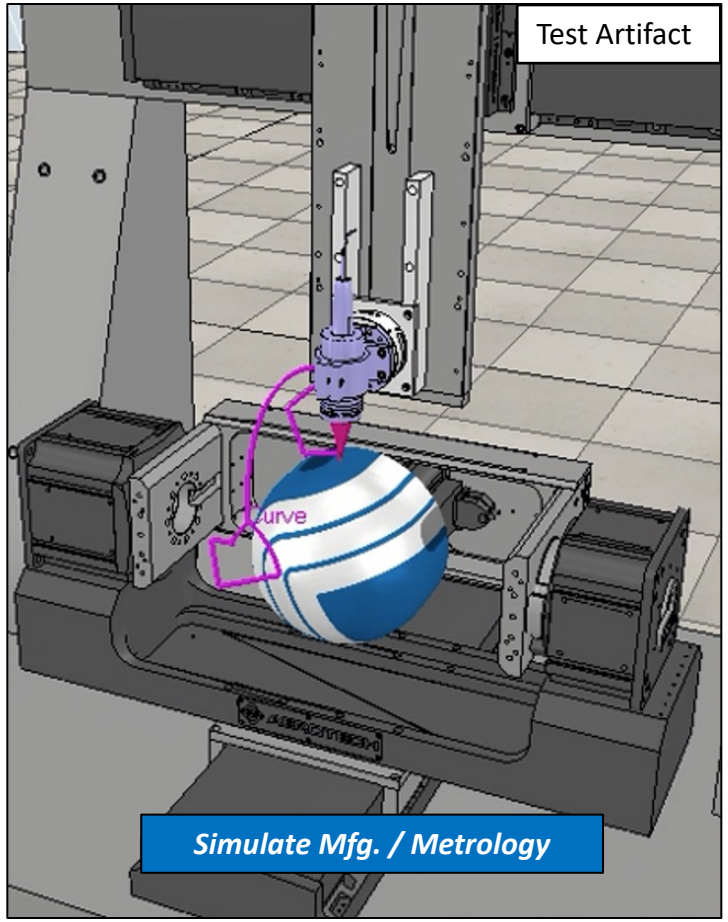
ML layer provides
real-time compensation

Revamped Digital Twin Data

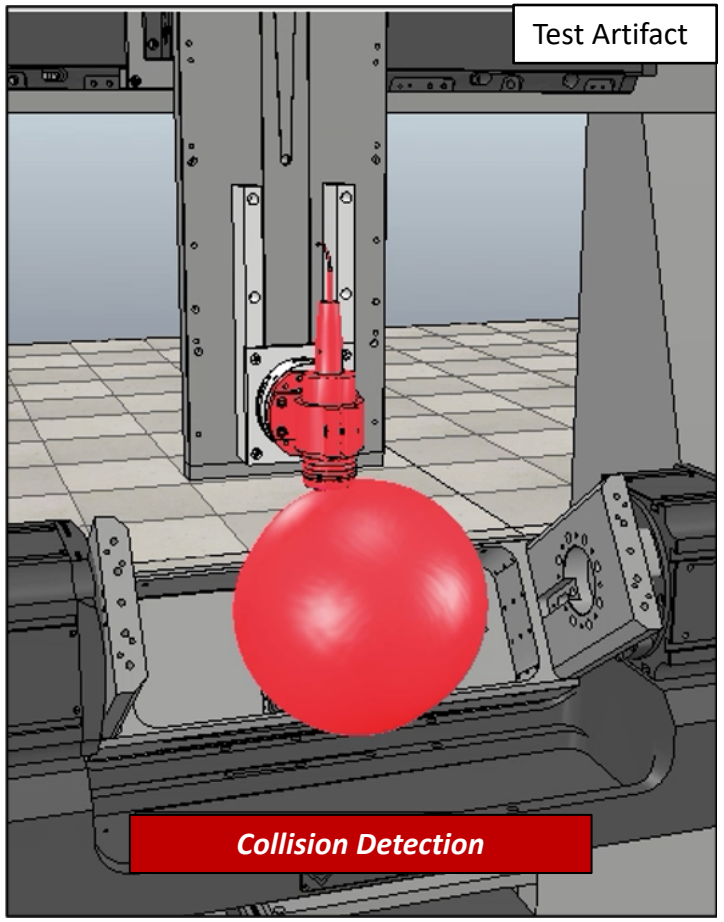


Accelerated AI-enabled digital twin development for performance optimization

Digital twins have already found direct applications for speeding process development and reducing risk at LLNL

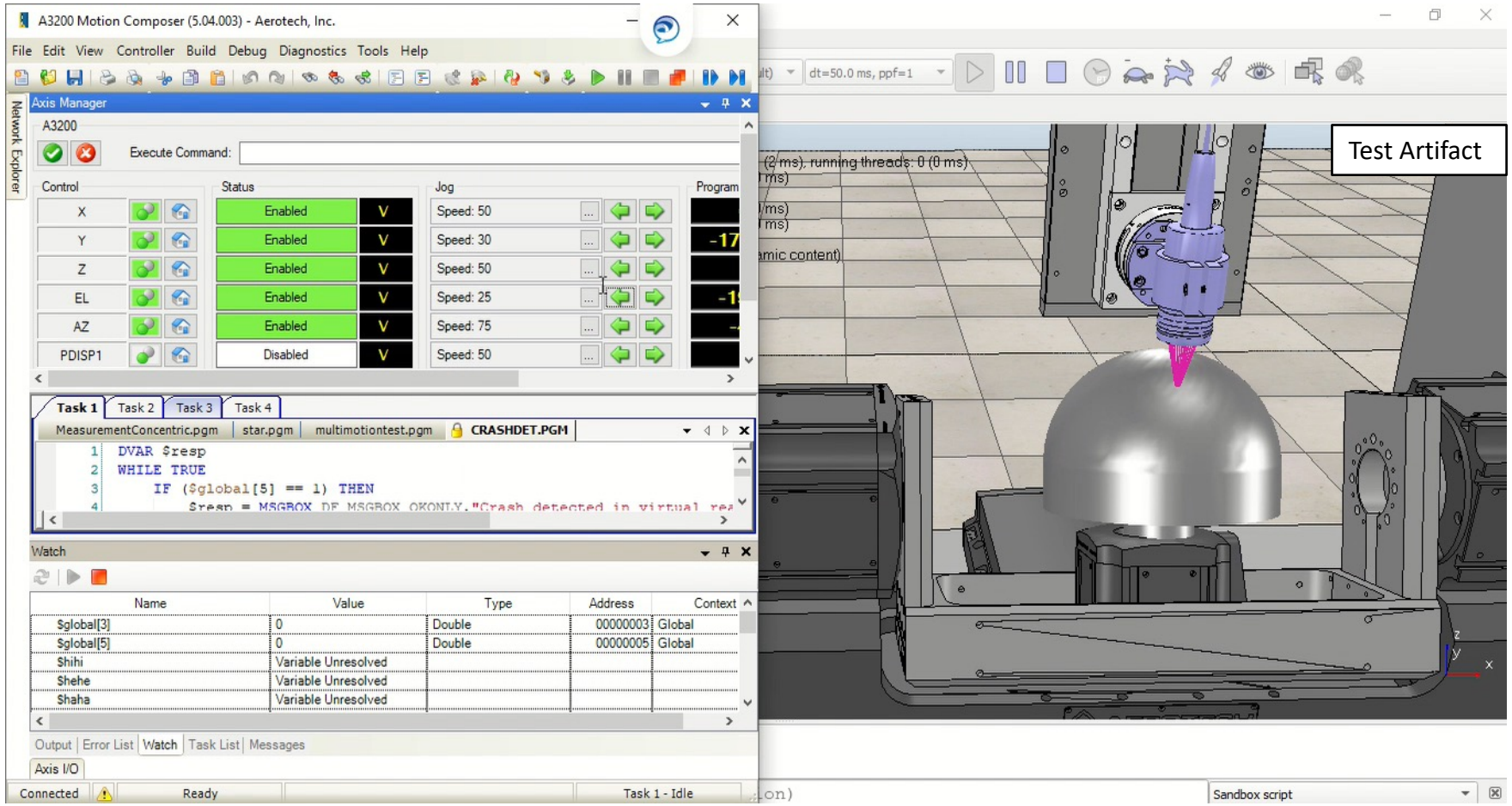


- Validate metrology routines
- Develop tool paths without risk to high-value components
- Research and development efforts can be performed offline and remotely
- Serves as a learning platform for new and experienced employees



Digital twins will make our enterprise more agile, enabling process optimization while minimizing machine downtime.

Crash detection capabilities in digital twin

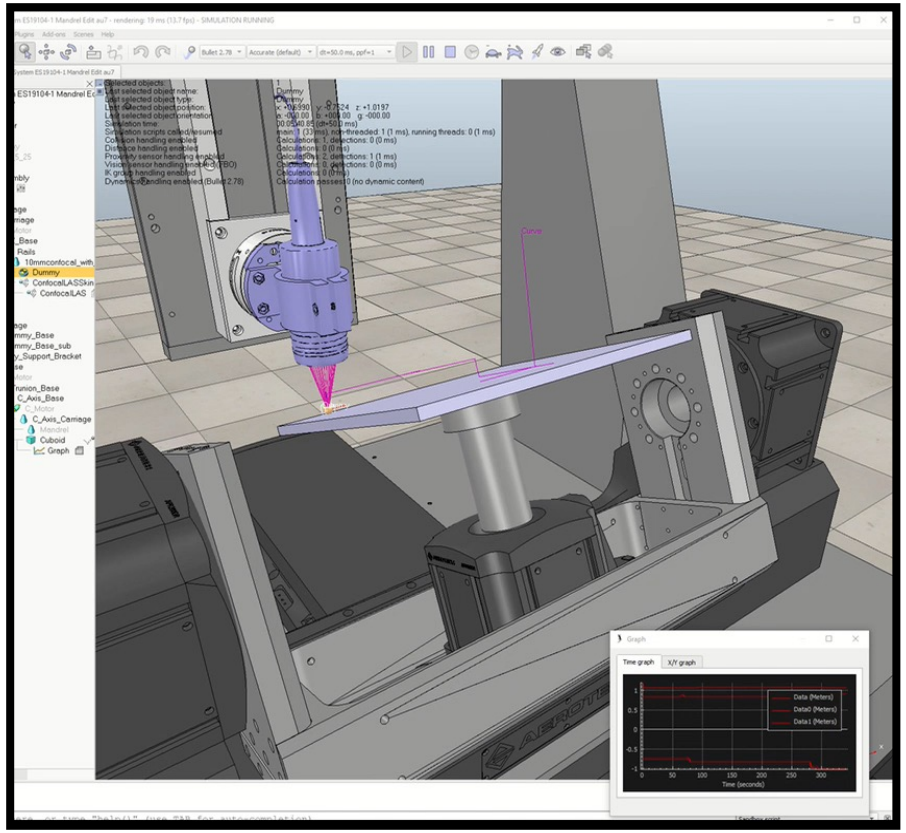


Digital twins create low risk environment for program validation and new hire training.

