National Aeronautics and Space Administration

Transformational Tools and Technologies (T^3) Project

MicroNet Assistant Tool: Rapid Annotation, Training, and Deployment of Microscopy Segmentation Machine Learning Models for Digital Twin Creation

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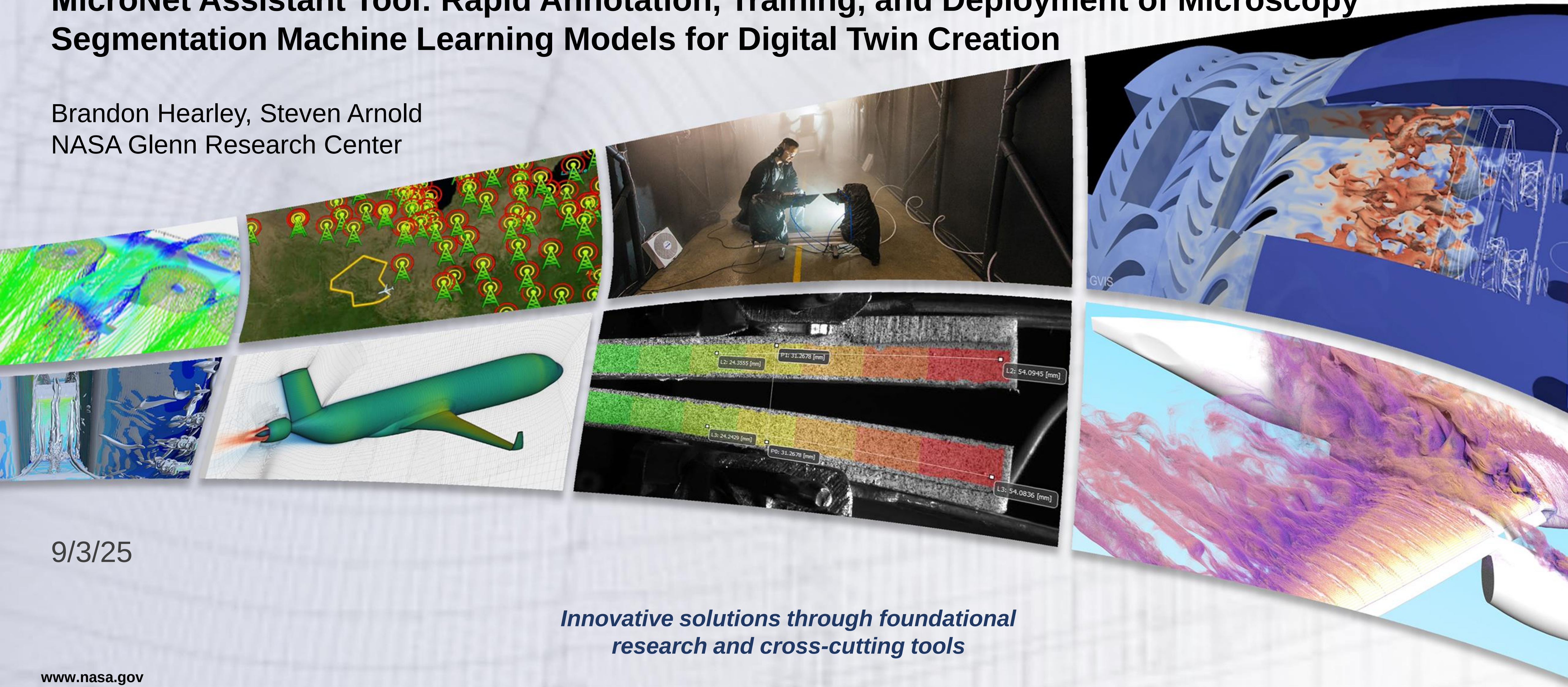

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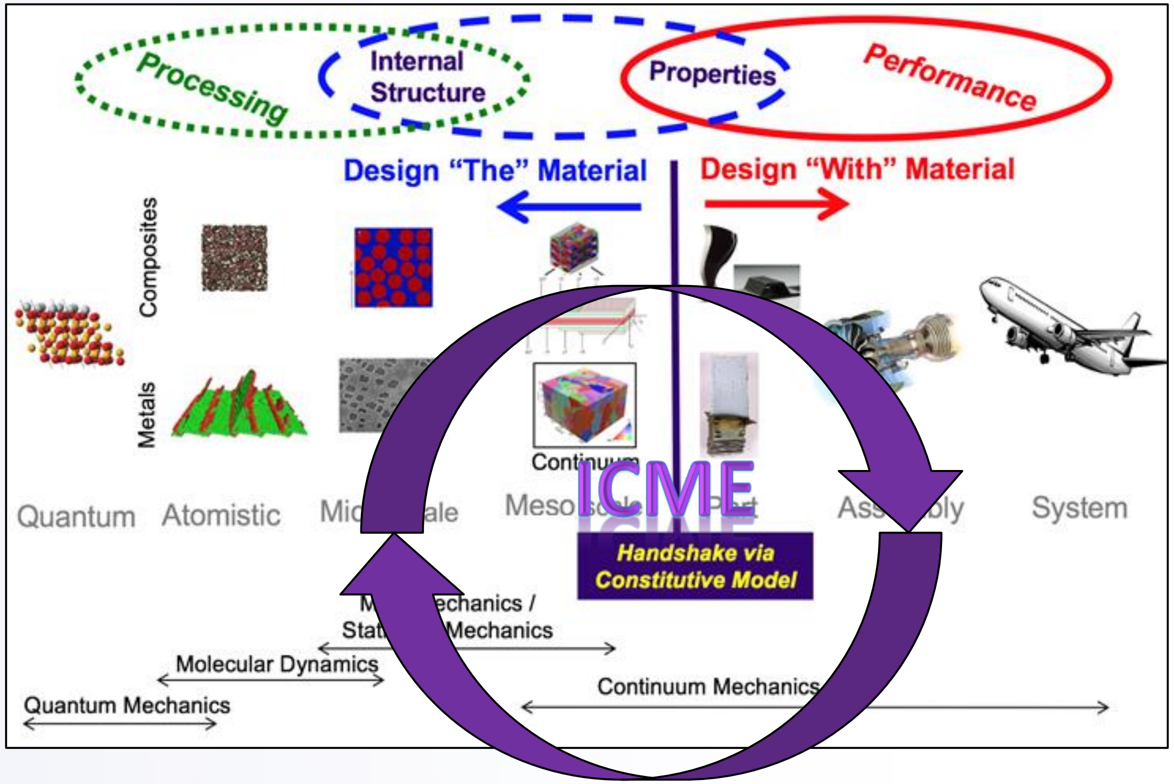
Innovative solutions through foundational research and cross-cutting tools

Agenda

- **Motivation**
- **Existing Segmentation Methods**
- **MicroNet Assistant Tool**
- **Composite Idealization Algorithm**
- **Digital Twin Creation**
- **Conclusions**

Integrated Computational Materials Engineering (ICME) Enables Innovation

- Top performing organizations rate **New Materials** as one of **THE MOST IMPORTANT** factors in meeting their innovation goals (Historically new materials ≥ 20 years)
- Integrated Computation Materials Engineering (ICME) looks to bridge the gap between the "Design-the-Material" (Material Science) and "Design-with-the-Material" (Structural) viewpoints
  - Enables design of 'fit-for-purpose' materials
- Requirements for ICME
  - Experimentally validated materials models at multiple length scales
  - Understanding processing-structure-properties-performance relationships
  - Integrated framework that can automatically pass information across scales during design optimization
  - Manufacturing capability to achieve desired microstructure at any location in an application



Vision 2040: A Roadmap for Integrated, Multiscale Modeling and Simulation of Materials and Systems

- In 2018, NASA Released the Vision 2040 report, outlining **technical** and **cultural** gaps preventing ICME design and suggested actions to close those gaps

NASA CR 2018-219771

https://ntrs.nasa.gov

Nine Identified Key Element Discipline Areas

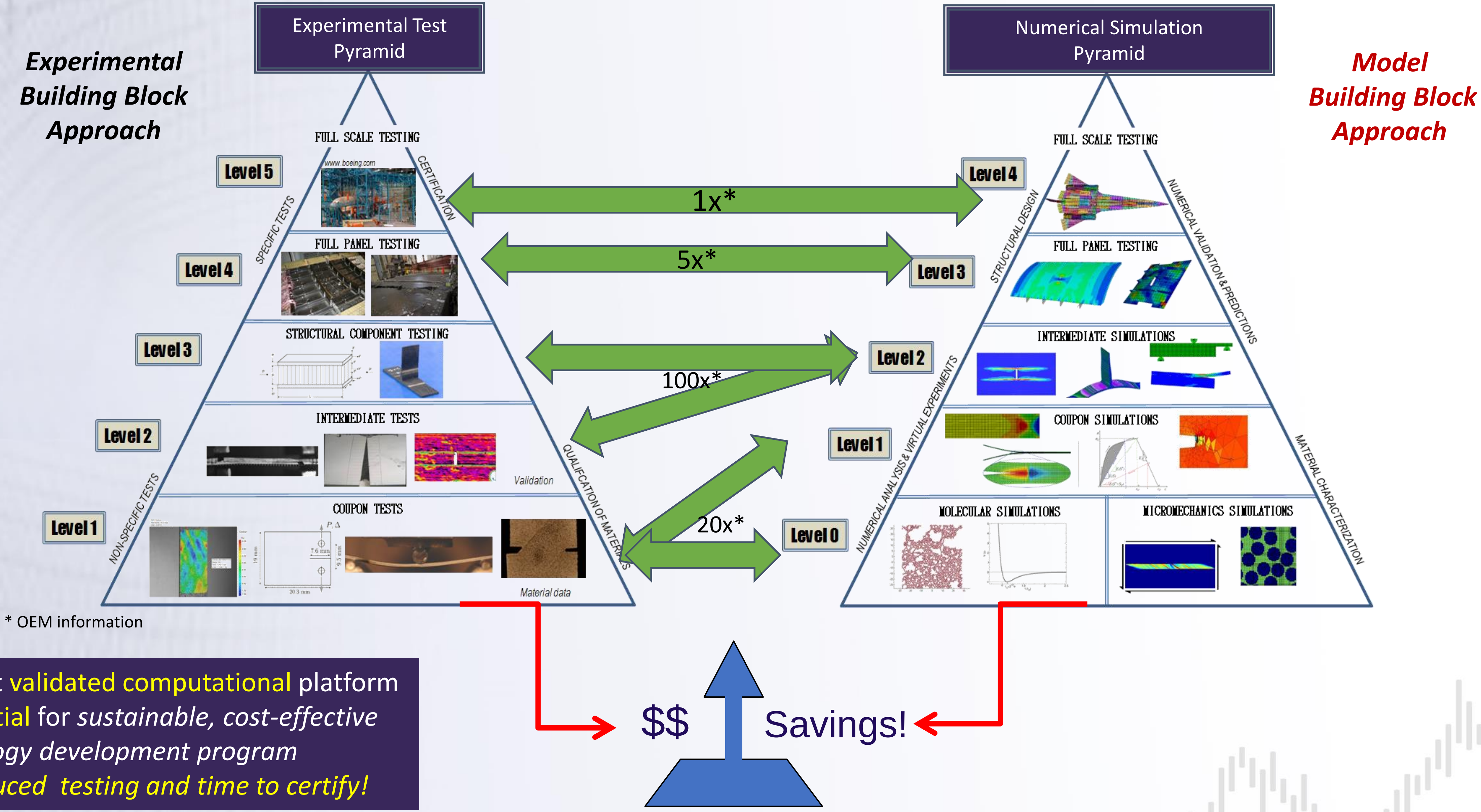
1. Models and Methodologies
2. Multiscale Measurement & Characterization Tools and Methods
3. Optimization & Optimization Methodologies
4. Decision Making and UQ
5. Verification & Validation
6. Data, Informatics, & Visualization
7. Workflows & Collaboration Frameworks
8. Education & Training
9. Computational Infrastructure