Debugging complex multi-axis systems in a risk free, simulated environment in order to speed up development

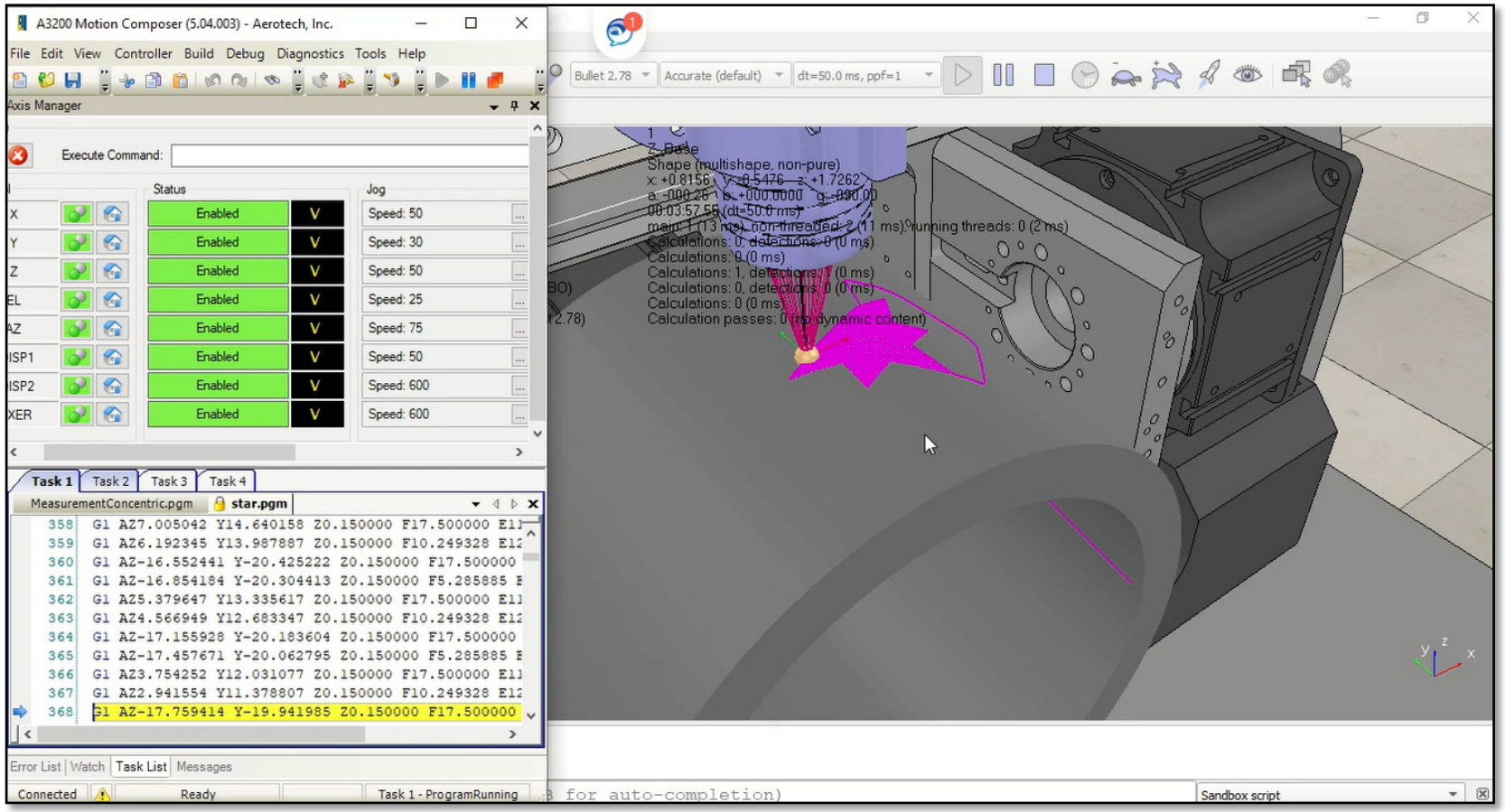
Input Commands

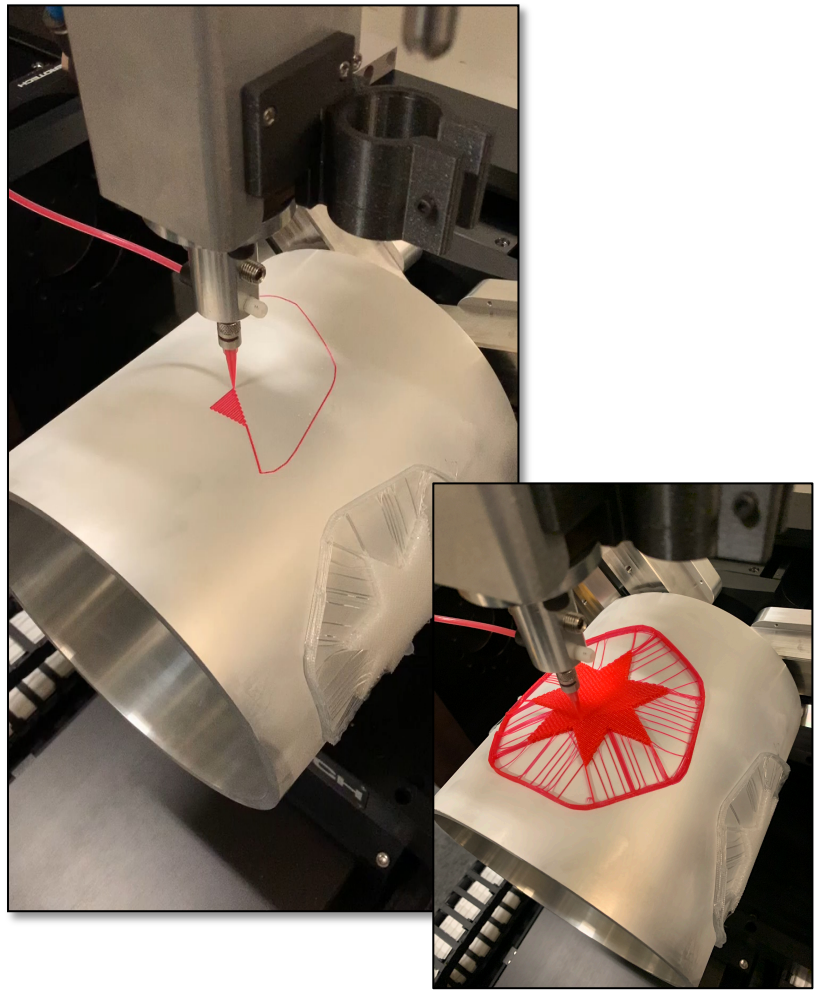
Virtual



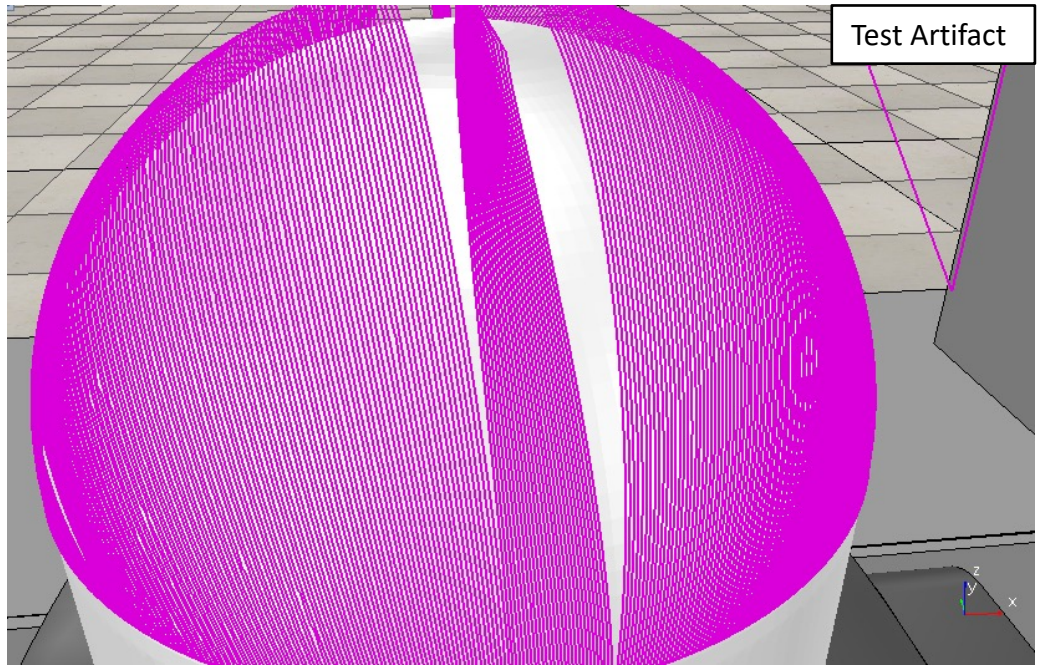
Real

Simulating multi-axis additive manufacturing process

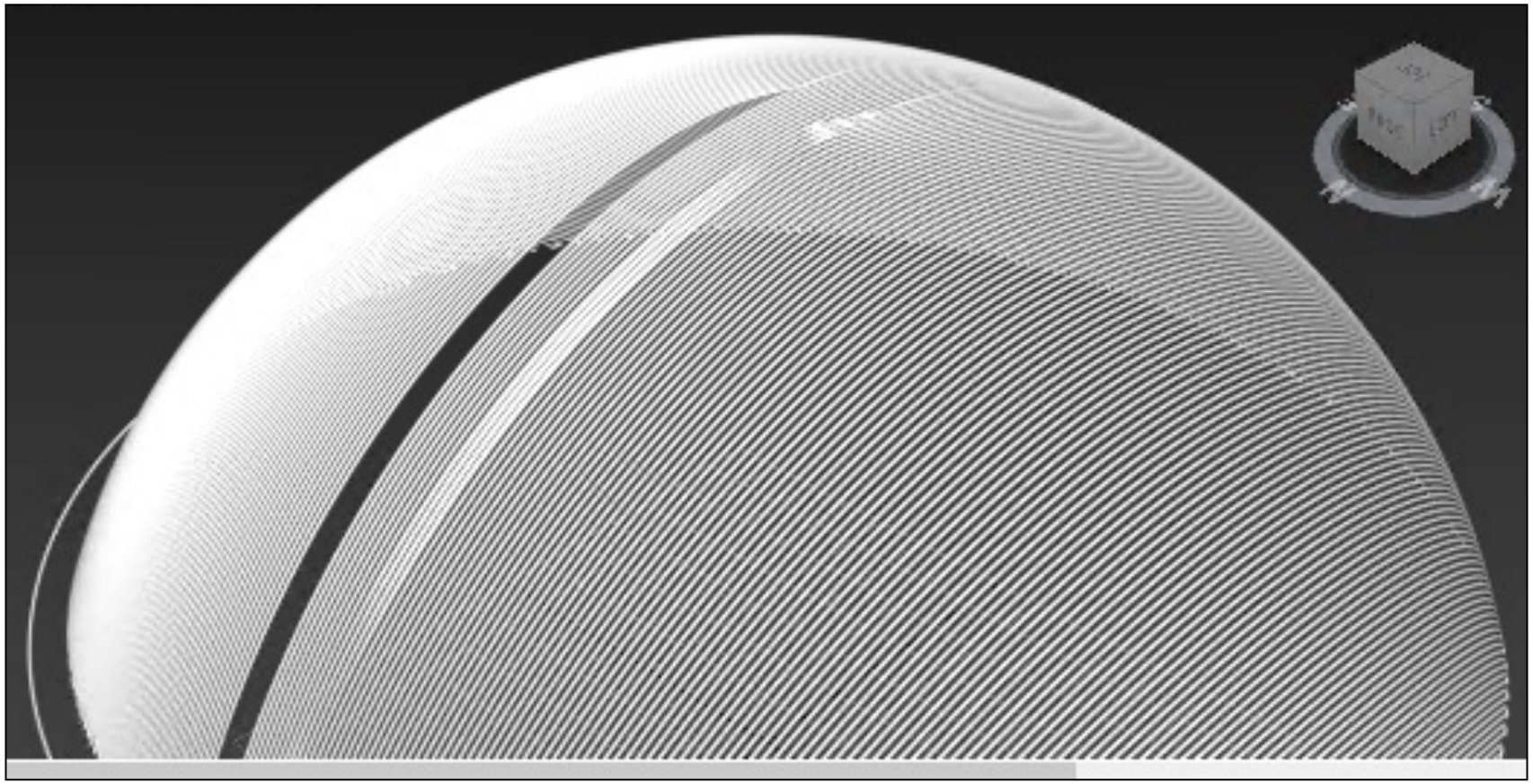




Same errors predicted with Digital Twin

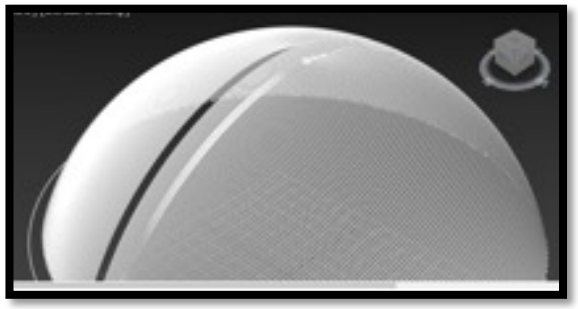


Turning simulation into simulated printed parts

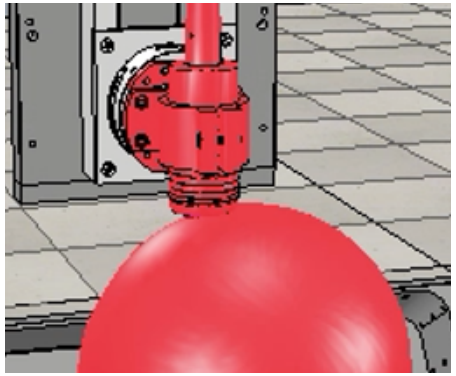


DTs improve our ability to move more responsively, and exciting new applications are arising continuously

Flaw prediction

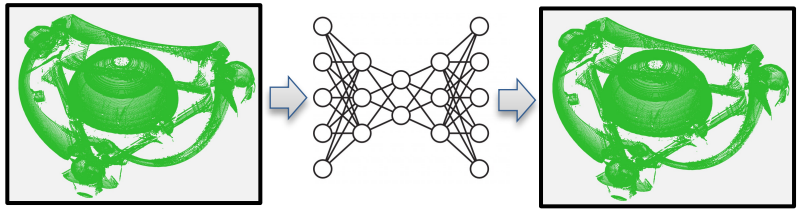


Collision detection

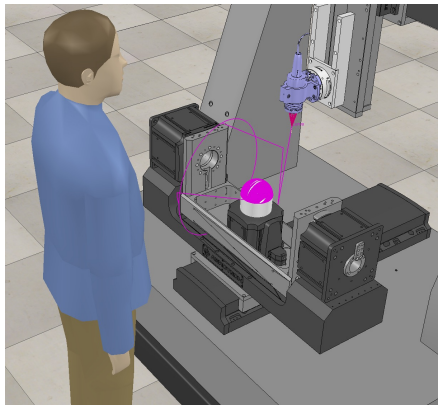


Developing Twins of Conventional Manufacturing Tools

Advanced tools for continuous twin refinement

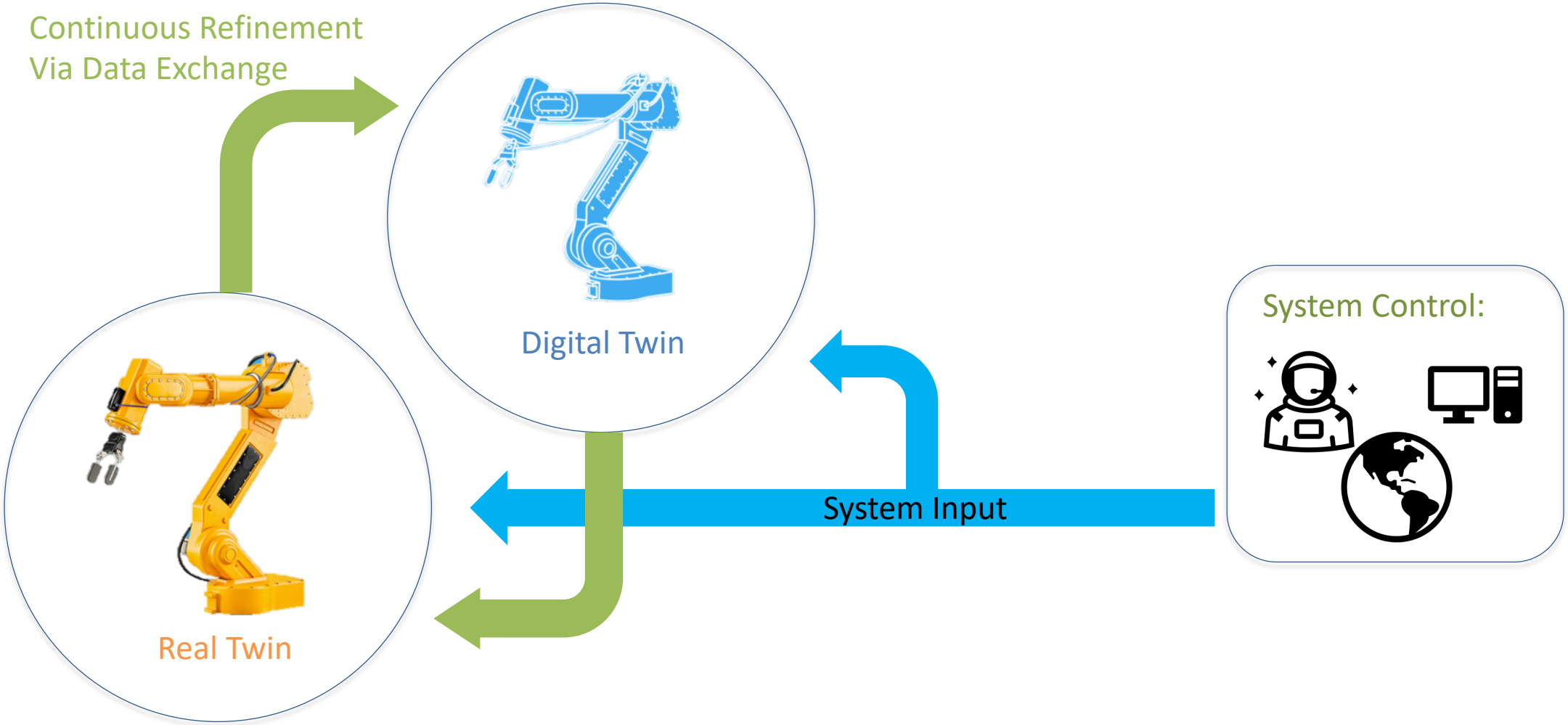


Training



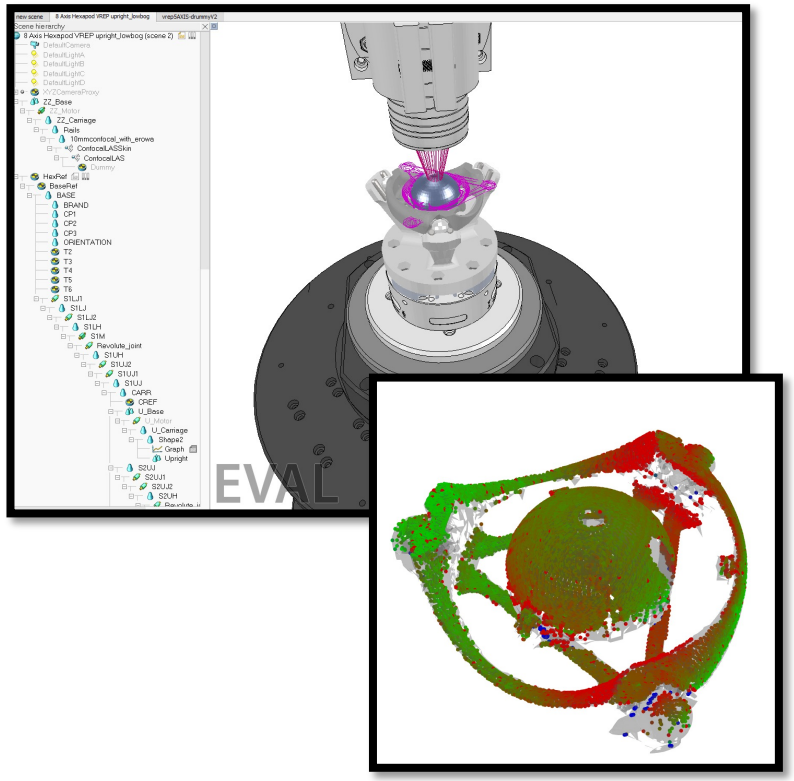
Digital twins have a steadily expanding role in the way we look at manufacturing development projects.