2040 Ecosystem Revolutionizes Design Paradigm

Today' s Design Paradigm	2040 Design Paradigm
Design Of Materials And Systems Is ***Disconnected***	Design Of Materials And Systems Is ***Integrated***
Stages Of The Product Development Lifecycle Are ***Segmented***	Stages Of The Product Development Lifecycle Are ***Seamlessly Joined***
Tools, Ontologies, And Methodologies Are ***Domain-specific***	Tools, Ontologies, And Methodologies Are ***Usable Across The Community***
Materials Properties Are Based On ***Empiricism***	Materials Properties Are ***Virtually Determined***
Product Certification Relies Heavily On ***Physical Testing***.	Product Certification Relies Heavily On ***Simulation***

The cyber-physical-social ecosystem that marries "the design of materials" (material scientist viewpoint) with "the design with materials" (structural analyst viewpoint) approaches into one concurrent transformational digital paradigm.

Virtual Testing Can Enable Significant Cost Savings in Certification Process



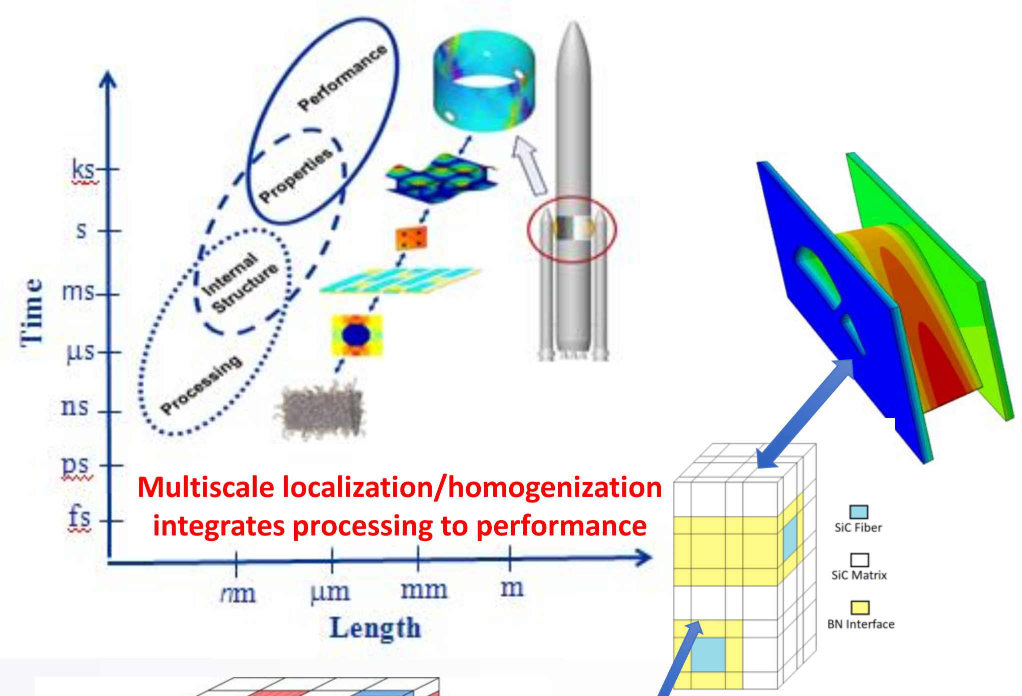
* OEM information

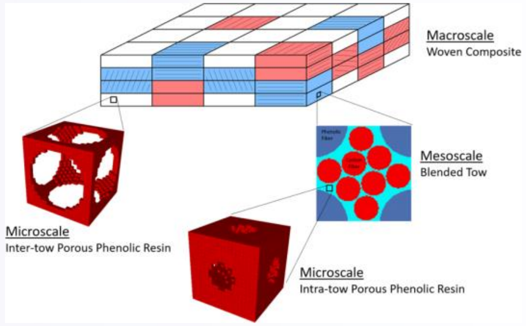
A robust validated computational platform is essential for *sustainable, cost-effective technology development program*

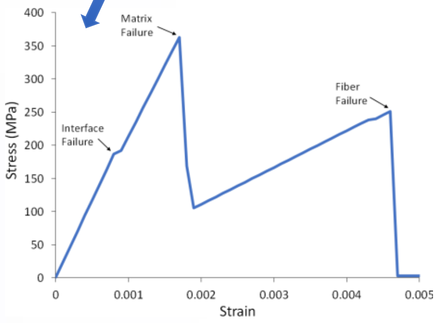
- *reduced testing and time to certify!*

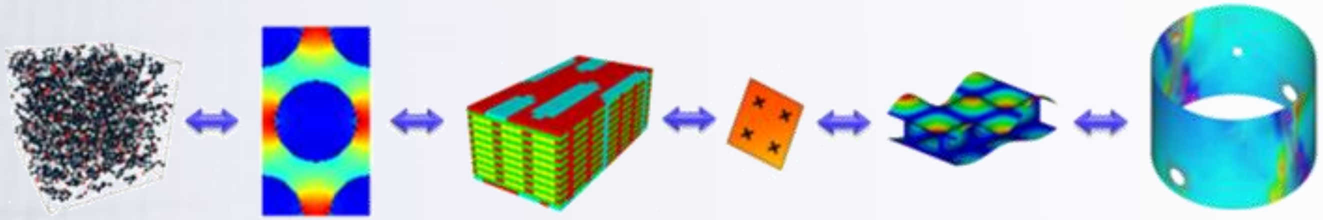
NASA Multiscale Analysis Tool (NASMAT)

- NASA GRC has released The NASA Multiscale Analysis Tool (NASMAT) for performing massively multiscale modeling
    - Solves real, large-scale, non-linear, thermo-mechanical problems
- Modular design to support “plug-and-play” capabilities
    - Operational components categorized into NASMAT procedures
- Developed for enhanced interoperability
    - Integrates with 3rd party structural analysis codes (e.g., FEA)
    - Library of constitutive laws/damage models
- Ideal for “design with” or “design of” the material
    - Enables Integrated Computational Materials Engineering (ICME)
    - Developed to support Vision 2040
- Availability: https://software.nasa.gov/software/LEW-20650-1



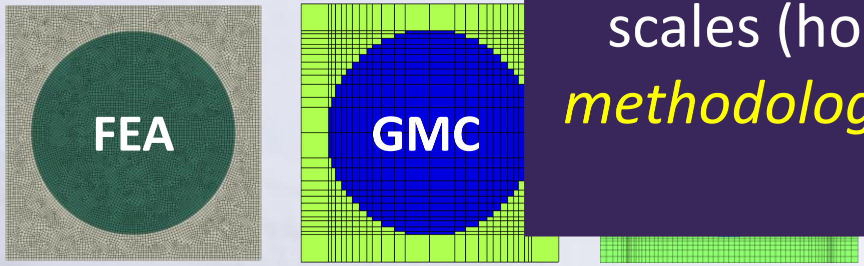




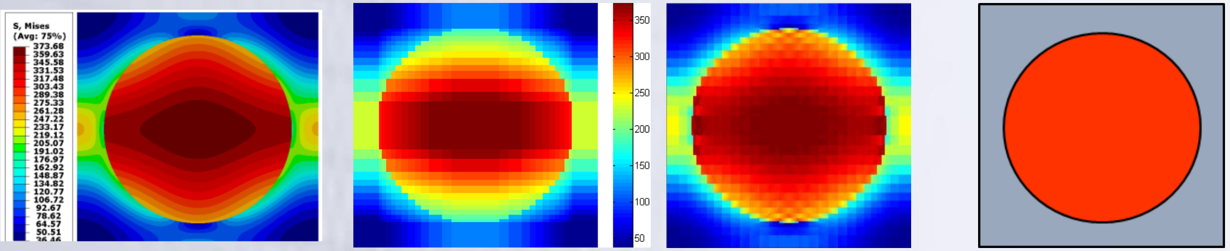


Micromechanics in NASMAT

- NASMAT offers various micromechanics theories for simulating microscale effects in composite materials for both deformation and damage for varying amounts of fidelity and efficiency:
  - Mori-Tanaka (MT)
  - Generalized Method of Cells (GMC)
  - High Fidelity Generaliz
    (HFGMC)



~11,000 GPS Elements | 676 Subcells | 1024 Subcells



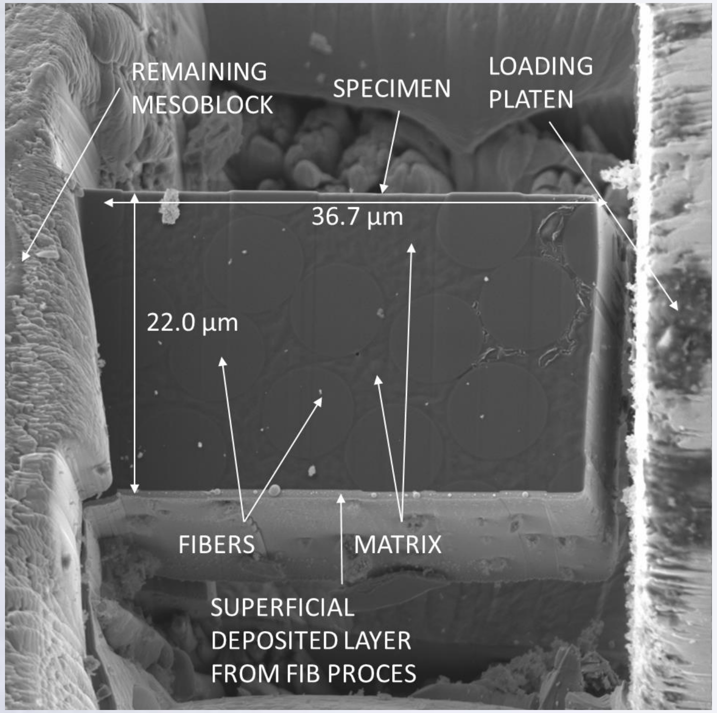
Von Mises stress (J_2) Prediction Comparison

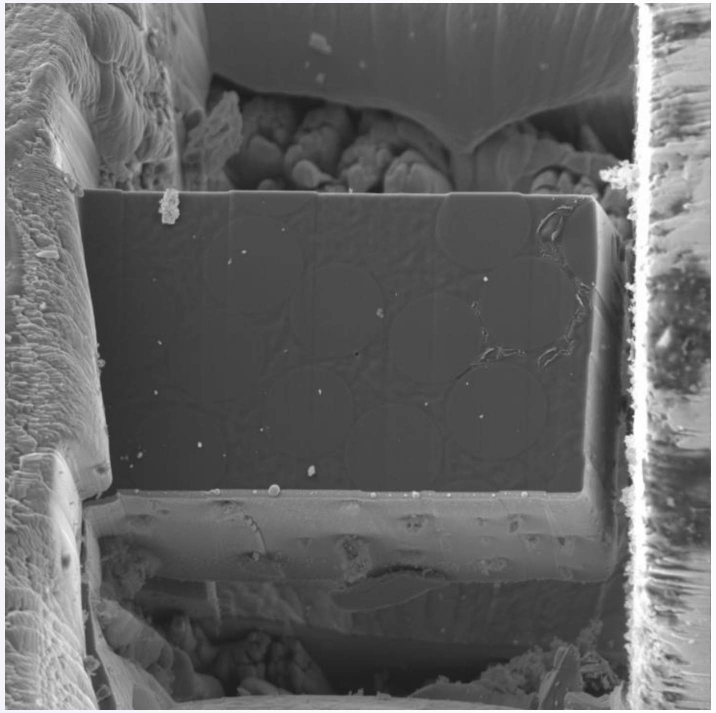
Feature/Capability	MT	GMC	HFGMC	FEA
General Global Accuracy	Good	Very Good	Excellent	Excellent
		Excellent	Fair	Fair
		Good	Excellent	Excellent
		No	Yes	Yes
		Yes	Yes	Yes
		Excellent	Good	Fair
		Yes	Yes	Yes
Ability to Model Debonding	Yes*	Yes	Yes	Yes
Ability to Model Disordered Microstructures	n/a	Fair	Excellent	Excellent
Local Fields Insensitive to Refinements in Mesh	Yes	Yes	No	No

Micromechanics validated against Finite Element Analysis or experimental data at higher length scales (homogenized response) → *no currently methodology for establishing **true digital twins** at this length scale*

Microscale Testing of Polymer Matrix Composites

- NASA GRC has recently begun compression testing of microscale polymer matrix composite samples using a custom testing rig developed my Micro Testing Solutions
  - Samples fabricated using a focused ion beam scanning electron microscope (FIB-SEM)
  - Images taken during testing using an SEM, test frame measures force and displacement



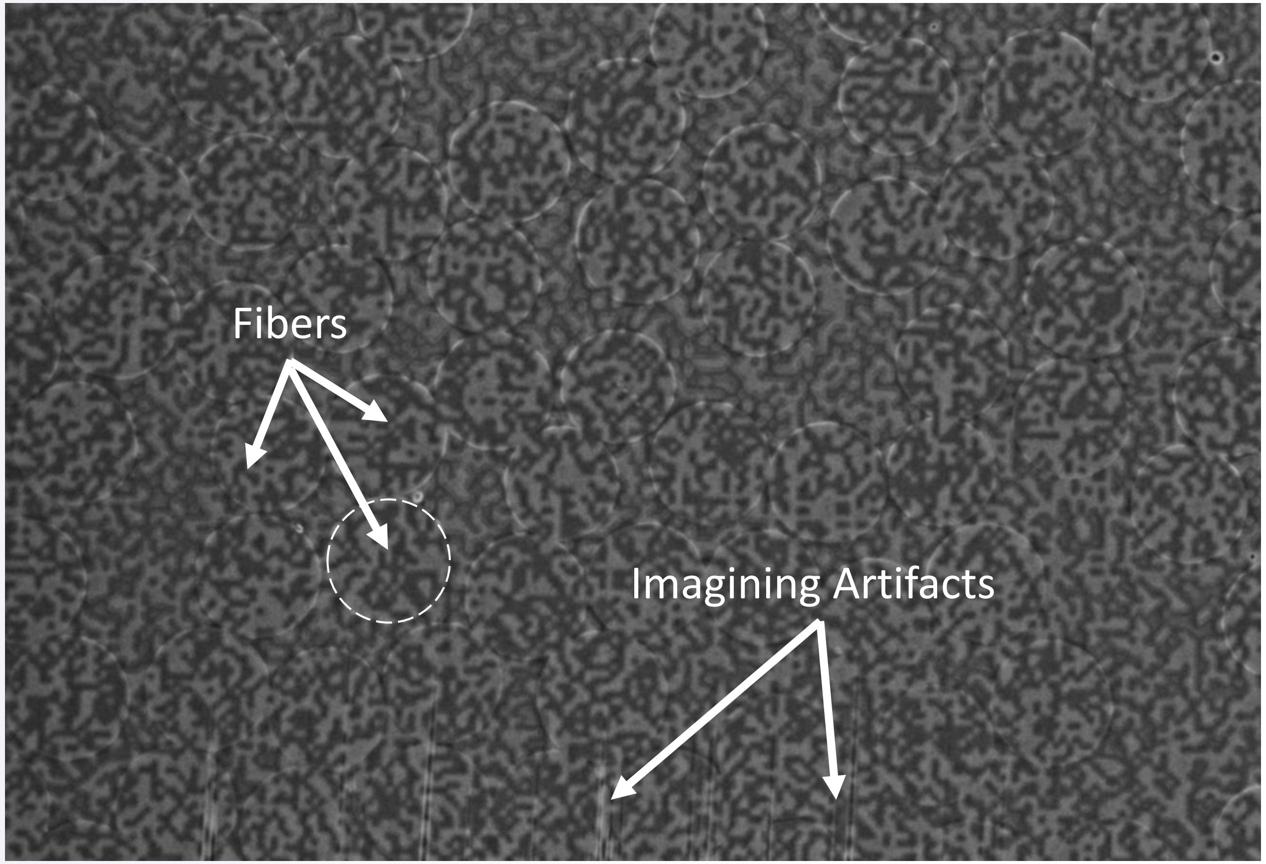


- Enables observation of the evolution of damage mechanisms in-situ during testing and at the fundamental scale at which they occur → provides experimental data for validation of microscale modelling
  - **Need accurate geometric representation of the specimen microstructure for microscale model validation and establishment of microscale digital twins**

Fiber Segmentation

Automatic Segmentation of Fibers from Microscopy Images

- **Objective**: Develop a machine learning model capable of automatically segmenting fibers in a specimen during testing
  - Must be robust enough to segment fibers with speckle applied
  - Must be able to ignore artifacts from imaging
- This work was completed before the microscale testing capability was available at NASA GRC. The segmentation model was trained from images provided by [1] using a similar test frame built by Micro Testing Solutions

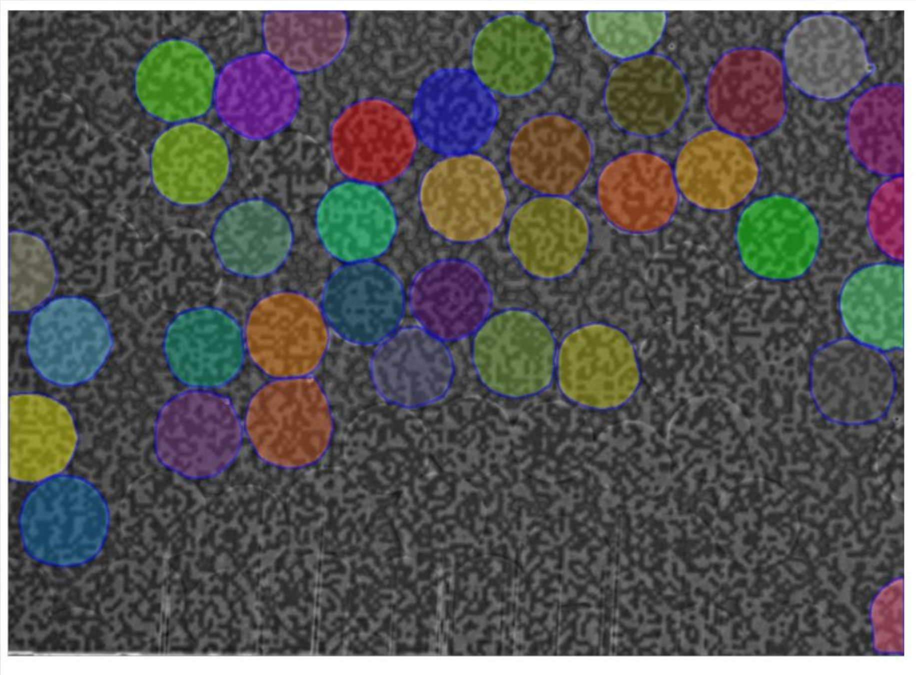


[1] M. Flores, A. Sharits, R. Wheeler, N. Sesar and D. Mollenhauer, "Experimental analysis of polymer matrix composite microstructures under transverse compression loading," *Composites Part A: Applied Science and Manufacturing*, vol. 156, 2022.