Digital twin is a living model that is continuously refined by data from its real-world counterpart

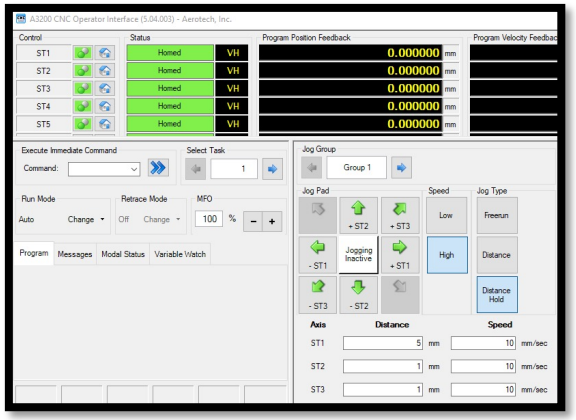


Application of DTs have increased our responsiveness and adaptiveness in today's landscape

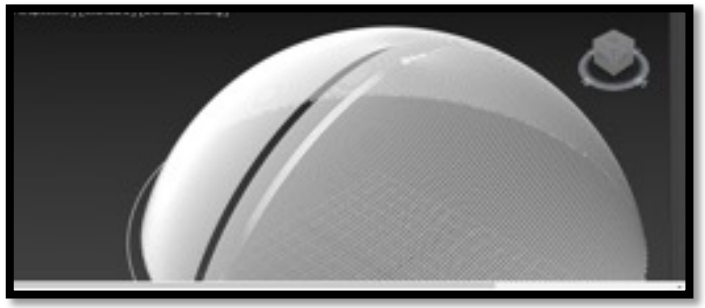
Virtual Fabrication and Metrology

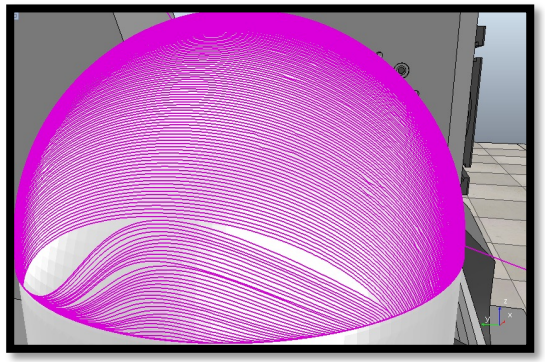


Operator Training



Creating simulated parts

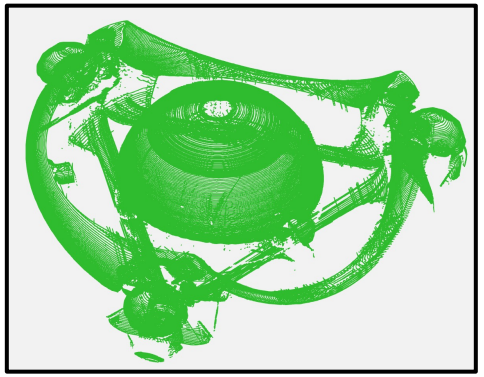




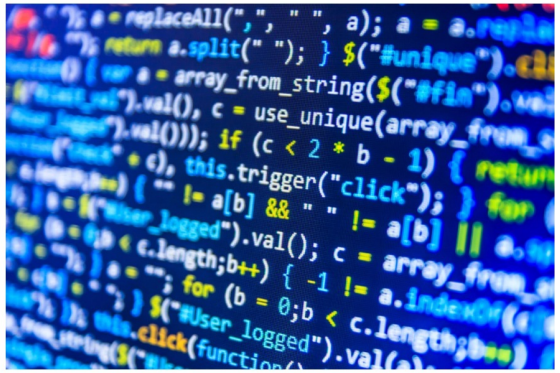
De-risk complex toolpath

By leveraging digital twins, we have sped up and de-risked our development cycle.

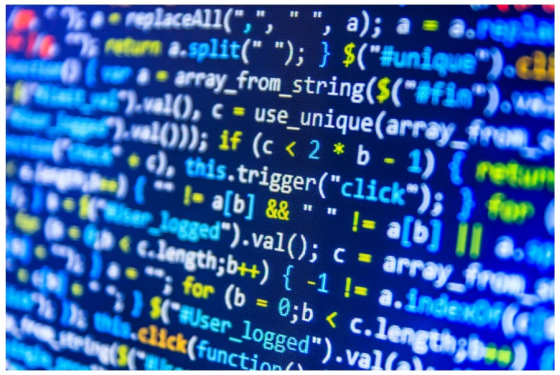
Option of simulating realistic behavior in confocal



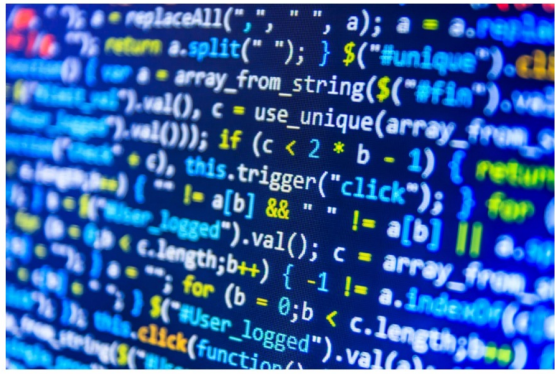
Digital Twin Data



Stage dynamics

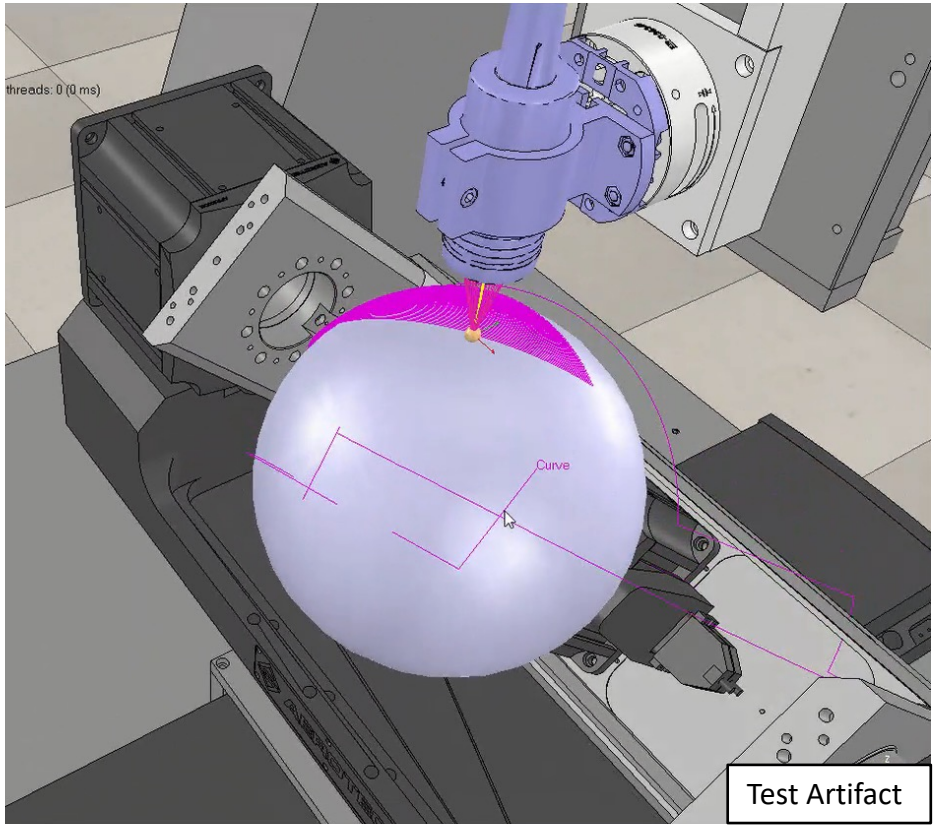


Surface reflection effects

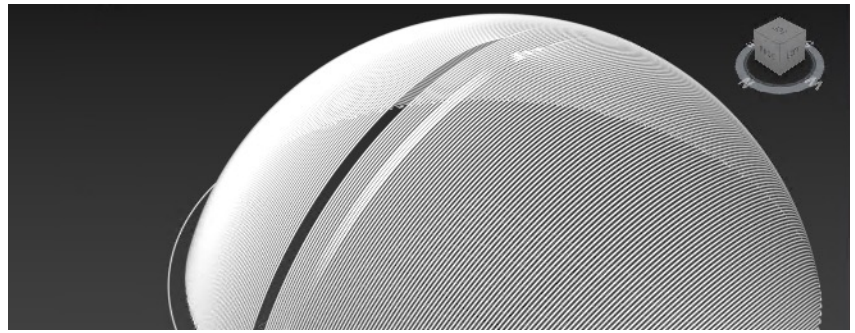


Data timing errors

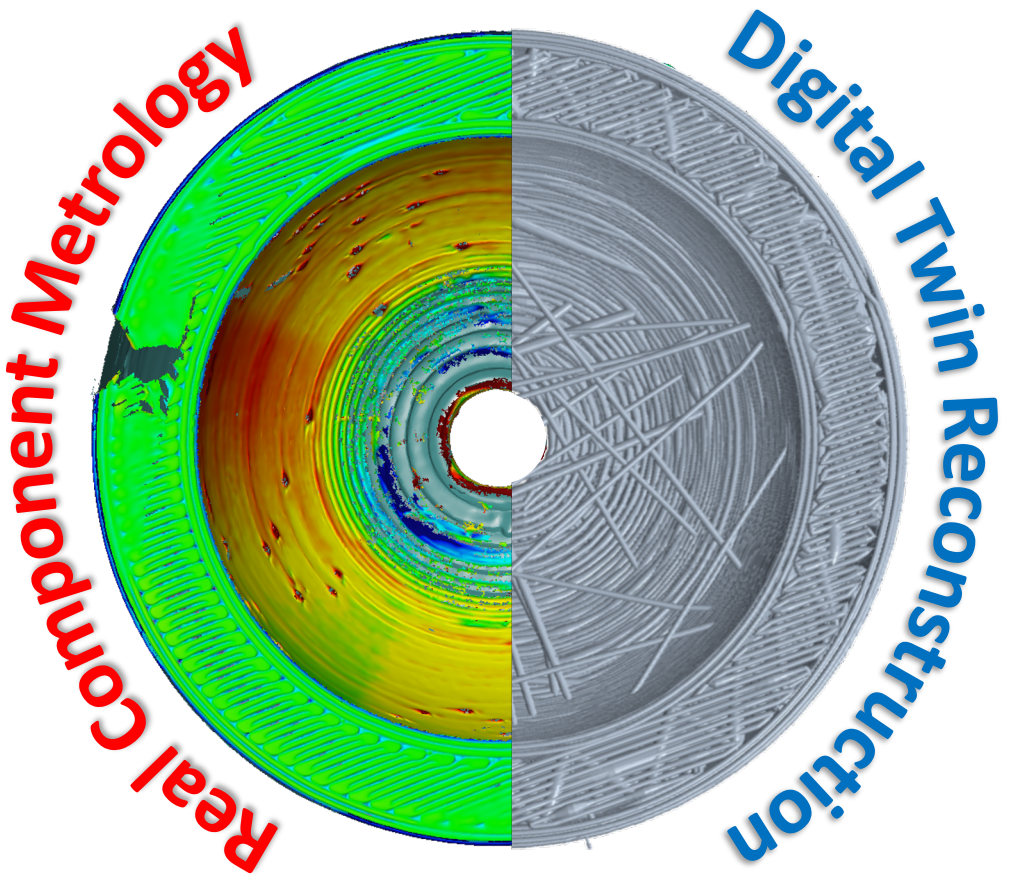
Simulating 5-axis prints

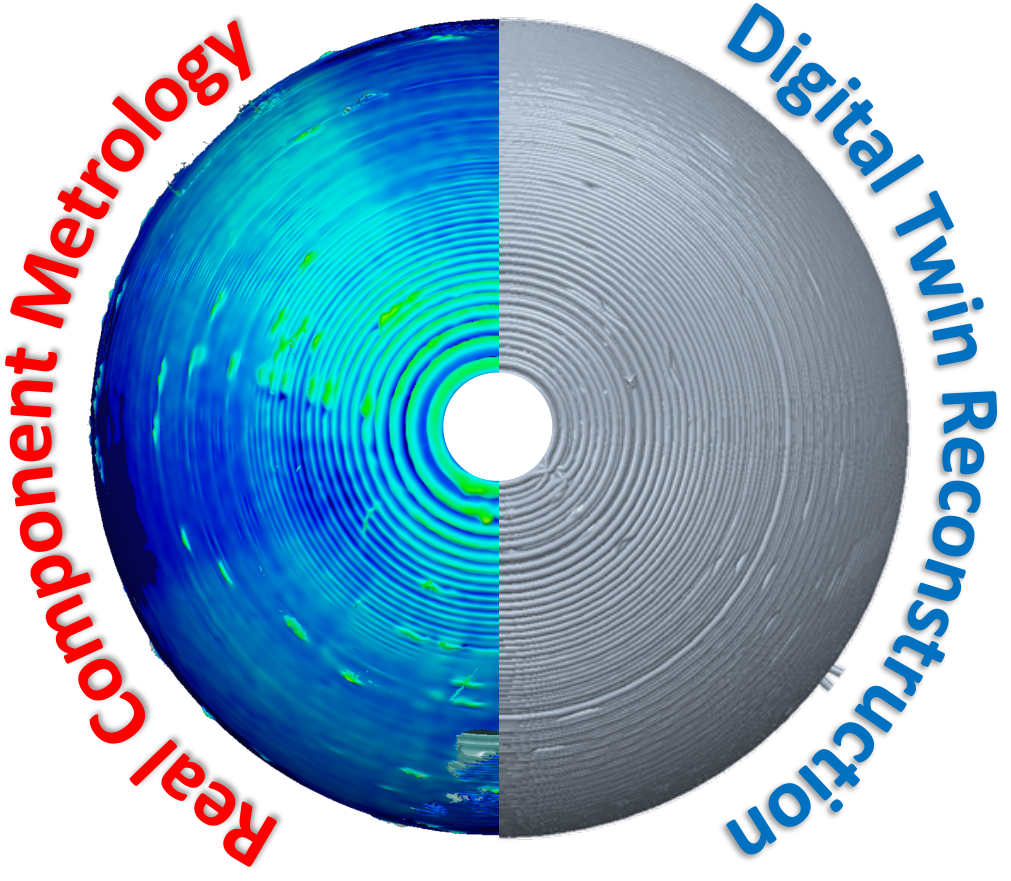


Test Artifact



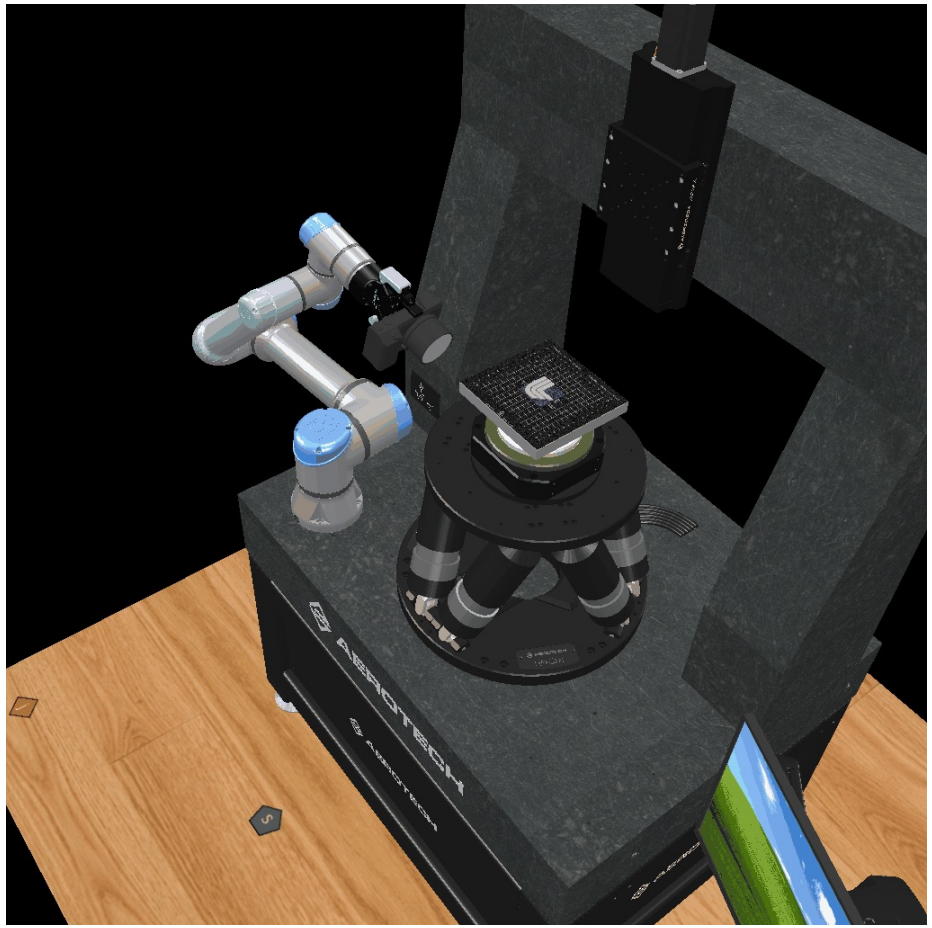
Surface Predictions Provide Quantitative Feedback





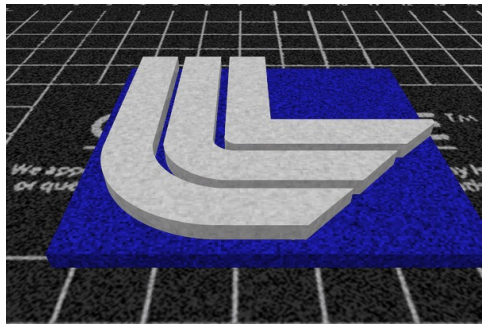
As the DTs and 3D representations mature, they will aid in *qualifying system* processes.

LLNL is developing “digital twins” of physical hardware systems and leveraging them for photogrammetry optimization



*Digital twin of Aerotech motion system in the Advanced Manufacturing Laboratory (AML)

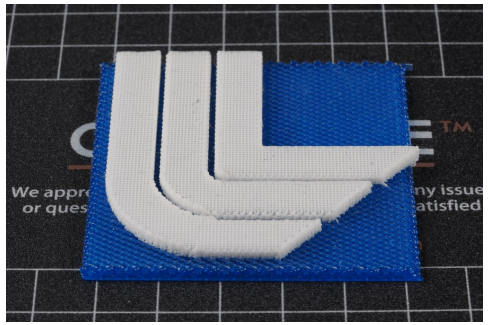
Digital component



Parameter set optimized via virtual testing.

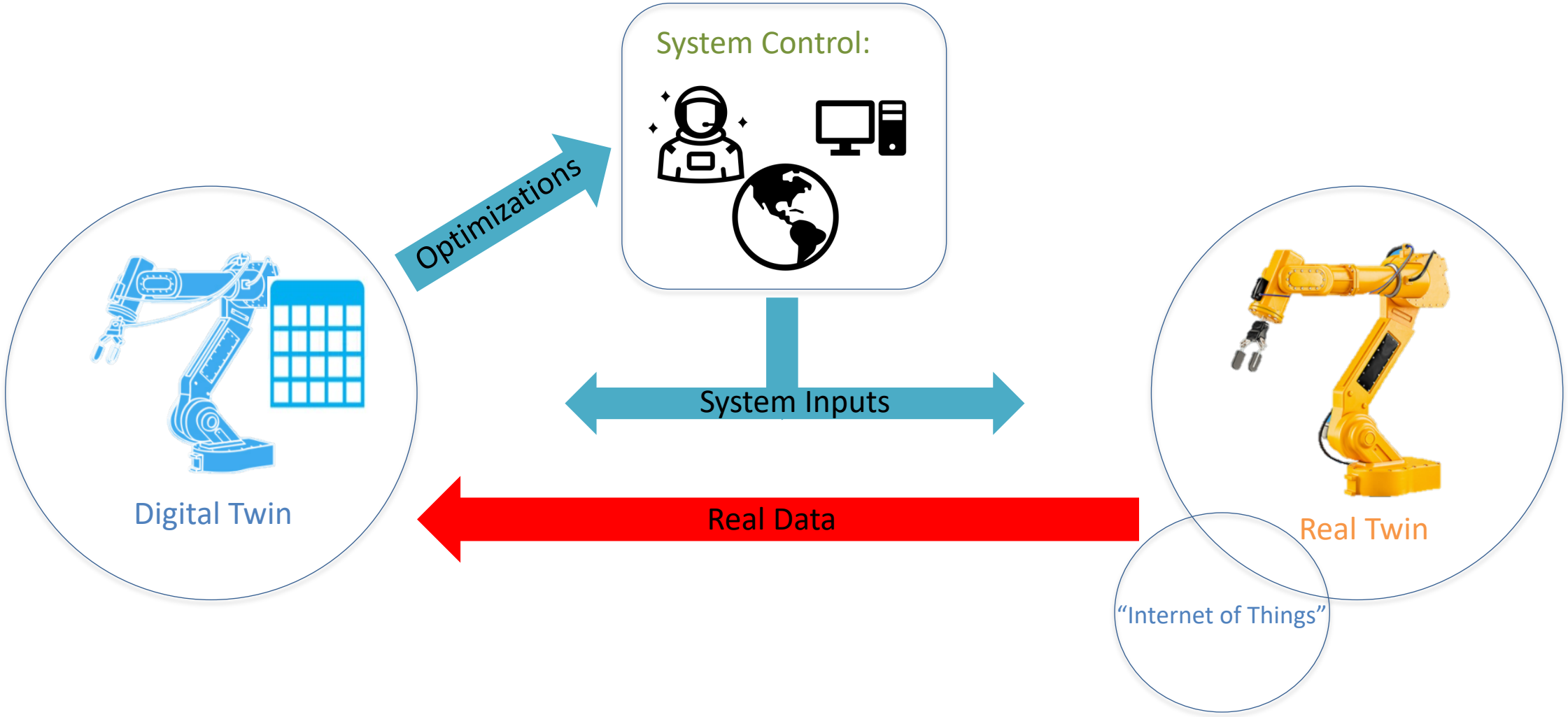
Optimal configuration implemented for final data collection.

Actual component



A digital twin enables massively parallelized testing.