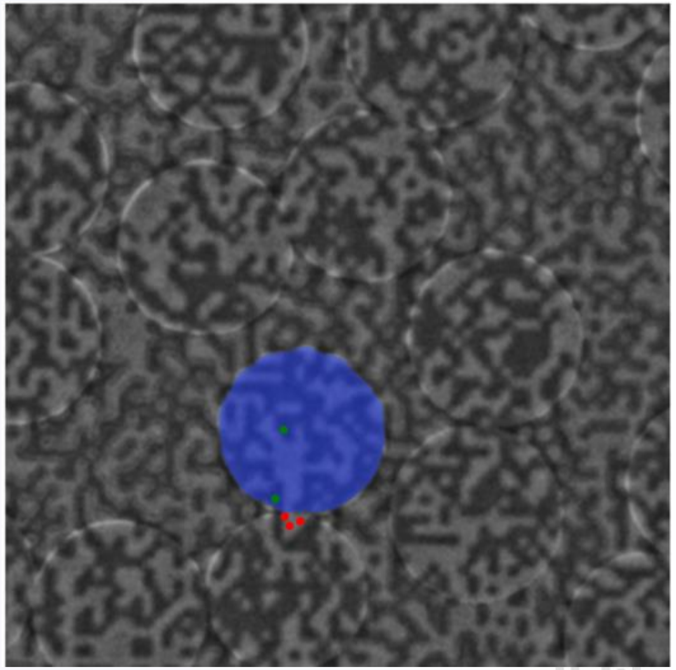
Limitations of Existing Segmentation Tools

Segment Anything Model (SAM)

- Pretrained, automatic segmentation tools require user prompts for each individual feature during segmentation
  - Inefficient for a large number of features/images
- Both user prompt driven and automatic segmentation from these tools are subject to higher error due to their generality
  - Prompt-based segmentation performs better than automatic segmentation



Segment Anything Model (SAM) Automatic Segmentation (No user prompt)

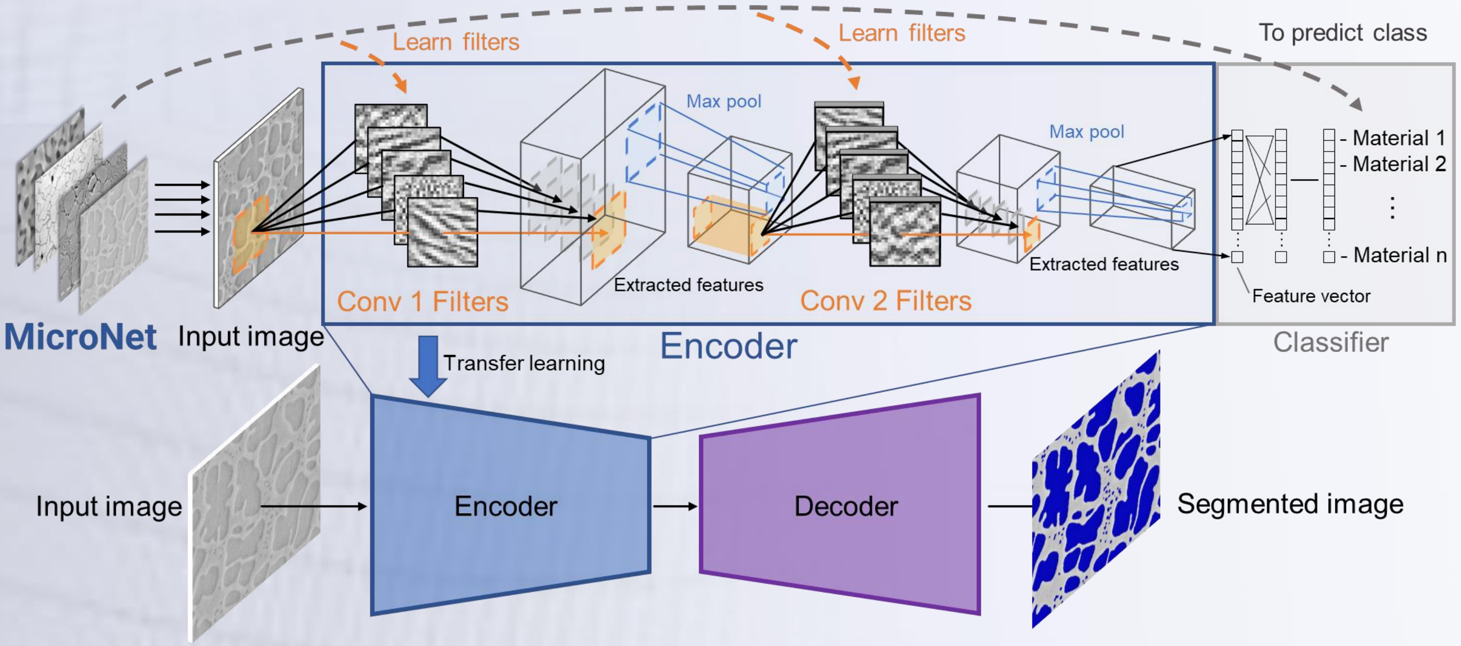


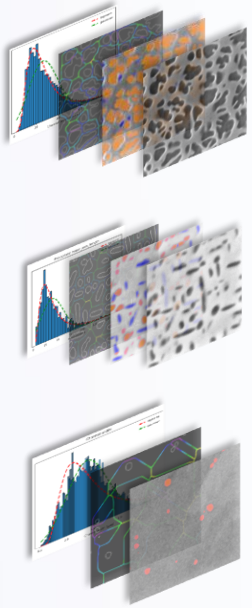
Segment Anything Model (SAM) Automatic Segmentation with user Prompt

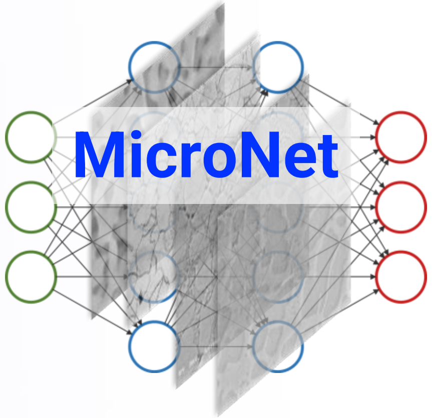
MicroNet: Pretrained Model for Microscopy

Microscopy-Specific Segmentation

- MicroNet, a software tool to build deep learning microscopy segmentation and analysis models with less training data, has previously shown its ability in rapidly segmenting microscopy images necessary for material characterization with high accuracy at a fraction of the cost manual annotation
  - Better performance compared to SAM model
  - Requires manually annotated/labelled images to train the model – **time consuming**
  - Requires Python scripting knowledge and PyTorch experience – **barrier to entry**



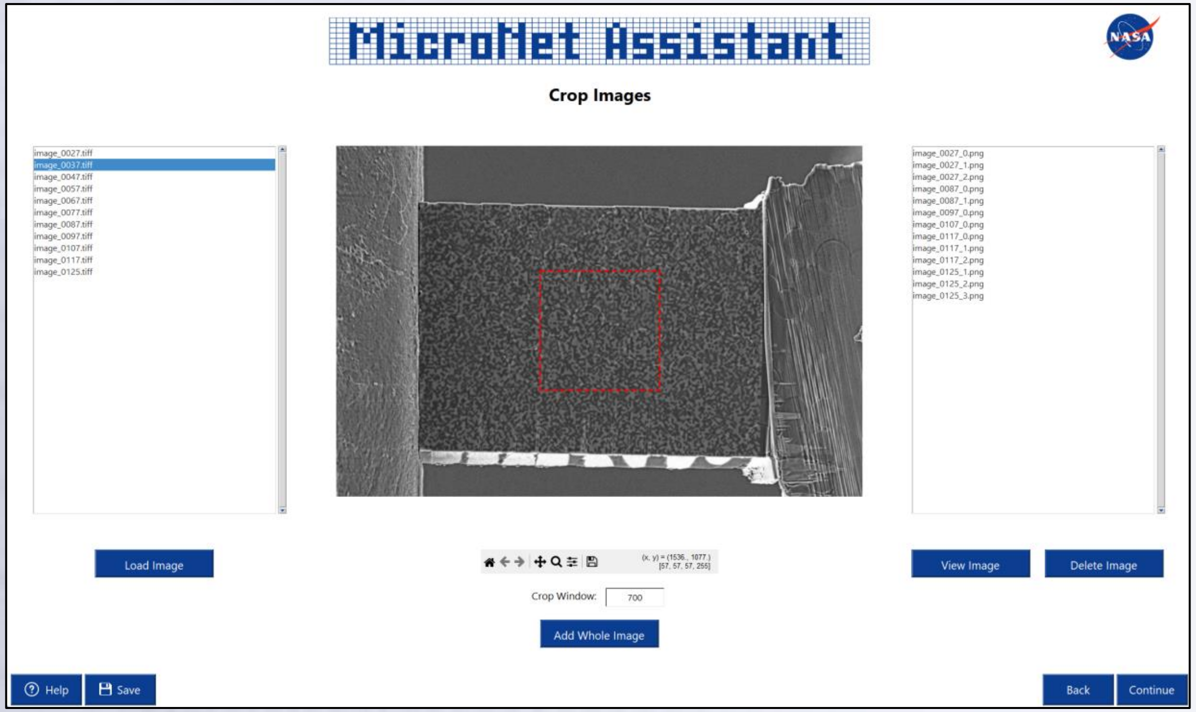




MicroNet Assistant Tool

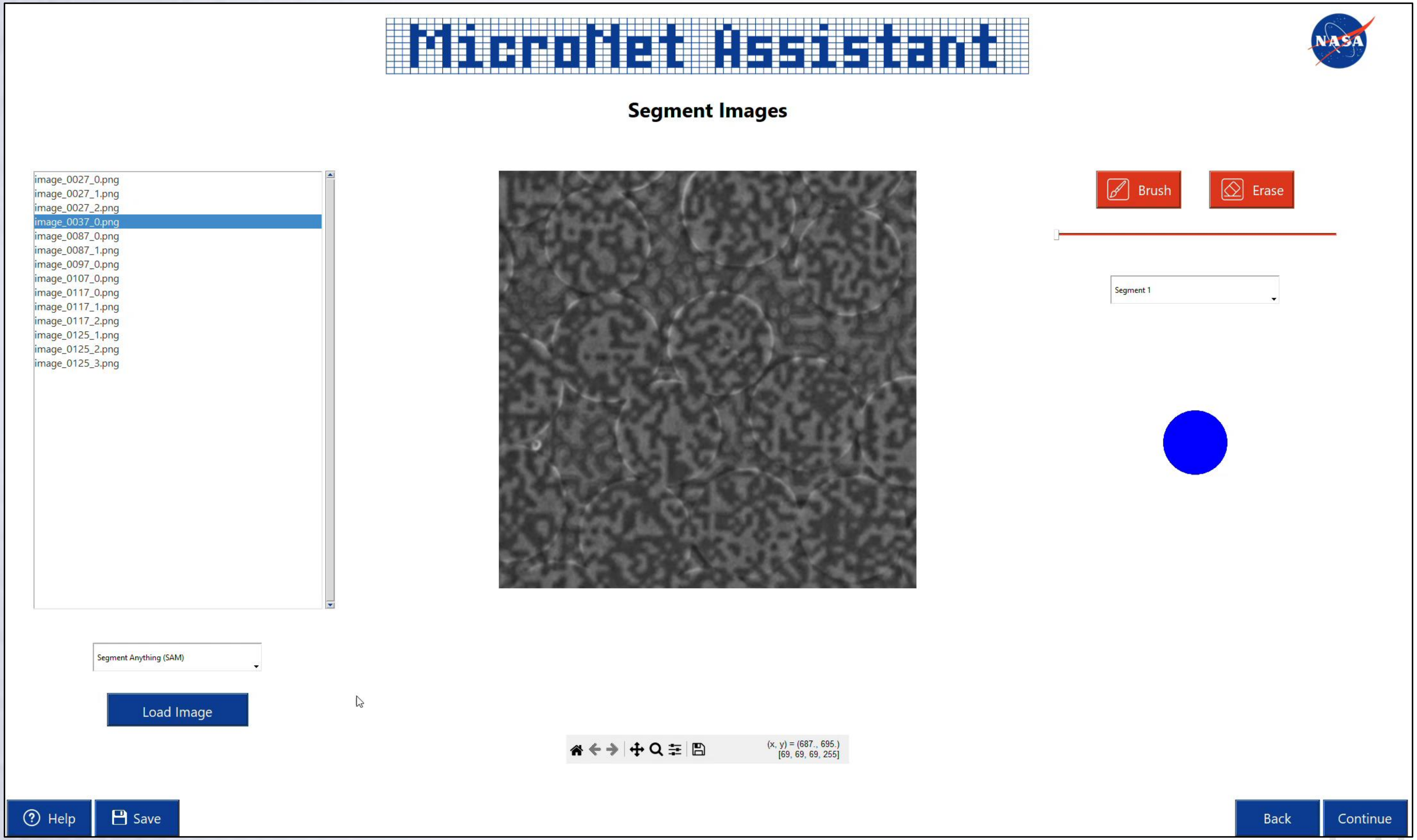
Rapid Annotation of Microscopy Images for MicroNet Training

- MicroNet Assistant Tool enables rapid preprocessing and labelling of images for model training
  - Designated User Interface for selecting images, resizing for MicroNet, and cropping images for training
  - Segment Anything Model built in to select features assigned to a class
  - Brush/Eraser tools to manually edit SAM predictions
  - Significantly reduces the time to label images for training



MicroNet Assistant Tool

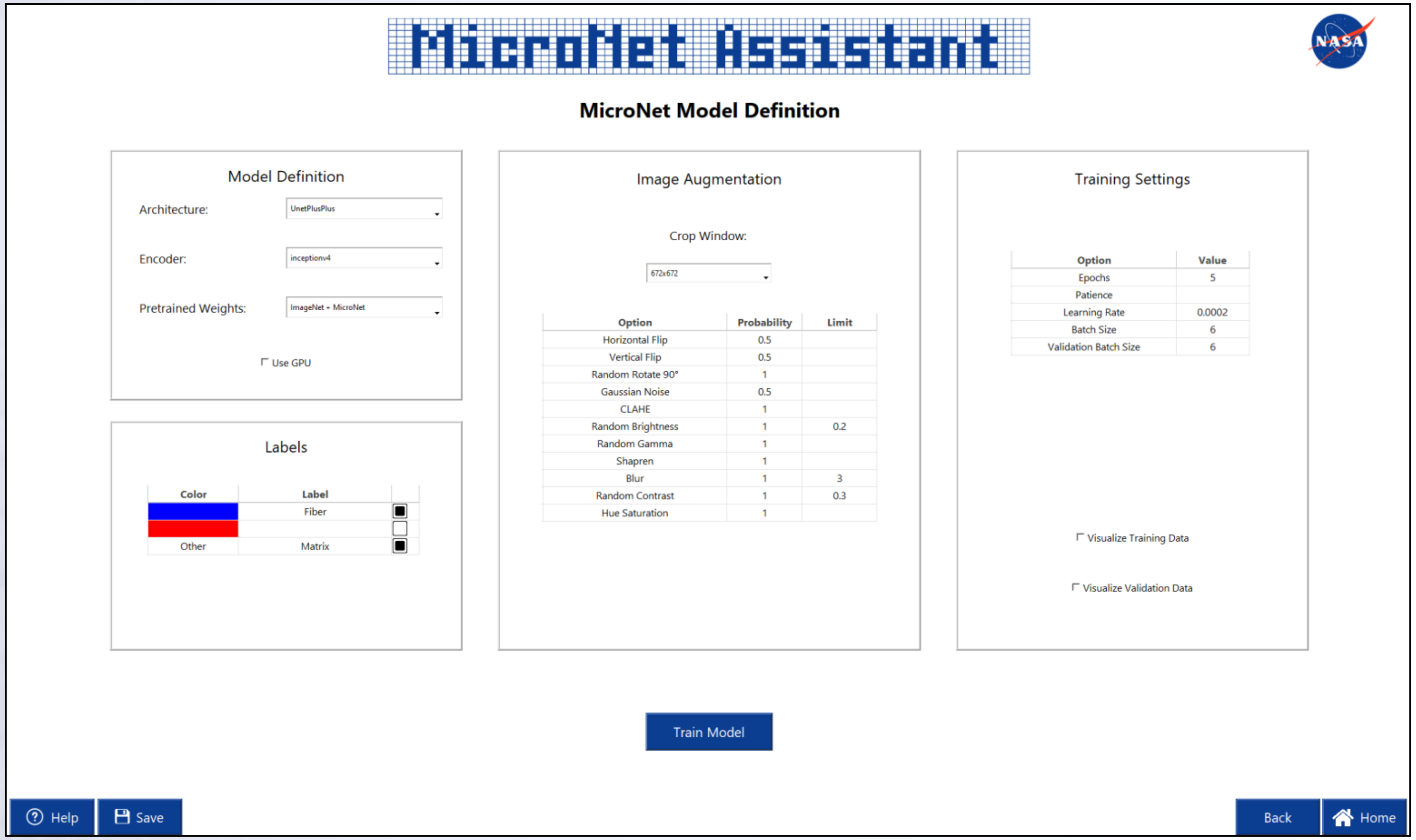
Rapid Annotation of Microscopy Images for MicroNet Training



MicroNet Model Parameters

Model Settings for Training

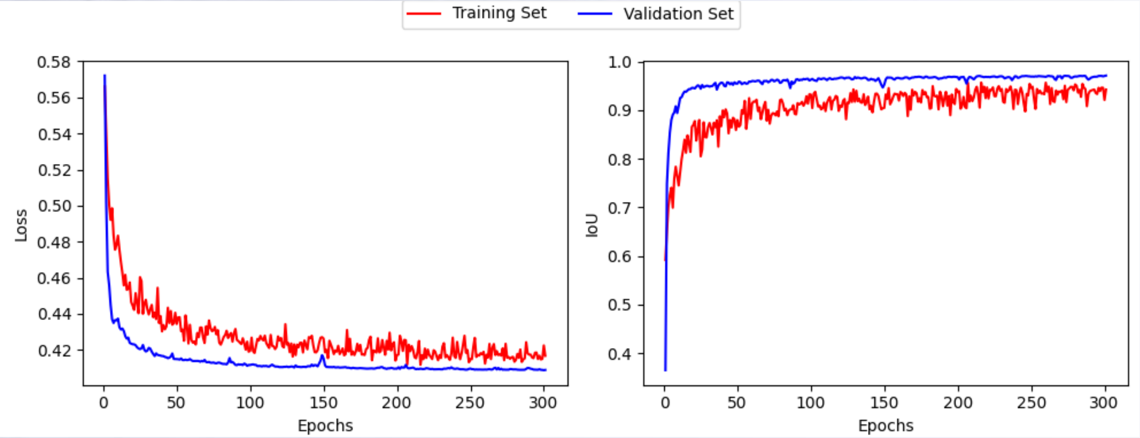
- GUI offers all options available in MicroNet to be selected and modified, including the model architecture, encoder, pre-trained weights, image augmentation settings, and training settings.
- Models can be trained, saved, and used within the GUI for segmenting images