Digital twin is a living model that is continuously refined by data from its real-world counterpart



Mimicking real time data handling

Digital Twin

Real Twin

A3200

A3200

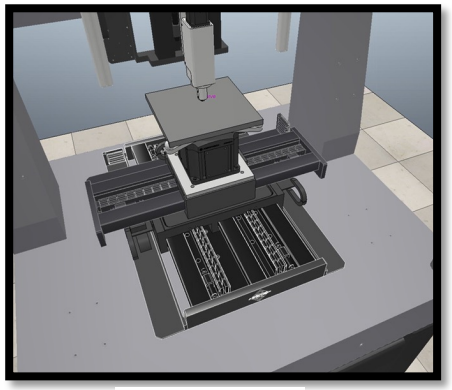
Motion Command

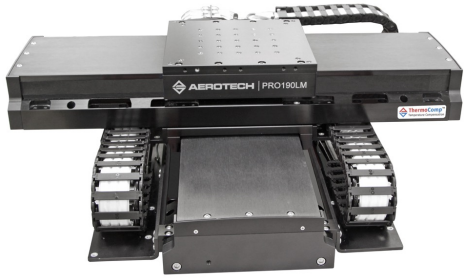
Virtual Measurement

Motion Command

Real Measurement

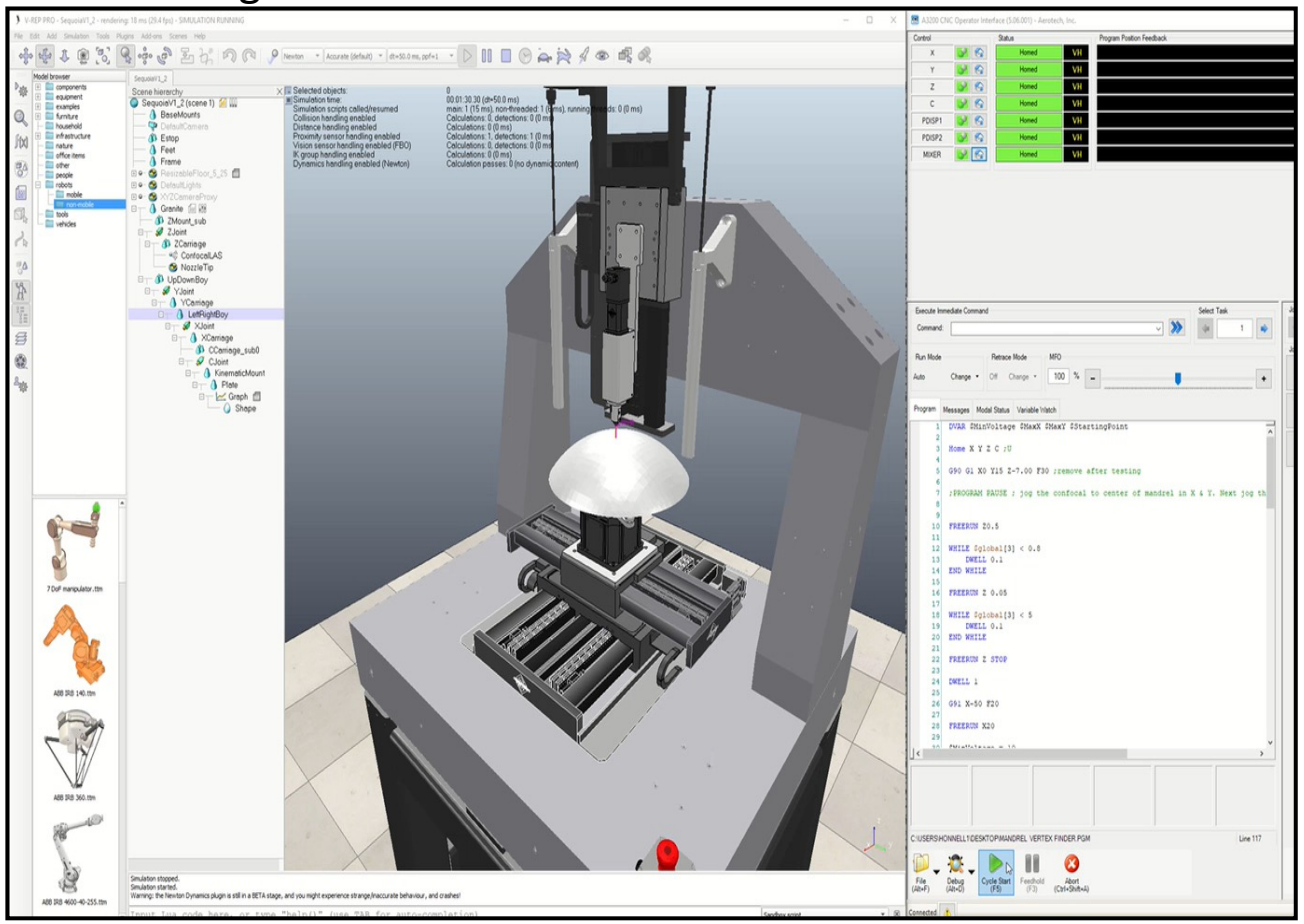
=





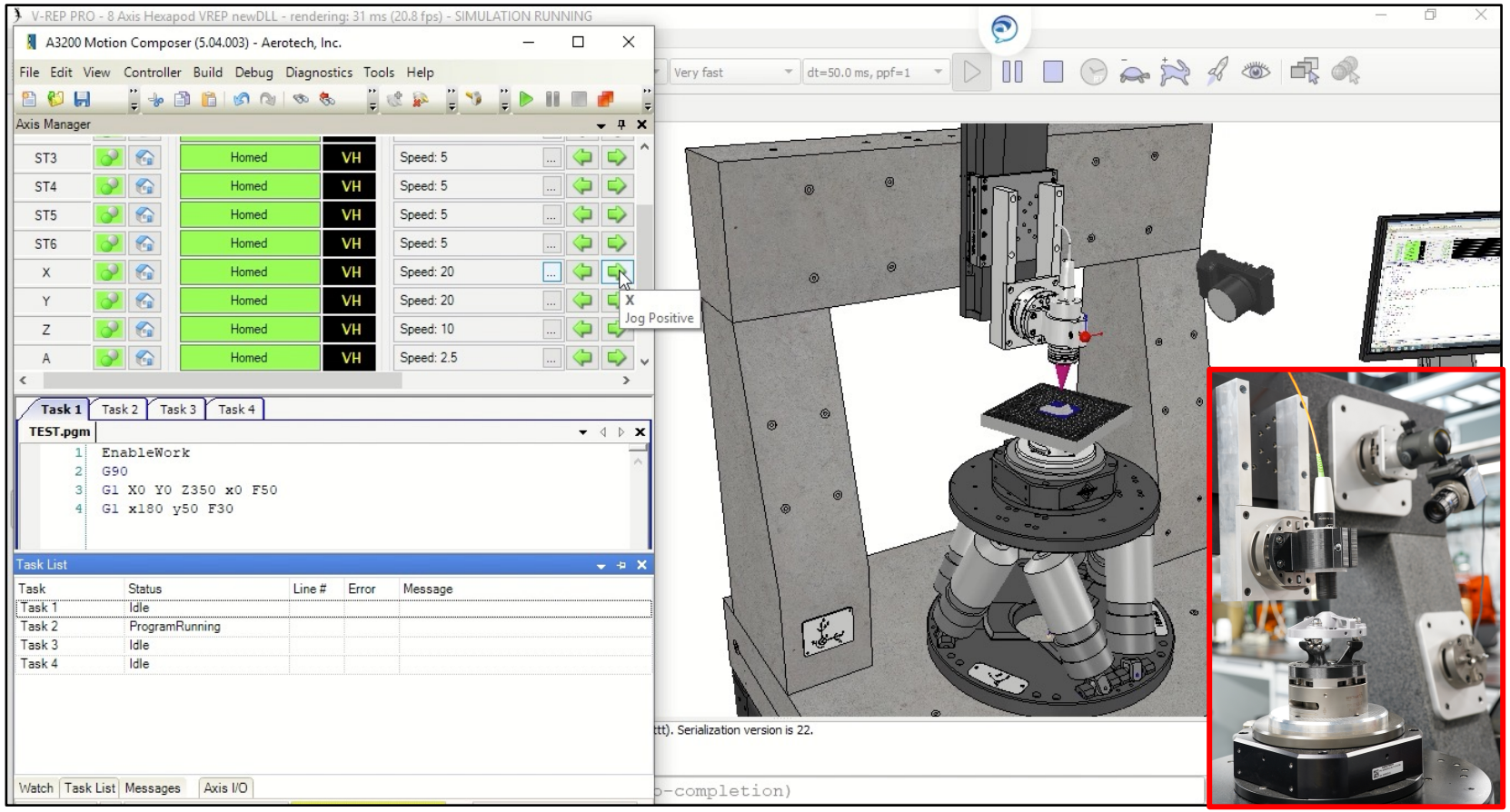
v-rep

XY Zero Program



Digital twins can mimic real time processes, allowing developers to run real time simulations to debug complex toolpaths.

Our objective for digital twins is to replicate real manufacturing systems from command inputs through data stream outputs



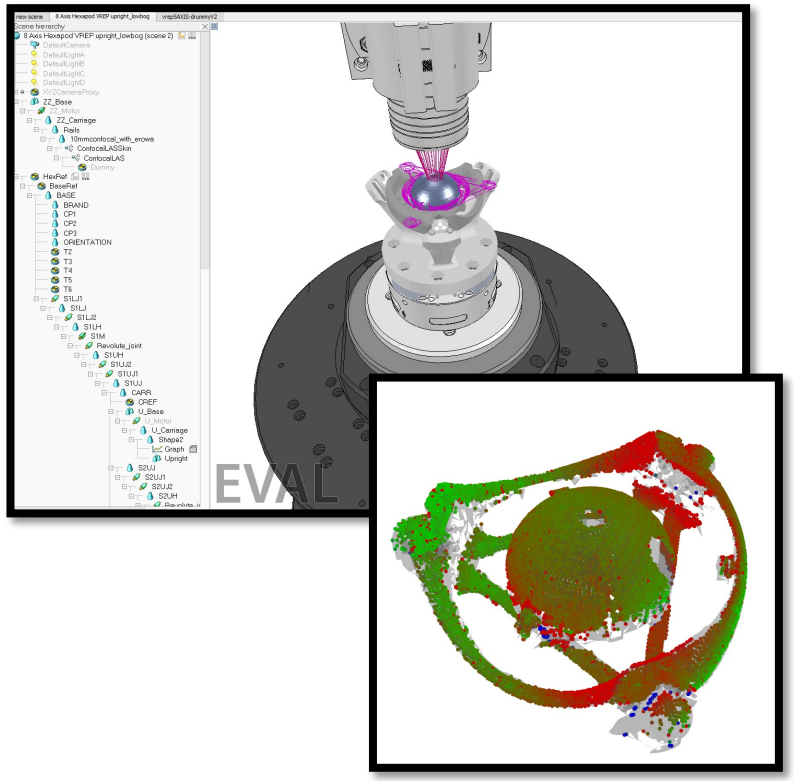
A digital twin is the confluence of physics-based models, sensing, and advanced analytics:

- Intrinsically evolves from *in-situ* and *ex-situ* data streams
- Replicates machine health and aging behavior, providing actionable insights on lifetime performance
- Reduces time, risk, and cost associated with process development and training

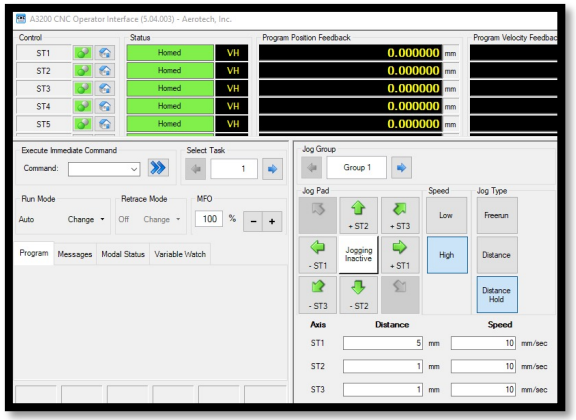
Inputs and outputs of a digital twin are indistinguishable from real-world counterparts

Implementing DTs at the laboratory and production scale

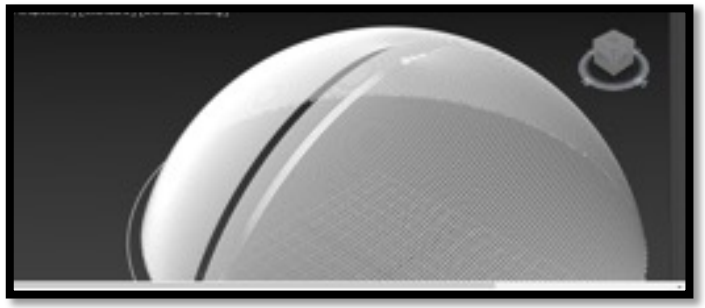
Virtual Fabrication and Metrology



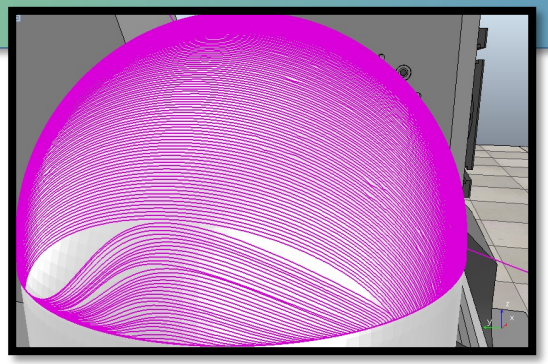
Operator Training



Creating simulated parts



Increasing Digital Twin Fidelity

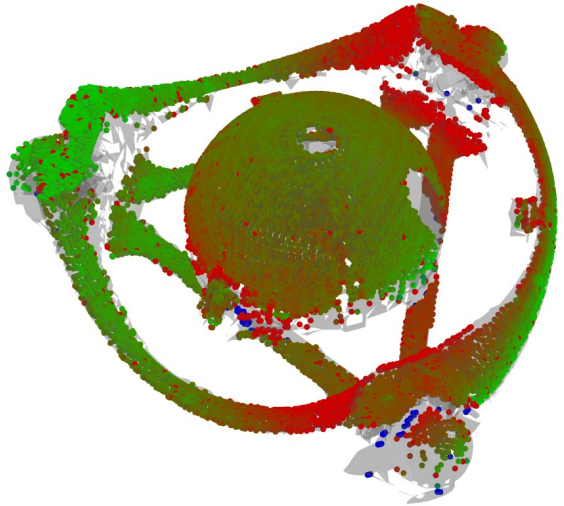


De-risk complex toolpath

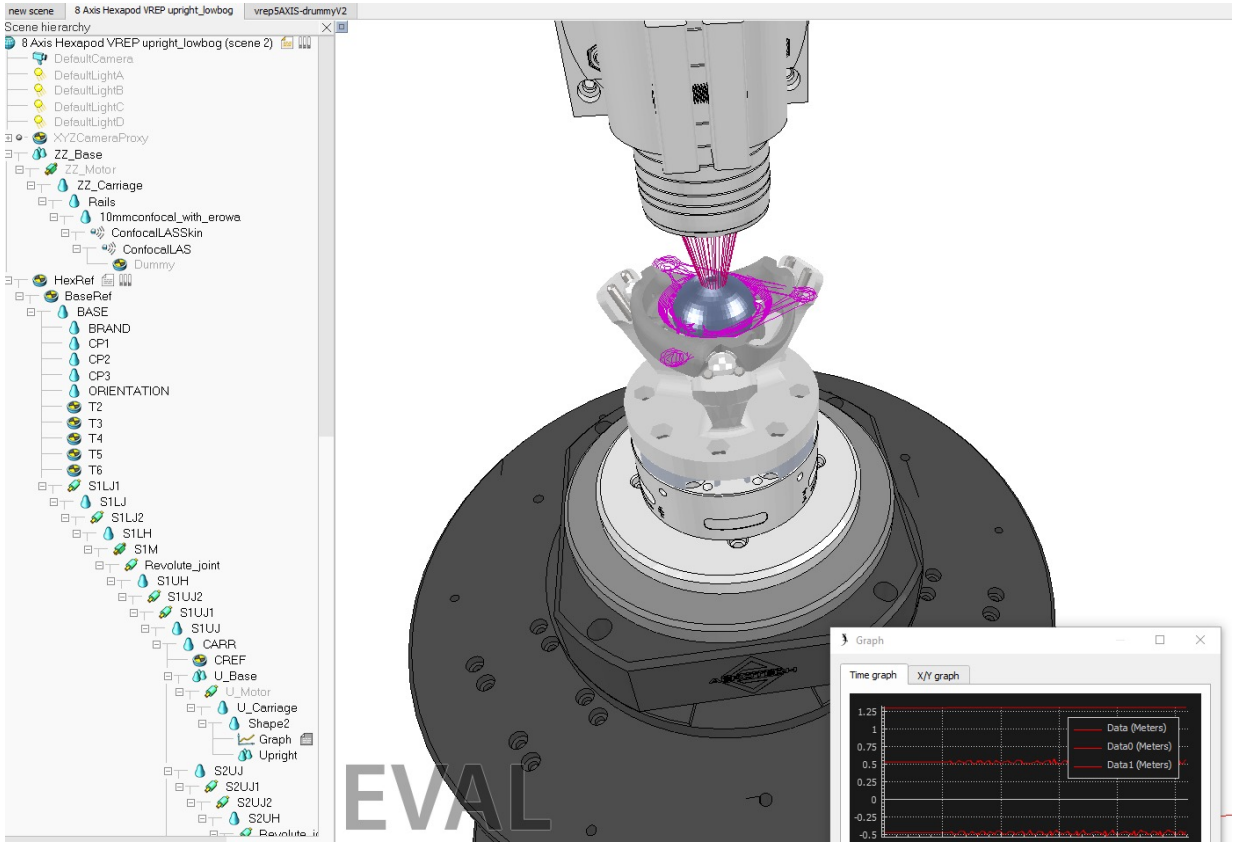
Digital twins developed in the LDRD space have found direct application in programmatic Direct Ink Write

Quick visuals to debug metrology toolpath

- Toolpaths can be plotted out to visualize metrology.
- Determined part was clocked incorrectly, turns out machine had X and Y axis reversed.

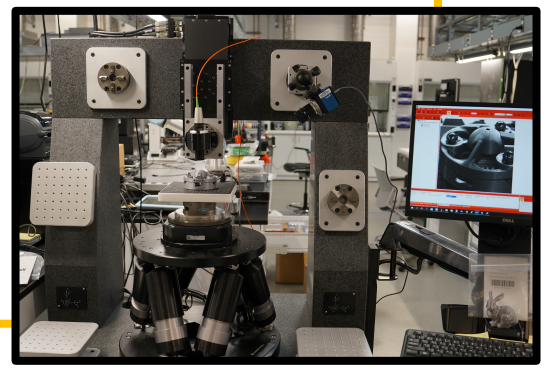


- Heat map from resulting point cloud

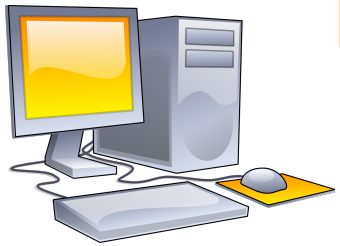


Digital twin system implementation

Real System

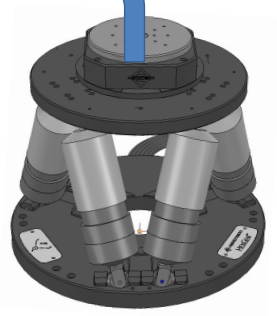


Computer



Digital Twin

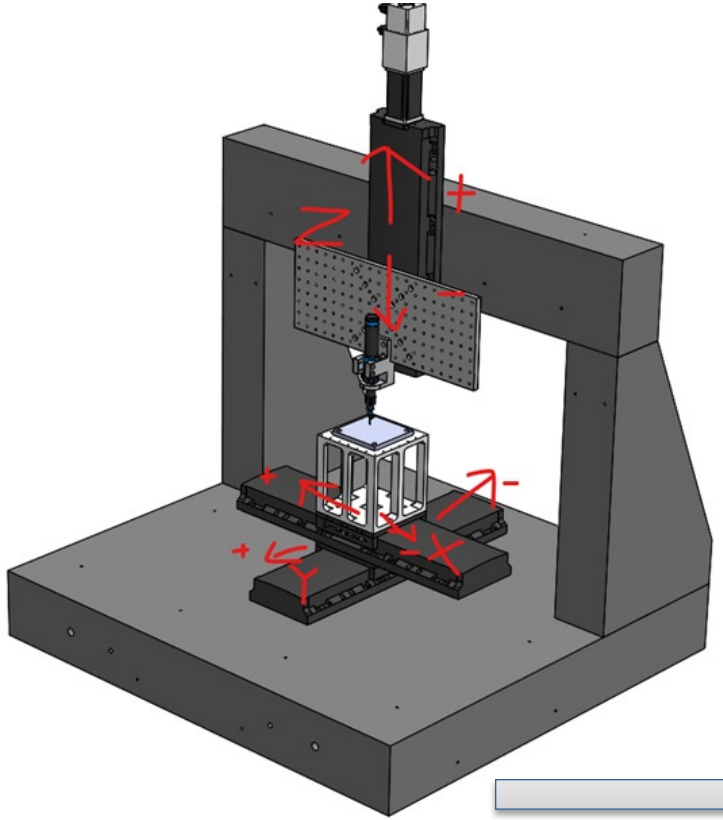
A3200



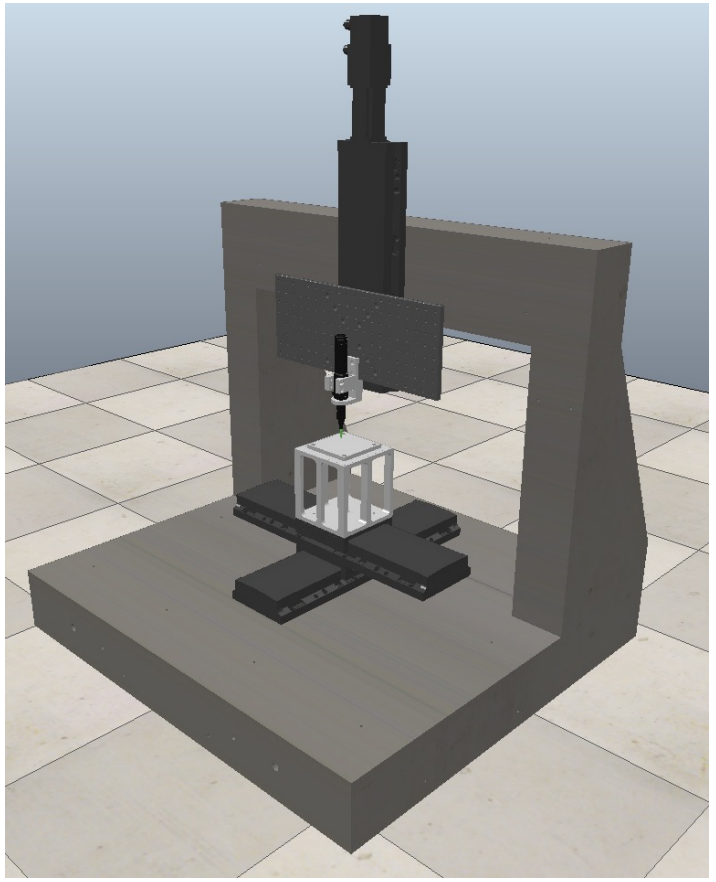
A digital twin attempts to mimic not only the components of the system but also the way these components interact.