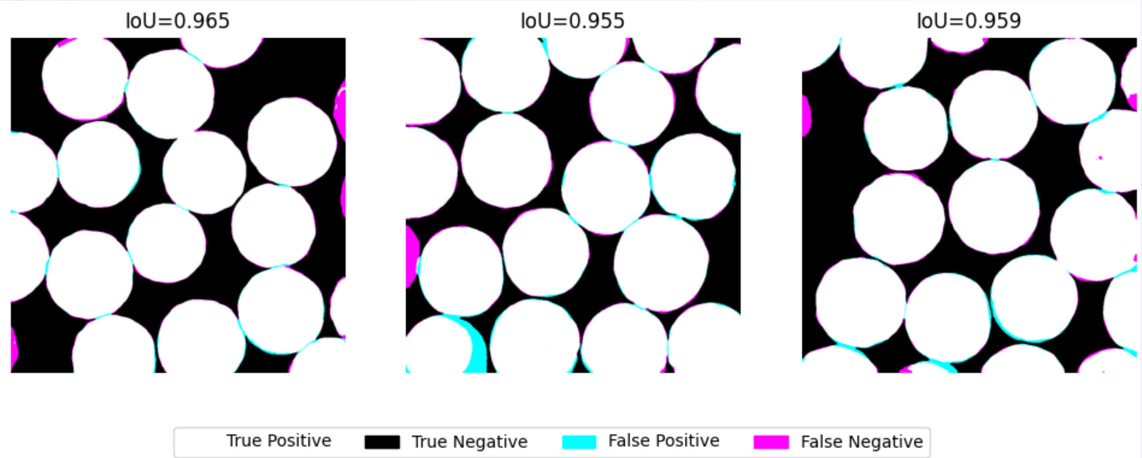


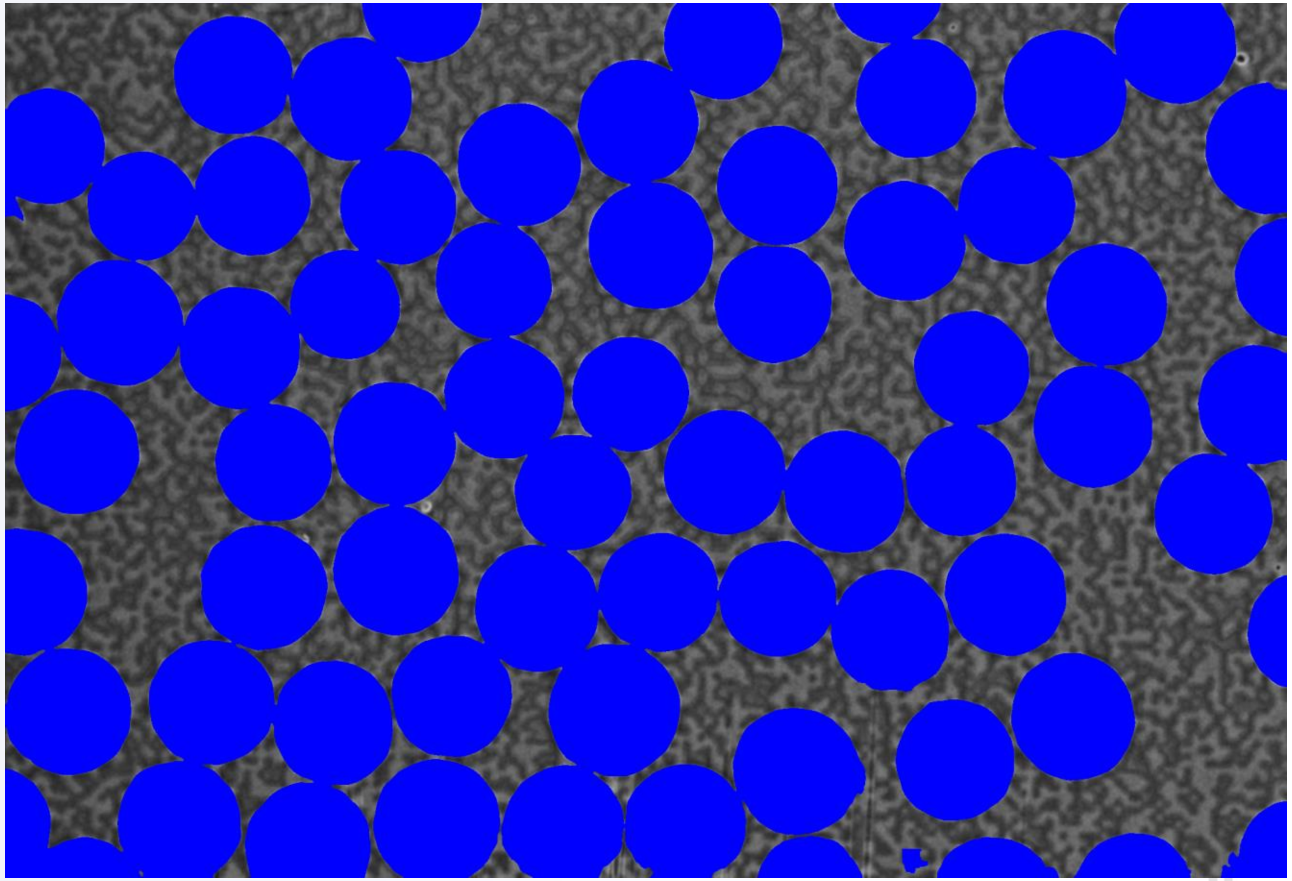
MicroNet Model Performance

Test Set and Full-Scale Model Predictions

Overall IoU: 0.971 – Trained on 10 images



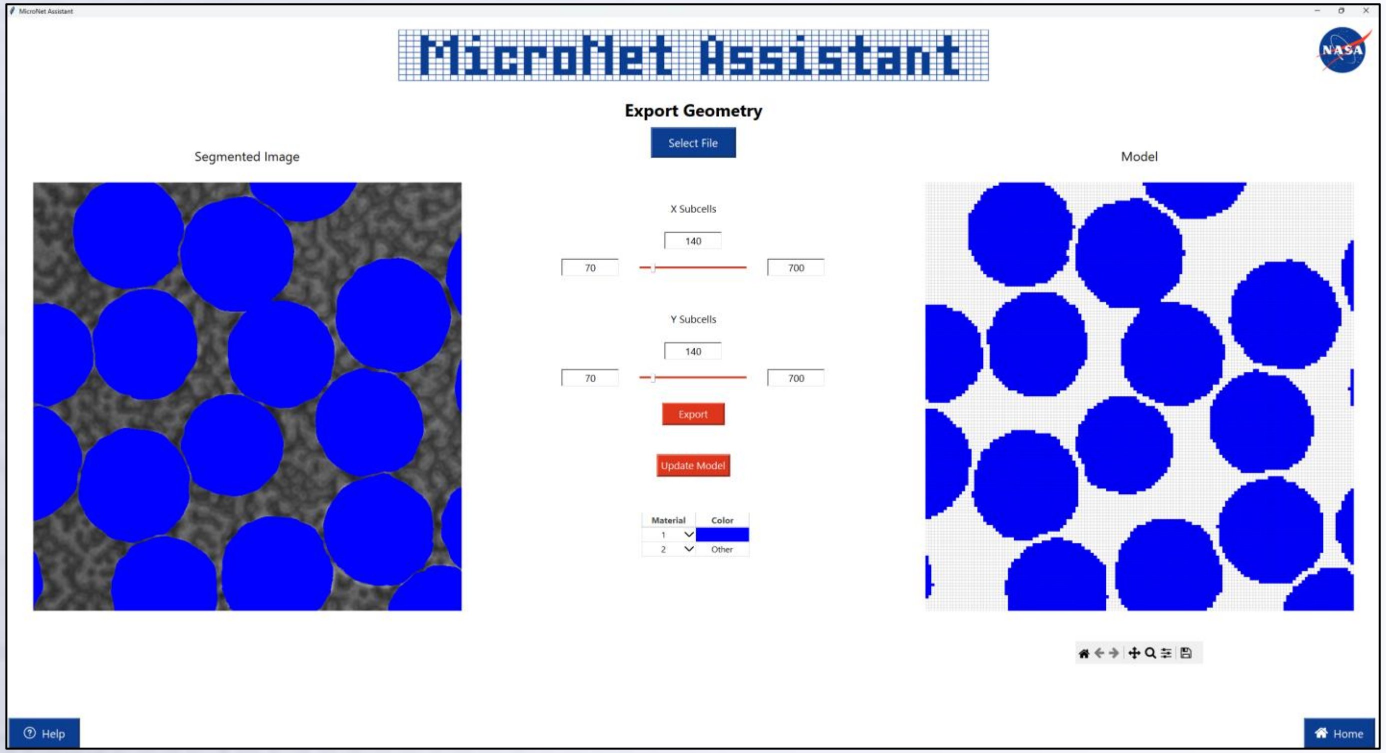


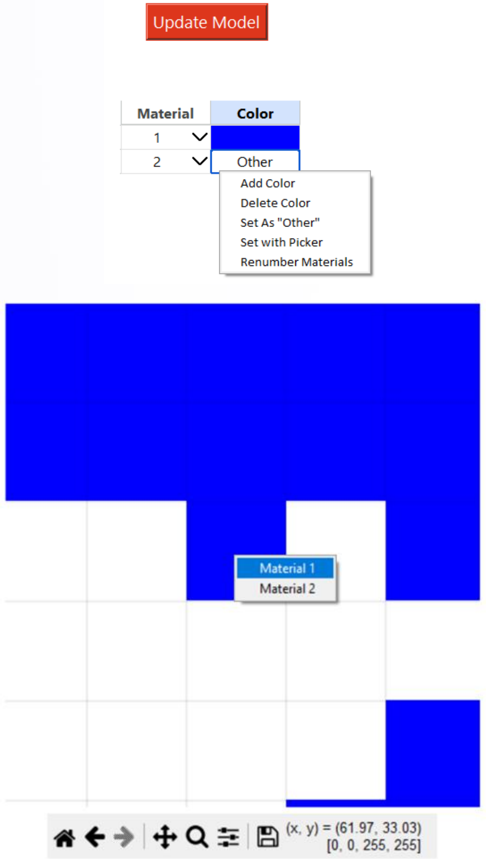


Generating Digital Twins

Geometry Exporter in the MicroNet Assistant Tool

- GUI allows users to generate voxelated models with set number of voxels (subcells) in the X and Y directions
  - Image interpolation can lead to anomalous subcell assignment (matrix surrounded by fiber, non-circular representation of the fiber, etc.)
  - Voxels can be manually assigned if desired
- Geometry can be directly exported to NASMAT for microscale simulations



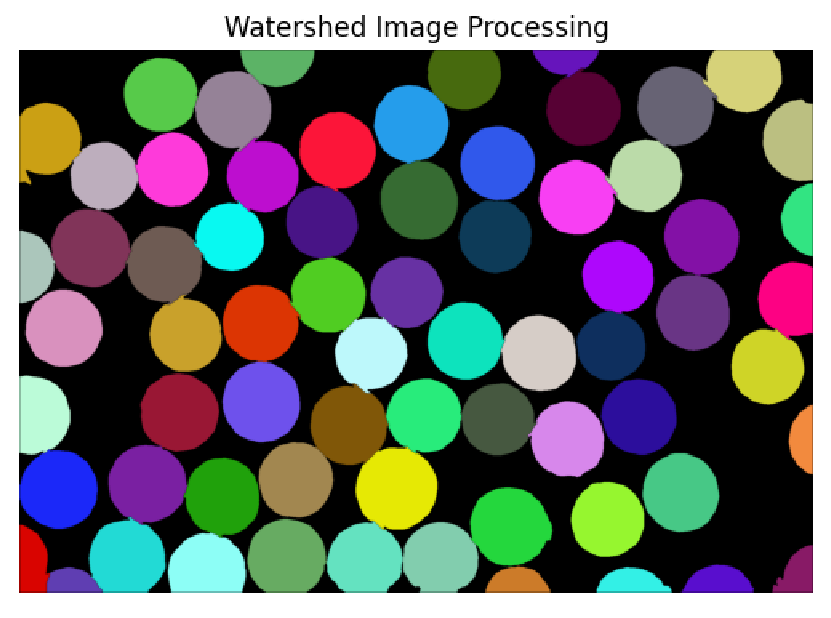


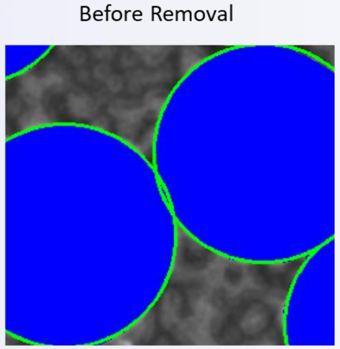
Individual Fiber Recognition

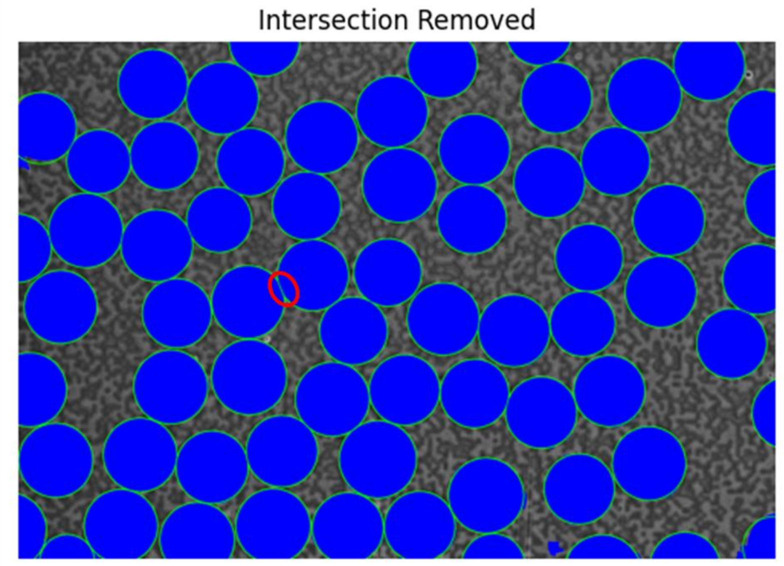
Find Boundaries of Each Individual Fiber in the Segmentation

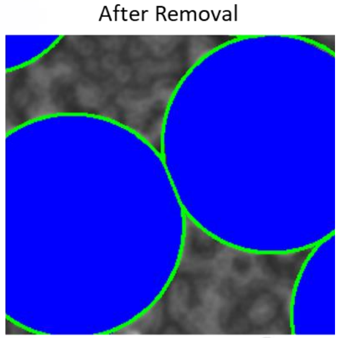
- Fiber recognition algorithm was developed to identify individual fibers within the segmented image and remove outlier fiber classifications from the segmentations
  - Touching fibers need to be modeled with debonding in NASMAT – need individual fiber boundaries