Fast implementation to other systems

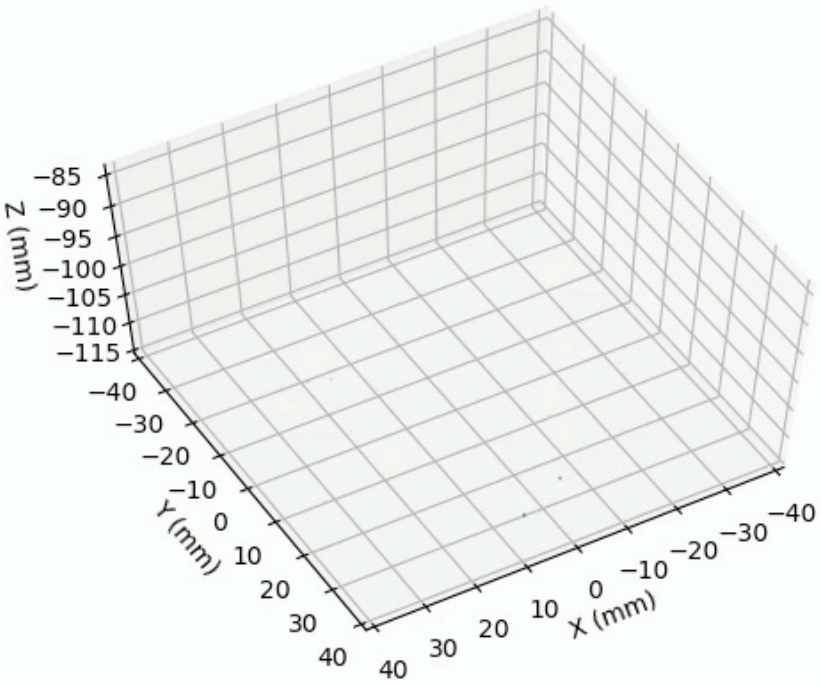
- Able to scale DT capabilities to other Aerotech machines easily using same communication methods
- Received CAD for motion system from Michael Grapes

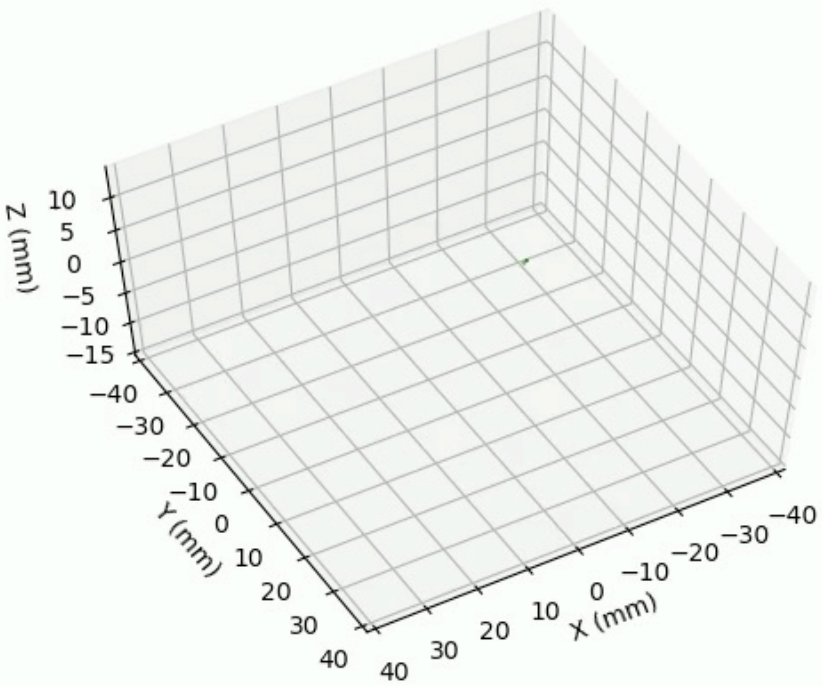


One day turnover

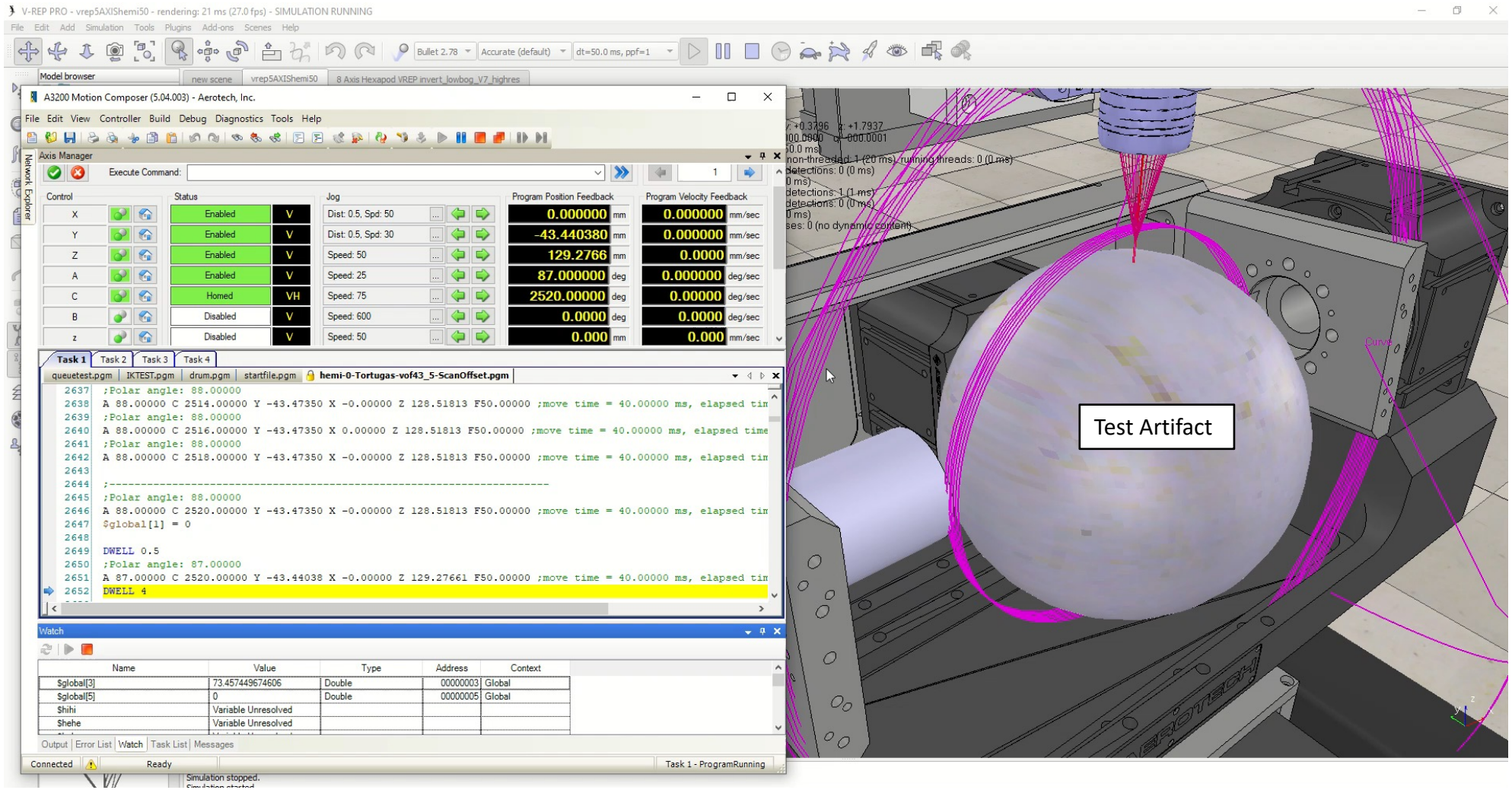


Real world measurements benefit from insights gathered under idealized conditions





Digital twins offer low-risk virtual environments for optimizing toolpaths and streamlining data management.


V-REP PRO - vrep5AXIShemi50 - rendering: 21 ms (27.0 fps) - SIMULATION RUNNING
A3200 Motion Composer (5.04.003) - Aerotech, Inc.
Test Artifact

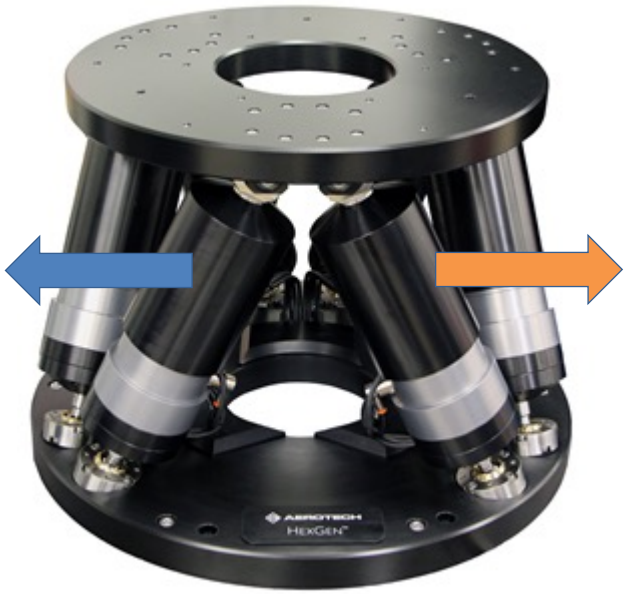
Digital Twin vs Simulation

Digital Twin

Software: User Interface → Software: Backend

Inverse Kinematics Calculations → Link Length

Motor Encoder Values → New Machine Position



Traditional Simulation

Inverse Kinematics Calculations → Link Length → New Machine Position

A Digital Twin attempts to mimic every aspect of the real system as closely as possible.