- Fiber Recognition Algorithm:
  - Watershed algorithm is used to identify individual bodies, then circles are fit to each boundary
  - Intersection Ing fit boundaries are identified and removed



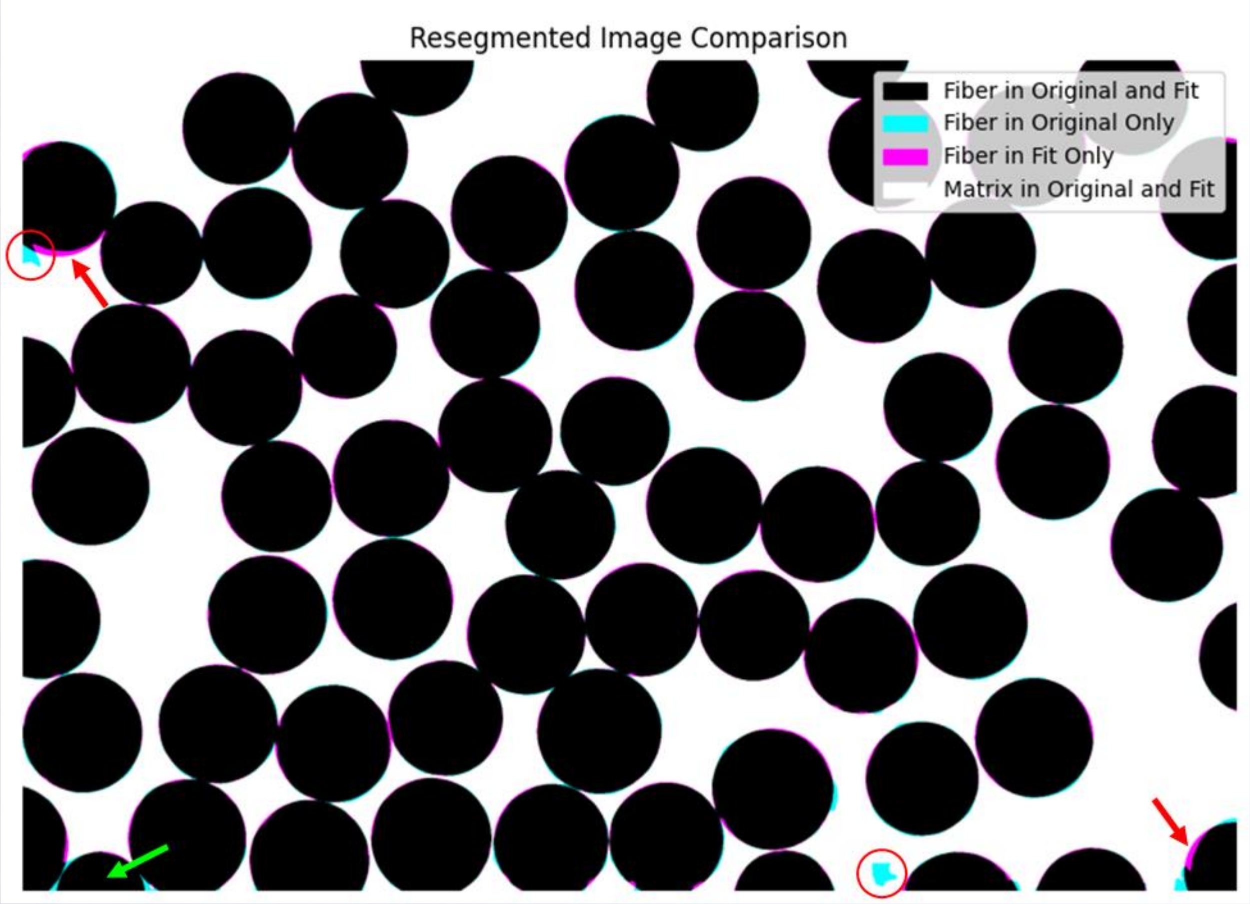


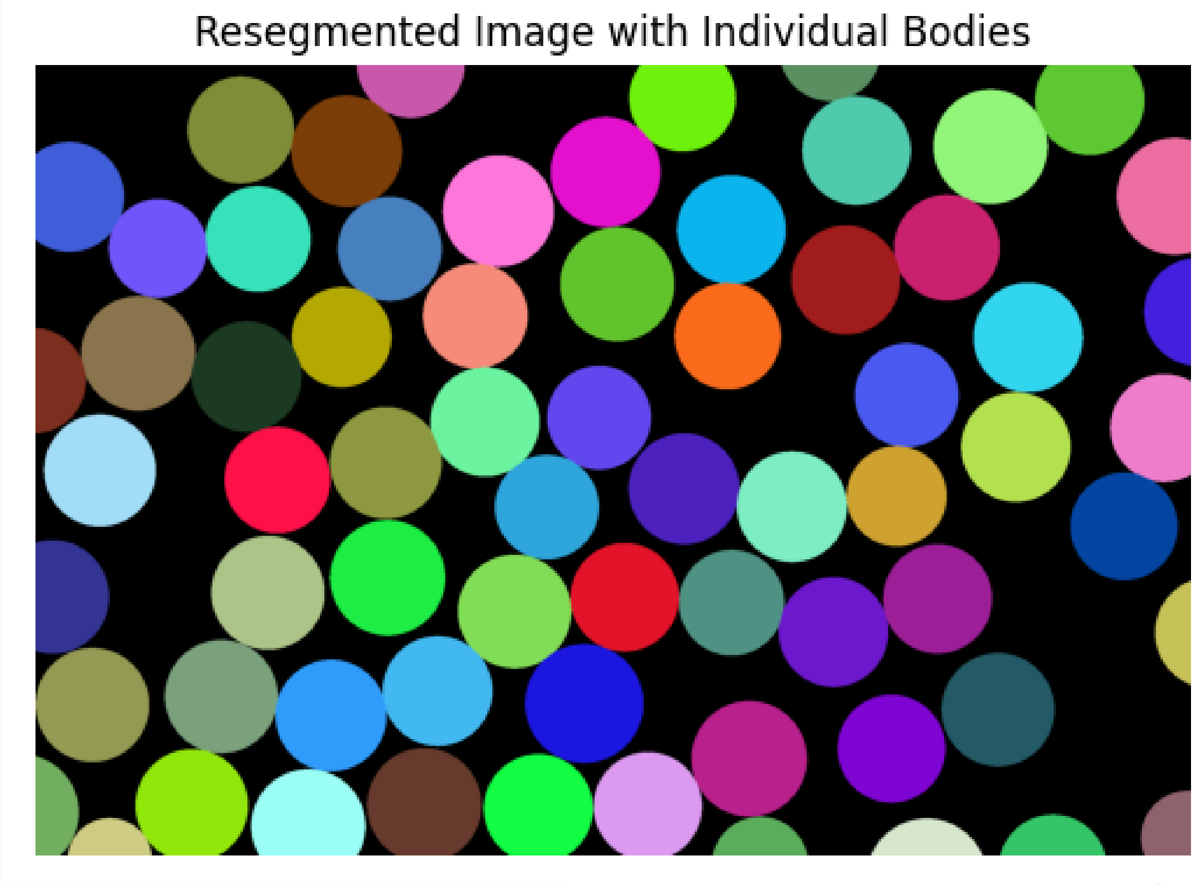




Idealized RVE Representation

Resulting Image after Idealization

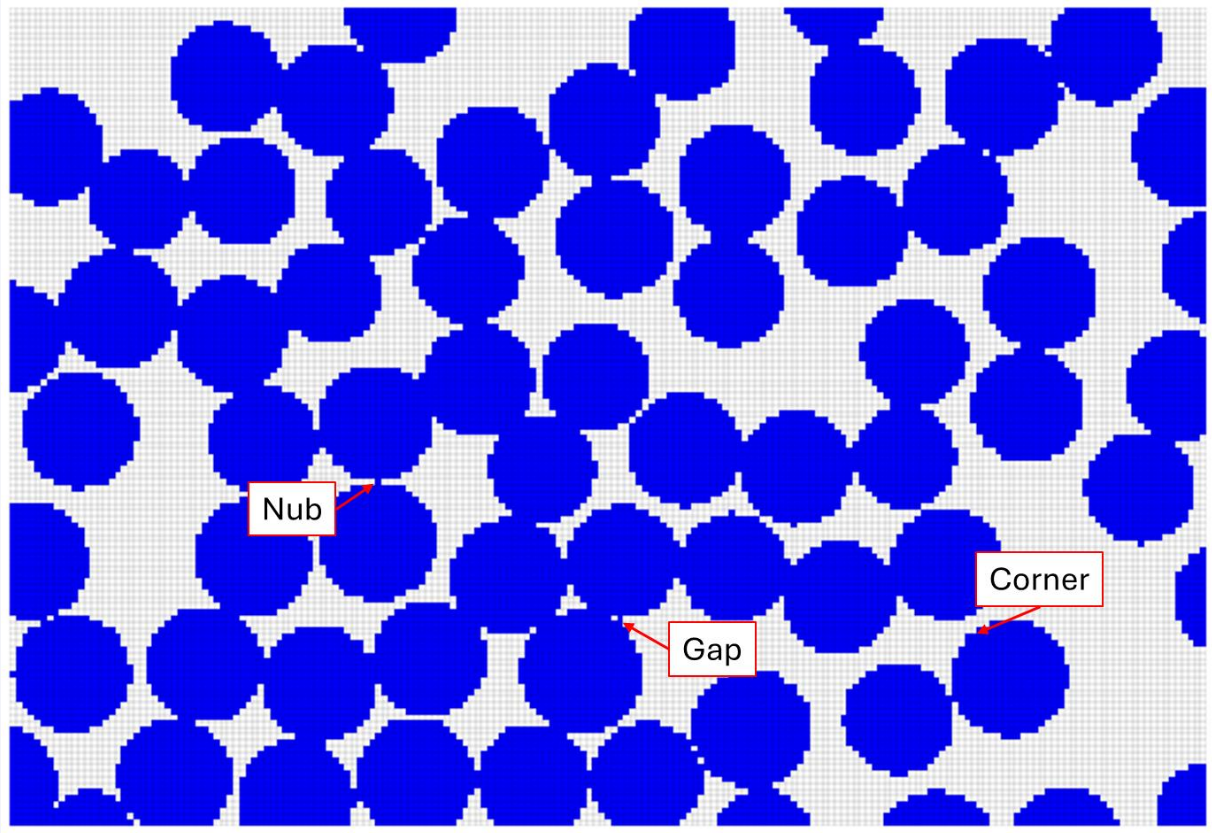




NASMAT Model Generation

Resizing the Image for NASMAT

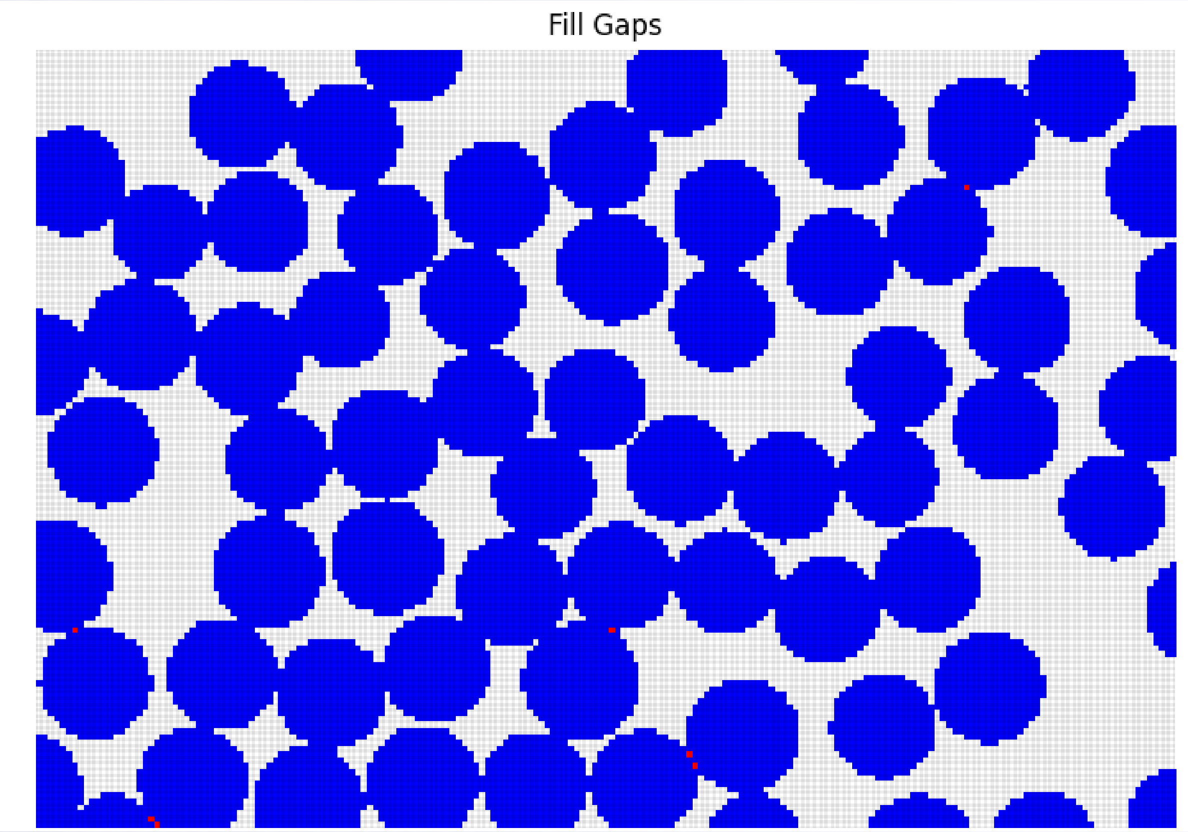
- Voxelated model can be generated with individual bodies recognized and outliers removed from the segmentation
  - Still susceptible to anomalous subcell assignments (gaps, nubs, and corners)



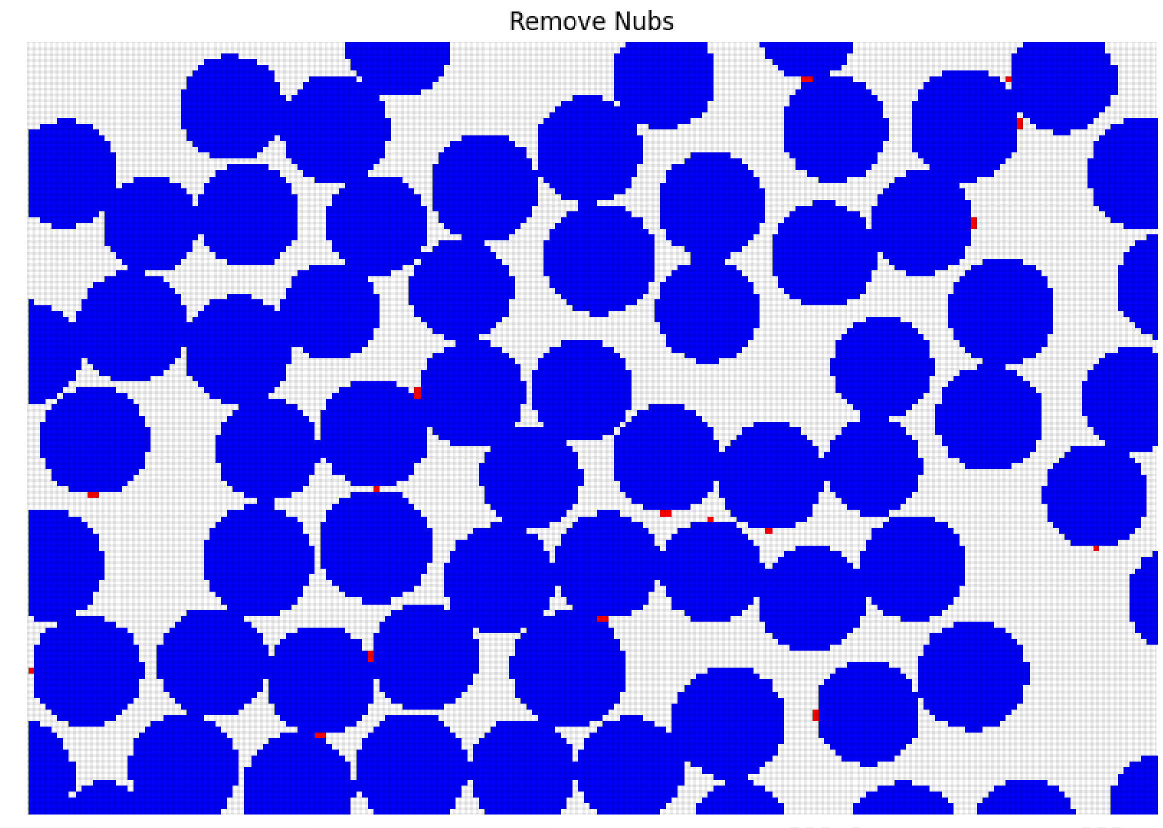
NASMAT Model Generation

Removing Anomalous Subcells

- Individual subroutines written for filling gaps and removing nubs and corners
  - Users can specify the “nub length” and “corner length” to get desired idealized microstructure



Red subcells changed from matrix to fiber

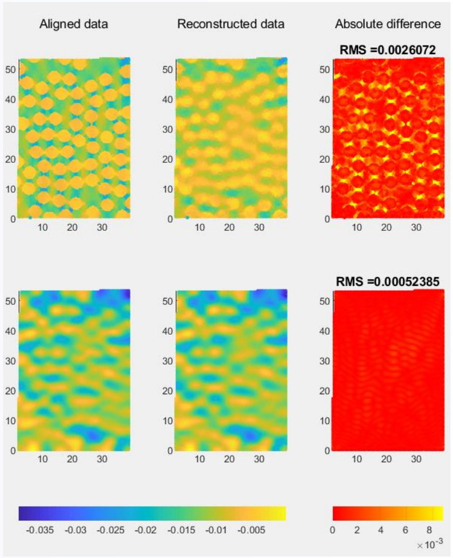


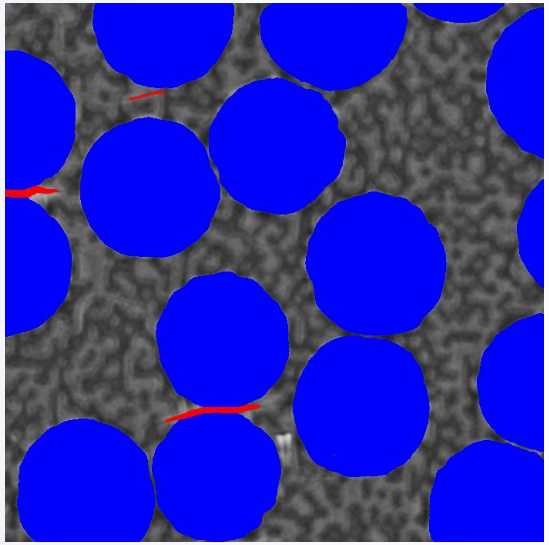
Red subcells changed from fiber to matrix

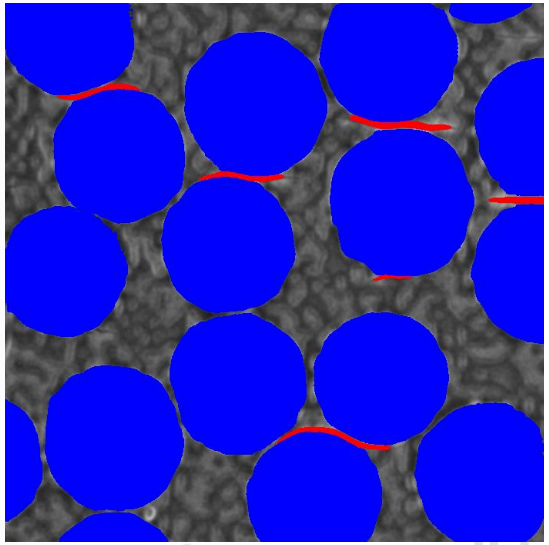
Ongoing Work

Creating and Validating Microscale Digital Twins

- Currently gathering in-house microscale compression test data with Digital Image Correlation (DIC) to compare simulations
  - MicroNet Assistant Tool Segmentation Model allows a 1:1 copy of microstructure → enables digital twin creation
- Investigating methodologies for quantitively comparing full field experimental data and predictions
  - Building off previous work in [1]
- Training segmentation models for automatic crack recognition and measurement during testing
  - MicroNet Assistant Tool enables multiple classes to be segmented in a single model







[1] T. Felgenhauer, I. Gallegos, M. Flores, E. Pineda, B. Hearley, S. Venkataraman, "Quantitative Comparison of Local Strain Data in Micromechanics Models and Experiments of Composite Micropillars", SciTech 2024.

Summary

- Development of experimentally validated digital twins at multiple length scales is critical in realizing the time and cost savings associated with ICME
- Currently, micromechanics theories can only be validated using finite element analysis as ground truth, or looking at homogenized experimental data at higher length scales → no true digital twin
- Digital twins must contain a 1:1 representation of a physical entity → need to accurately capture the microstructure of a material in a simulation
- The MicroNet Assistant Tool offers users a democratized methodology of rapidly pre-processing, annotating, and training robust segmentation models for microscopy images
    - Users with little-to-no Python and machine learning knowledge can train and use segmentation models
    - Fiber idealization algorithm improves segmentation accuracy and enables automatic generation of geometric models for simulation
- Current efforts in collecting microscale test data and developing methodologies for quantitively assessing full field predictions and experiments will result in a methodology for establishing microscale digital twins

NASA